FUTURE FORESTS RESEARCH

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Modelling Radiata Pine Wood Density in Relation to Site, Climate and Genetic Factors

Part 1: Density Surfaces

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EXECUTIVE SUMMARY

Wood density in *Pinus radiata* is often used as a surrogate for stem stiffness and is central to the accounting of carbon sequestration in plantations. Therefore it is important to be able to map and model its distribution across New Zealand, and to understand how it is influenced by environmental variables and management. Previous work has provided regional wood density classes, but more detailed maps would improve the current state of knowledge. Wood from New Zealand plantations is known to be variable in density, and past studies are largely determined by tree age and mean annual temperature. There is now a large amount of data available from hundreds of studies which can be combined with geospatial information to create a more accurate tool for density prediction. The objective of this study is to collate basic density data from past studies in order to create new models for:

1. Generating new regional maps of the development of outerwood basic density with stand age and silvicultural treatment, based on geographical, site and genetic variables.
2. Using a comprehensive dataset of within-stem density variation to generate a new model to estimate tree component densities based on actual or predicted outerwood values. Allow for the prediction of outerwood density forward and backwards in time.
3. Investigate the need for genetic adjustments in the prediction of wood density components to cater for the introduction of specific breeds.

This report (Part 1 of the project) covers Objective 1 while Objective 2 is covered in Report Part 2. Work on Objective 3 is ongoing.

Using an extensive dataset (*n* = 1214), a regression model was developed to predict outerwood density. Mean annual air temperature and stand age were the two variables most influential on outerwood density. Mean annual air temperature was included in the model as a positive linear relationship, whereas the natural log of age was fitted with a polynomial function that increases to maxima at ~60 years. Planting decade was added to the model as a categorical variable that demonstrated that wood density was higher in stands established in the 1920s to the 1960s, but declined by around 15-20 kg m^{-3} in stands established in the 1980s and 1990s, probably due to a combination of silviculture and genetics.

A national map of *P. radiata* age 20 outerwood density was produced using these variables, with spatial adjustments to account for variation not explained by the regression model. The map of outerwood density varies widely across New Zealand, with highest values in the warmer northern latitudes of the upper North Island and in the north of the South Island. Conversely, cooler southern latitudes and higher elevations had the lowest outerwood density values.

For the wood density surface analyses, validation data (n = 200) found the developed model accounted for 70% of the variance in outerwood density at the plot level, and over 99% at the regional level. The resulting model can be used to assign outerwood values to greenfield sites (i.e., new forest sites without forests previously on them) and to feed into the within-tree density model produced as Part 2 of this project, which provides predictions of log densities and carbon content. The map and associated density model will be implemented in FFR's Forecaster

INTRODUCTION

Over the past 40 years, improvements in tree breeding and silviculture have resulted in a reduction of the rotation age of about 50%, and some substantial changes in wood quality. The wood properties of radiata pine vary significantly across the growing range, between crops, between individual stems and within stems.

Geographic variation in wood characteristics is known to exist with radiata pine in New Zealand and Australia[1-4]. Several studies have concluded that both tree age and climatic variables are of major importance[5,6]. Increased density is associated with higher mean annual temperatures and sometimes with summer rainfall[5,7-9]. Another common feature is the significant tree-to-tree variation in wood density, which necessitates a careful sampling strategy[10-11]. Most studies analysed wood samples only from the breast height position.

Forest companies traditionally predict yield in terms of volumes and log grades for planning purposes. In recent years, additional log grade criteria can include wood quality measures, including estimates of stiffness. Wood basic density is the most widely used indicator of quality, as it affects many end use properties, including timber stiffness[12] and pulp and paper yield and quality, and also contributes to carbon sequestration measures[13-17]. Foresters are interested in the implications for the whole stem, and attempts have been made to create models to describe variations in branch and wood properties, and predict product characteristics[18-21]. Some of these approaches also integrate with growth models to take silviculture into account[22].

Past research has allowed the evaluation of crop age and climatic effects on density[23], along with silvicultural influences[24-29] . Models which predict regional density and stem log densities[30-31] have been developed. These tools have been used extensively in resource surveys in both New Zealand and Australia.

More recently, the Wood Quality Initiative (WQI)[32], reviewed an existing predictive model[33] and concluded that while it performed reasonably well, there were some small limitations, particularly with genetic data. WQI subsequently created a new separate model from industry data, mainly Central North Island, but supplemented by data from some 33 sites nationwide[34] to extend the range[35]. Findings of several studies have indicated that most of the observed variation in outerwood density arises among individual tree values. This trait is closely related to crop age, and the relationship between diameter and outerwood density is mostly negative and very weak[9,33,35].

All of the previous models have used smaller datasets with limited regional coverage. There is now an opportunity to create a more comprehensive density database to model log and stem density and predict stand dry matter accumulation by combining databases. Scion has data from around 1,000 sites covering all regions of NZ (and some of Australia) and has negotiated access to the WQI data set.

While geographic location explains much of the variation in outerwood density[2,33,35], for many sites there is additional information available to explain inter-site variation by including other external drivers such as silvicultural, genetic, or climatic variables.

Wood density is highly heritable[36], and efforts have been made to create a "high density" breed[37]. While many assessments have been carried out in young material, there are limited data on the effect of genotype on forest crops. Data on GF Plus relating to density will be available. Existing genetic gain and special purpose breed trials largely represent historic tree improvement stock-types. In order to represent present-day and future tree improvement stock-types, consideration and action is required towards the next generation of tree improvement trials.

Objectives

The objective of this study is to collate basic density data from past studies in order to create new models for:

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2. Using a comprehensive dataset of within-stem density variation to generate a new model to estimate tree component densities based on actual or predicted outerwood values. Allow for the prediction of outerwood density forward and backwards in time.
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METHODS

Data Acquisition and Preliminary Screening

Studies by Scion over the past 40 years were screened for potential data to be included in a new comprehensive *Pinus radiata* density database. There are hundreds of individual wood quality studies, covering effects of site, silviculture, genetics and crop age on measures of wood density (gravimetric and X-ray), containing information for over a thousand sites. Site outerwood wood density values (mean and range) were collated from around New Zealand to support a global surface study by site and crop age. Many studies included both breast height outerwood and individual log density values to allow prediction using site, crop age and silviculture data.

The final outerwood density database contains measurements from a total of 1214 sites. At each site, breast height outerwood density was obtained from about 30 sample trees, but occasionally from a much larger number (range 5–1825 trees per site, median 30, mean 146). Outerwood cores were taken at breast height from each sample tree, and density was determined using the maximum moisture content method for either the outer five rings or the outer 50 mm (with the data being approximately evenly split between these two sample types). Outerwood density was averaged for each site. Where geographic coordinates were not recorded, the spatial locations were estimated from forest compartment maps. The final dataset spatially covers the majority of New Zealand (Figure 1).

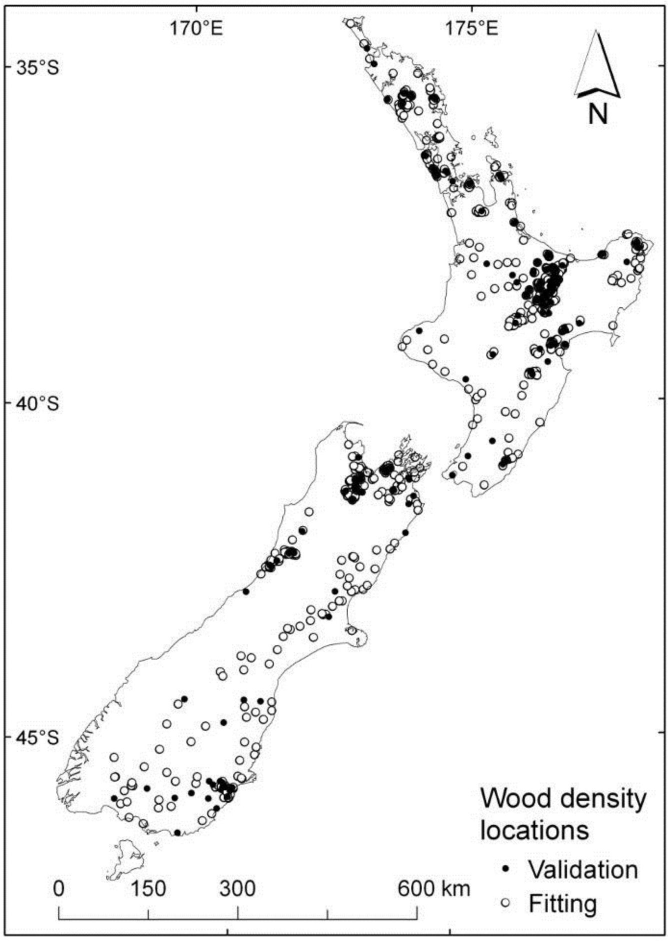

Figure 1. New Zealand map showing the location of *Pinus radiata* outerwood density data used for the fitting (open circles) and validation (filled circles) of the model.

Meteorological and Biophysical Data

The mean monthly climate data used in this study were obtained from NIWA (National Institute of Water and Atmospheric Research Ltd.). The maps representing air temperature were derived from data collected over a 30-year period from 1971 to 2000, and are at a 500 m cell size resolution. Meteorological data used in exploratory correlation analyses included mean monthly temperature, rainfall, rain days, relative humidity, solar radiation, vapour pressure deficit, and wind speed.

From each of the outerwood density observation co-ordinates, data were extracted from the climate and environmental data. Data included monthly climate variables[38], carbon to nitrogen ratio[39], land use capability and fundamental soil layers[40-41](NWASCO, 1979; SCRCC, 1974)(NWASCO, 1979; SCRCC, 1974), Land Environments New Zealand[42-43], and the vegetation cover map[44].

Predictive Variables Included in the Model

Independent variables used in the outerwood density model included the continuous variables tree age, and planting year. The planting year was further grouped into 8 classes to be representative of the genetic and management influence occurring across the dataset period. The only meteorological data included in the final model was mean annual air temperature.

Regression kriging is a method of predicting values at unknown sites through spatial interpolation of known observations. It consists of two components, (1) a regression model using auxiliary variables related to the dependent variable (wood density in this case), and (2) spatial interpolation of the residuals from the regression model. The combined effect of these components can provide better predictions than a simple regression model or spatial interpolation model. Further details of the regression kriging model and statistical analysis can be found the Appendix.

RESULTS

Final Outerwood Density Model

Mean annual air temperature and mean daily solar radiation varied substantially across sites, ranging from 7.3 to 16.4^{o}C and 11.5 to 15.4 MJ m^{-2} per day, respectively. Rainfall ranged nine fold across sites from 368 to 3,564 mm per year (Table 1).

Table 1. Range in mean annual air temperature, mean daily solar radiation, and total annual rainfall for the *Pinus radiata* outerwood density plots.

Variable	Range	Mean
Mean annual air temperature (^{o}C)	7.3-16.4	12.0
Mean total daily solar radiation (MJ m^{-2} day^{-1})	11.5-15.4	14.1
Mean total annual rainfall (mm year^{-1})	368-3,564	1458

The final regression model for outerwood density included the natural log of stand age, mean annual air temperature, and planting decade, and accounted for 66% of the variance in outerwood density. All the variables were highly significant ($P<0.0001$) and had partial R^2 values of 39.4% (combined effect of ln(Age) and ln(Age)^2), 25.2%, and 1.3%, respectively (Table 2). The outerwood densities in the data were measured using either 50-mm cores or the outer five growth rings. However, a test confirmed there was no significant difference in density between these two methods of sampling (mean values 433.5 and 431.8 kg m^{-3} respectively).

The regression model was:

$$\text{Outerwood density} = a + b \times \ln(Age) + c \times \ln(Age)^2 + d \times Temp + e \times Decade \qquad (3)$$

where *a*, *b*, *c*, and *d* are empirically derived parameters for the variables (Age, Temp), with separate parameter values (*e*) for each of the classes within planting decade (see Table 2 for parameter values). After developing the regression model, the second step in the regression kriging process was to fit a spatial model to the regression residuals (actual minus predicted values). An isotrophic spherical model was found to best fit the residuals of the regression model, and provided a map with substantially improved predictions. Further details of the regression kriging technique are given in the Appendix.

Model Validation

The final model inclusive of spatial covariance accounted for 70% of the variance in the validation dataset, with a Root Mean Square Error (RMSE) of 21.3 kg m^{-3} (see Table 2, *Validation set*). Residuals for the final model were normally distributed, and exhibited little apparent bias with predicted values (Figure 2). The model has significant error in prediction when applied to an individual plot. For example, 5% of plots will have prediction errors greater than twice the RMSE or 42 kg m^{-3}. However, when plots are grouped, for example to the regional level, the prediction error was greatly reduced. Using the validation data, the error of regional mean predictions was extremely low (1.5 kg m^{-3}) (Fig. 3).

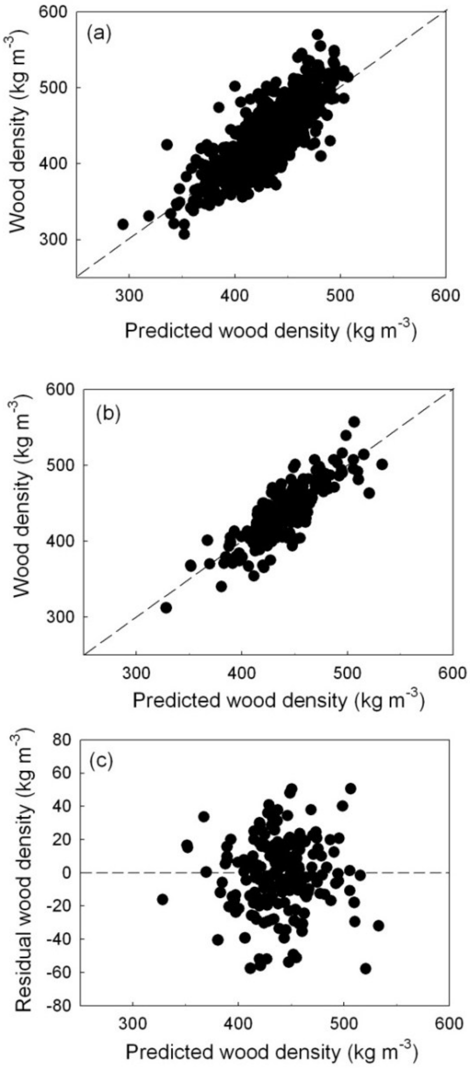

Figure 2. Relationship between predicted and actual *Pinus radiata* outerwood density for (a) the fitting (*n*=1014), and (b) the validation datasets (*n*=200). Also shown is the relationship between predicted outerwood density and its residual (c).

Table 2. Summary of statistics used to describe *Pinus radiata* outerwood density for the final predictive model. Parameter values and variable partial R^2 and cumulative R^2 values are shown. For the significance category, the *P* categories from an *F*-test are shown. For planting decade the values of the coefficients (*e*) are shown with comparisons between them made using the least significant difference (LSD) test. Values followed by the same letter are not significantly different at *P*=0.05.

Equation:
Outerwood density = *a* + *b*×*ln(Age)* + *c*×*ln(Age)*^{2} + *d*×*Temp* + *e*×*Decade*

Para.	Coeff.	Term		Units	*Partial* R^2 Model set†	R^2 Model set†	R^2 Validation set‡	P-value & LSD
a	-26.5	Intercept						<0.0001
b	150.3	log(Age)		Years	37.4	37.4	35.4	<0.0001
c	-13.9	log(Age)^2			2.0	39.4	37.2	<0.0001
d	9.4	Mean air temp. (T_a)		°C	25.2	64.6	65.8	<0.0001
e		Planting decade* (*D*)			1.3	65.9	67.3	
	3.9	1920 - 1930						cd
	12.6	1930 - 1940						ab
	15.6	1940 - 1950						a
	14.2	1950 - 1960						a
	9.2	1960 - 1970						bc
	1.1	1970 - 1980						d
	-5.6	1980 - 1990						d
	0.0	> 1990						d
		Residual kriging			12.9	78.8	69.7	

*** Values followed by the same letter do not differ significantly (*p*=0.05)**
† Variance explained calculated for the model data set
‡ Variance explained calculated for the validation data set

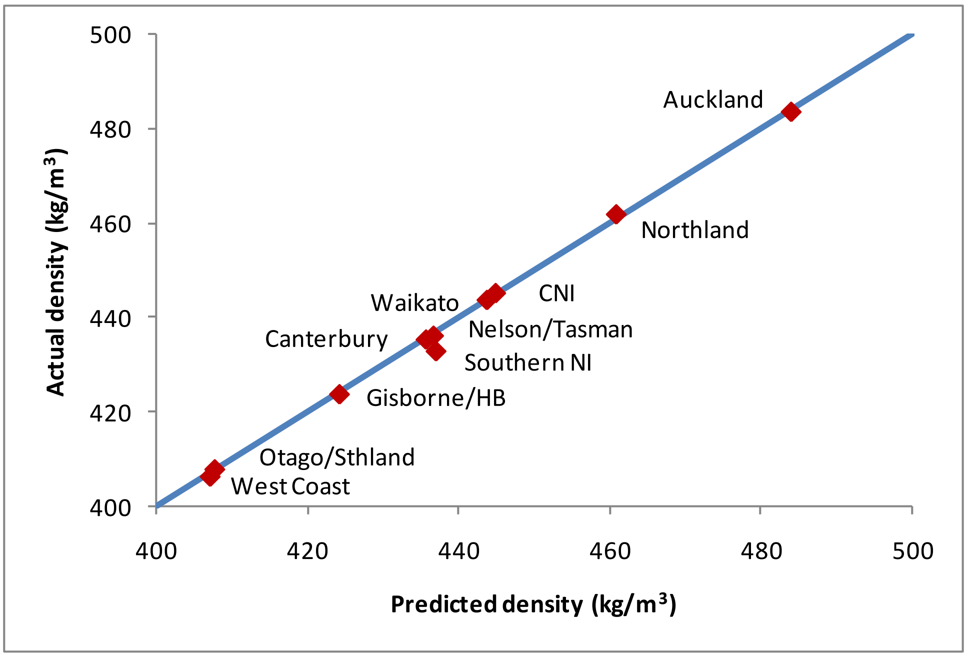

Figure 3. Observed versus predicted *Pinus radiata* outerwood density for regions for the validation dataset.

Regression Model Partial Responses and Least Square Means

Using the final model, partial response surfaces were generated to characterise the functional form of age, planting decade and mean annual air temperature. A quadratic relationship was found between Age and outerwood density that increased to a maxima at 60 years before declining (Figure 4a). Outerwood density also increases linearly with air temperature, ranging from 380 kg m^{-3} at 7°C to 480 kg m^{-3} at 17°C (Figure 4b). Planting decade was less sensitive to outerwood density, with a smaller increase in wood density across the 1920 to 1960 period of 11.4 kg m^{-3}, peaking at 443.9 kg m^{-3}, before decreasing to a low in the 1980s of 425.7 kg m^{-3} (Figure 4c).

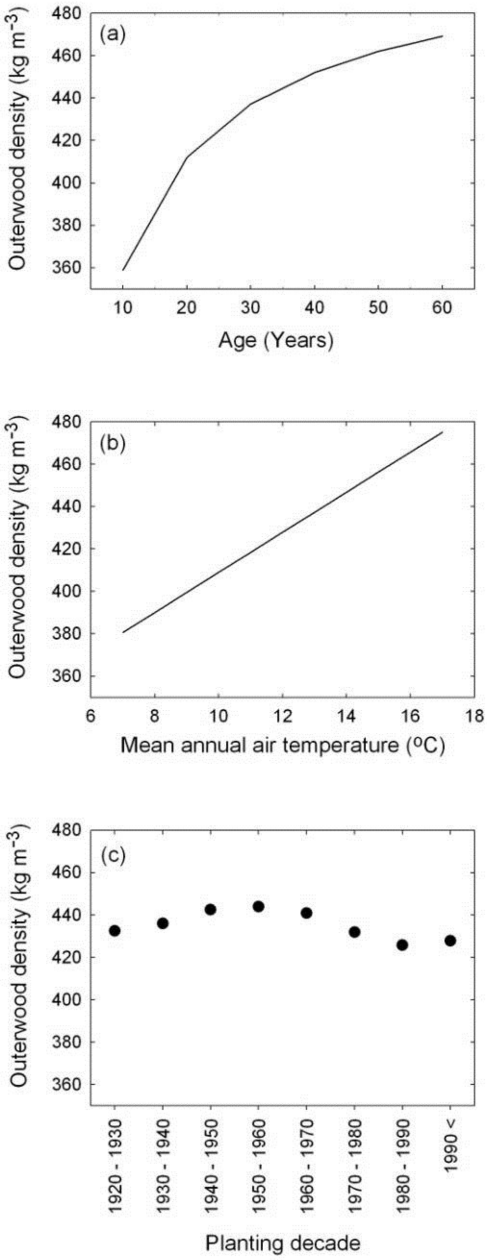

Figure 4. Partial response curves of *Pinus radiata* outerwood density for (a) age, (b) mean annual air temperature, and (c) planting decade. When each partial response curve was generated, all other variables in the model were held constant at mean values.

Investigation into the differences between the categorical variable planting decade using least square means provides insight into the main groupings of outerwood density values. Two main distinctive groupings stood out for the 1930-1960 period, and 1970 through to present day. The 1920-30 period stood alone, but did not differ significantly from the later period of 1970 through to the present day, whereas the 1960-1970 period did not differ significantly from the 1920-1930, and 1930-1940 periods (Table 2). Overall density declined by around 15-20 kg m^{-3} in stands established in the 1980s and 1990s compared with those established in earlier decades, probably due to a combination of silviculture and genetics.

Spatial Predictions

A map of the final regression kriging surface (Figure 5) confirms the predicted outerwood density shows a wide variation throughout New Zealand, particularly in the North Island. Values of outerwood density are highest in warmer northern regions of the North Island and the far north of the South Island. Reductions in outerwood density occur with decreasing latitudes of the South Island and with decreasing temperature in elevated regions.

This final map consists of the summation of the regression model surface and the spatially interpolated map of the regression residuals. These two components are shown in Figures 6 and 7. Although the regression model (Figure 6), which is primarily driven by air temperature, explains much of the variation in wood density, there was significant spatial variation in the errors of this model, which when spatially interpolated and added to the regression model, significantly improved predictions (Table 2). The surface of kriged residuals (Figure 7) shows which parts of the country are over- or under-predicted by the regression model.

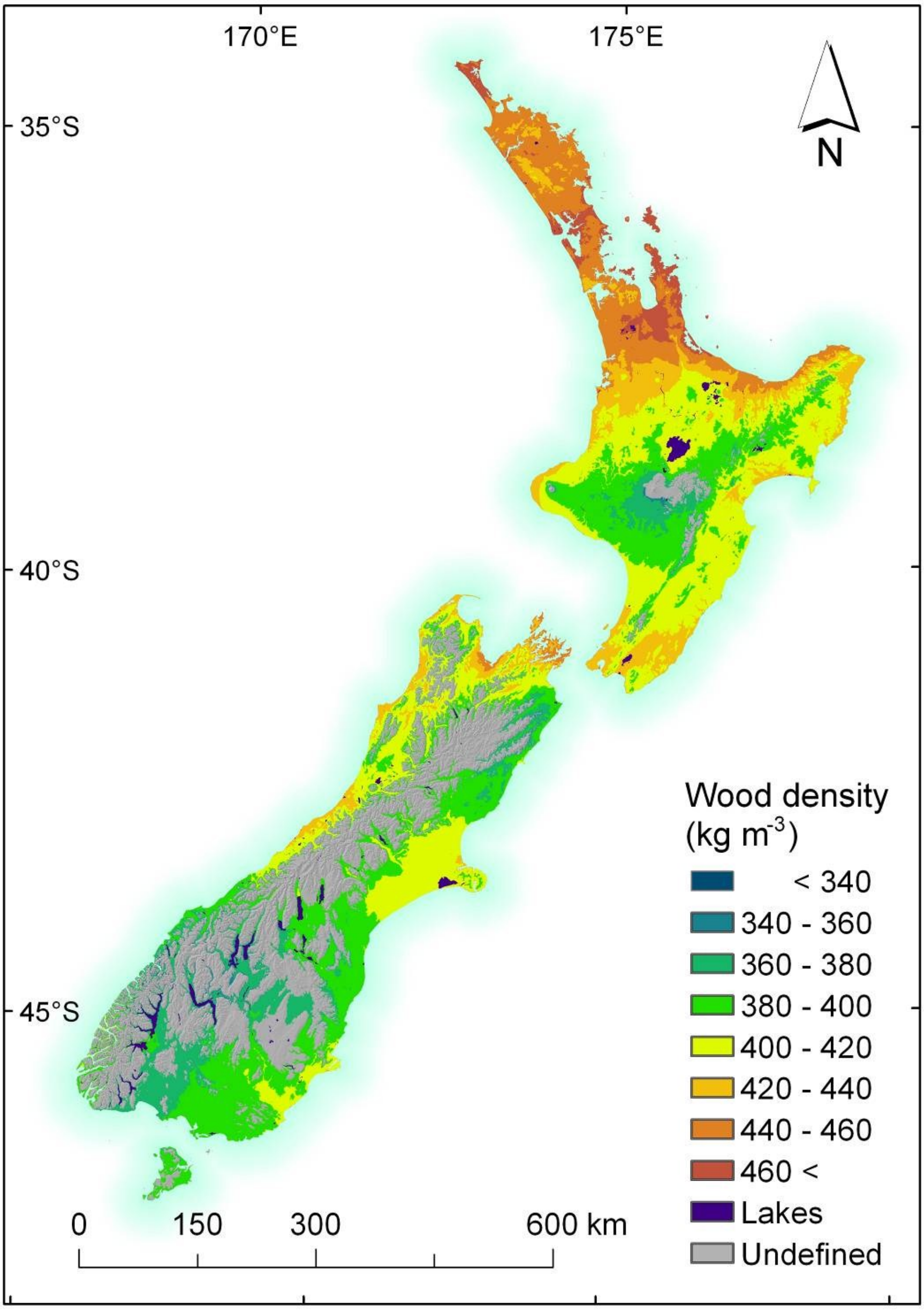

Figure 5. Regression kriging surface showing spatial variation in predicted *Pinus radiata* outerwood density across New Zealand. Tree age was set to 20 years and planting decade held constant at the 1990 level.

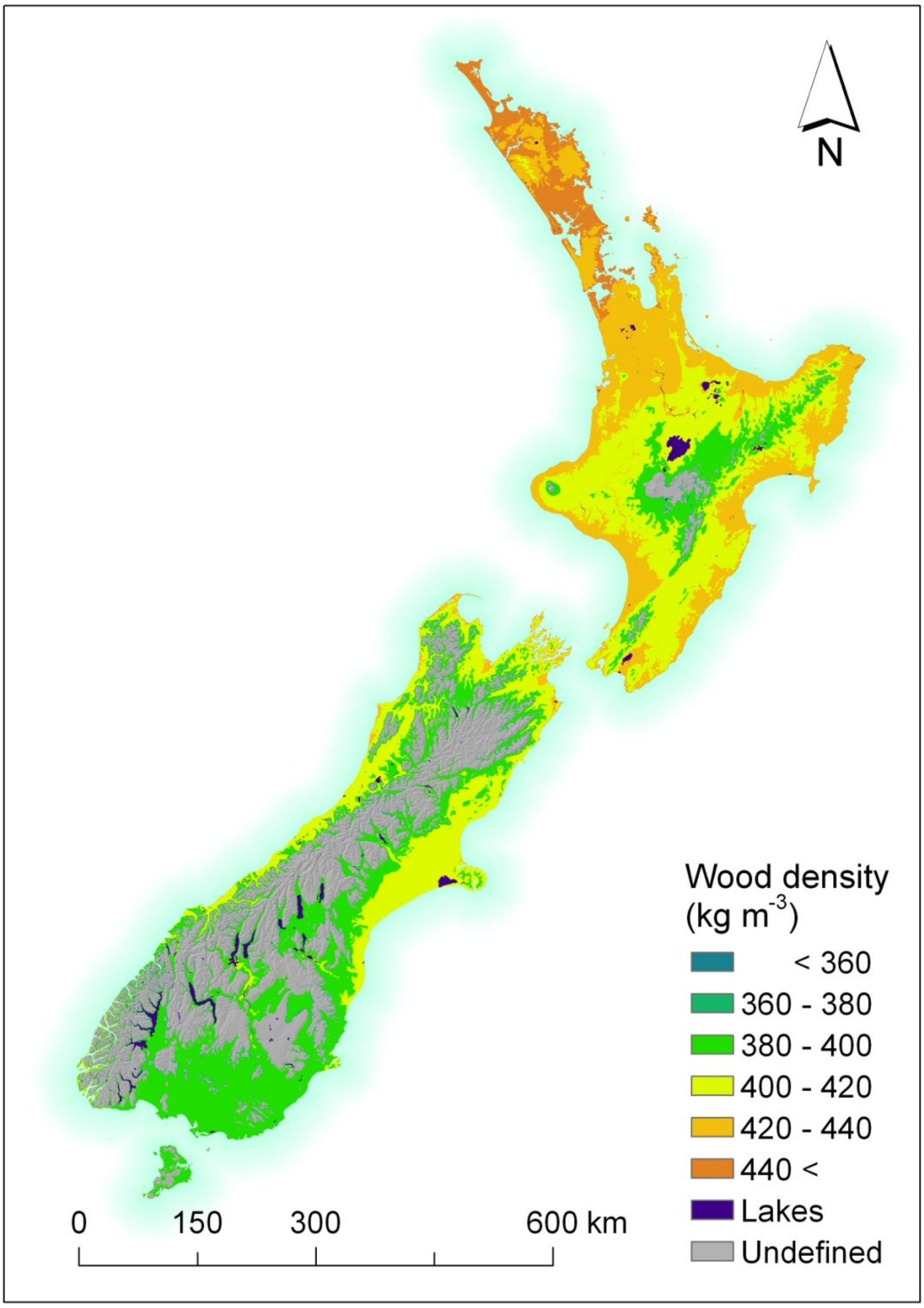

Figure 6. Mapped surface of the regression model of *Pinus radiata* outerwood density across New Zealand.

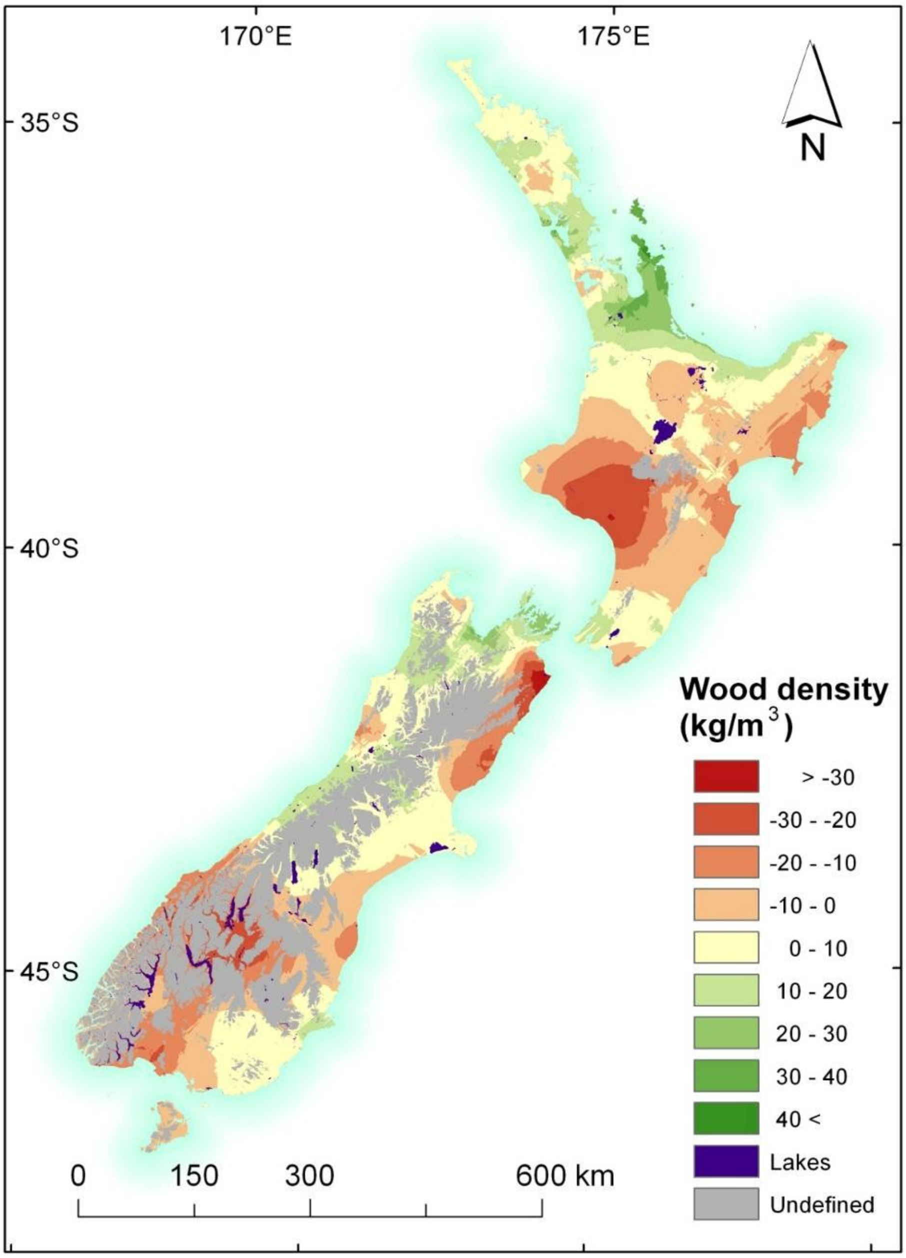

Figure 7. Mapped surface of kriged residuals from the regression showing spatial variation of the error in the *Pinus radiata* outerwood density regression model across New Zealand.

DISCUSSION

We analysed a very large database of wood density data in order to create a new model for predicting density. The results confirmed that the two most important influences on wood density are crop age and geographic location.

Outerwood density varies widely across New Zealand, with highest values in the warmer northern latitudes of the upper North Island and in the north of the South Island. Conversely, cooler southern latitudes and higher elevations had the lowest outerwood density values. The new model explained a large portion of the observed variation (70% at the plot level). The remainder of the variation not accounted for by the model at the plot level reflects all the influences of microsite, silviculture and genetics, which can be statistically significant[25-26,45]. However, when summarised to the regional level, almost all this unexplained variation disappears with 99% of the variance.

Another feature of the current study was that it utilised data largely from traditional forest sites, with only 36 out of over 1200 sites being ex-farm. Therefore, the range in fertility of this largely historical dataset is probably lower than the range of the current national forest estate. This also implies that the fitted surface may tend to over-predict wood density in forests established on ex-farm sites.

The analysis of planting decade indicated a moderate increase in outerwood values at age 20 years from establishment the 1920s to the 1960s before declining by around 20 kg m^{-3} in the 1980s, and rising slightly to 15 kg m^{-3} below the 1940s level in the 1990s. The reasons for this could involve management and genetic effects. The oldest stands tended to be highly-stocked, untended and suppressed, and as shown in Part 2 of this study, wood density tends to increase with stocking. However, the planting decade effect is also associated with a change in genetics that occurred with the introduction of open pollinated genetic material in the 1970s and 1980s, which in some cases tended to be of lower wood density. The prediction surface is standardised to the 1990s planting decade, and is therefore applicable to the management practices and genetics used during this decade.

CONCLUSIONS

The study confirms previous research that indicated age and temperature are the most important factors affecting outerwood values, but added additional information on regions with both positive and negative variations from the general trend.

The model will contribute to:

- Estimating biomass for the forest carbon pool
- Predicting the properties of wood products
- Strategic planning of forest estates for future markets
- Pre-planting decisions of silvicultural regimes
- Pre-planting decisions on use of breeds
- Pre-harvest prediction of log yields and product values

The map and associated density model will be implemented in FFR's Forecaster.

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APPENDICES

Appendix 1: Details of Statistical Analysis

Regression Kriging Model

Regression kriging is a method of predicting values at unknown sites through spatial interpolation of known observations. It consists of two components, (1) a regression model using auxiliary variables related to the dependent variable (wood density in this case), and (2) spatial interpolation of the residuals from the regression model. The combined effect of these components can provide better predictions than a simple regression model or spatial interpolation model.

The outerwood density observations can be denoted as z(s1), z(s2), . . ., z(sn), where si = (xi, yi) is a location and xi and yi are the coordinates and n is the number of observations. Regression kriging was used to predict outerwood density at an unvisited location (s0) by summing the predicted drift and residuals as,

$$z(s_0) = m(s_0) + e(s_0) \quad (1)$$

where *m* represents the trend model and *e* the residuals. Expanding equation 1 yields,

$$z(s_0) = \sum_{k=0}^{p} B_k q_k(s_0) + \sum_{i=1}^{n} w_i(s_0) e(s_i) \quad (2)$$

where B_k are the estimated regression model coefficients, q_k (s_0) is the *k*th external explanatory variable or predictor at location s_0, *p* is the number of predictors, $w_i(s_0)$ are weights determined by the covariance function and $e(s_i)$ are the regression residuals.

Data Analysis

All analyses were undertaken using the statistical package SAS[46]. There were 1,215 observations available for modelling of which 1,015 were randomly selected and used for model fitting (fitting dataset), while the remaining 200 observations were withheld from the modeling for validation (validation dataset).

A linear mixed effects modelling methodology[47] was used to model outerwood density using the fitting dataset. Regression analysis can be undertaken using linear mixed effects models using data with spatially correlated error structures. This statistically robust method uses Restricted Maximum Likelihood (REML) to estimate the regression model and parameters of the covariance function simultaneously from the data. Appropriate degrees of freedom for the statistical tests and adjusted standard errors for fixed effects were determined by well established methods[48] and used, as this technique allows for correlation in error terms.

Spatial covariance of residuals were modelled using a range of anisotropic and isotropic spatial covariance structures (spherical, exponential, power, and gaussian)[47]. Comparisons among the model structures were undertaken using the -2 Res Log Likelihood, with lower values indicating better fit with the data. Model precision and bias were assessed by plotting the fitted model with the validation dataset. The effect of including spatial covariance on the model was tested by comparing the observed outerwood density with predictions from the two fitted models, (i) only fixed effects and no spatial covariance between errors (i.e. independent errors), and (ii) with fixed effects and spatial covariance, as described by the isotropic spherical model, the influence of including spatial covariance to model precision could be assessed. These analyses showed that the isotrophic spherical model best represented the spatial covariance. Model precision was assessed by determining the coefficient of determination (R2) and the root mean square error (RMSE). The RMSE is the mean square root of sum of squared prediction error with values closer to zero indicating increasingly precise models. Model bias was determined by plotting measured against [redacted]

The impact independent variables have on outerwood density was examined with partial response functions calculated from the final model. Partial response functions were generated for each continuous variable by holding other continuous variables at their mean values and using the class with the average coefficient for each categorical variable. For the categorical variables, comparisons between classes were undertaken to identify significant differences between the least square means at P = 0.05.

Using the multiple linear regression model coefficients, spatial predictions of outerwood density were calculated from mean annual temperature[38]. The surface was developed using Arc Macro Language (AML) where age was set to 20 years, and planting decade held constant to the 1990 – 2000 planting decade.

Kriging of the residuals from the regression model was undertaken using the parameters for the nugget, sill, and range from the SAS model. These parameters were used in ArcGIS version 10 to develop a residual surface. The final surface was developed by addition of the kriged residual surface to the multiple linear regression surface. All surfaces were developed using New Zealand Map Grid projection at a 500 m cell size resolution.

Using ordinary kriging, a spherical model was found to best fit the residuals of the regression model. Estimated parameters for the nugget, and the partial sill (difference between the nugget and sill) were 227.6, and 340.9 (kg $m^{-3})^2$, respectively with a range of 209.9 km (distance). The sill, which represents the sum of the partial sill and nugget, was 568.5 (kg $m^{-3})^2$. Figure 2 demonstrates that the model behaves well across the whole data set without obvious bias. Using these kriged residuals improved the variance explained. The variance explained for this final regression kriging model was 79% for the fitting data (Table 2).