Mapping and explaining the productivity of *Pinus radiata* in New Zealand

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Abstract

Mapping *Pinus radiata* productivity for New Zealand not only provides useful information for forest owners, industry stakeholders and policy managers, but also enables current and future plantations to be visualised, quantified, and planned. Using an extensive set of permanent sample plots, split into fitting (n = 1,146) and validation (n = 618) datasets, models of *P. radiata* 300 Index (an index of volume mean annual increment) and Site Index (an index of height growth) were developed using a regression kriging technique. Spatial predictions were accurate and accounted for 61% and 70% of the variance for 300 Index and Site Index, respectively. Productivity predicted from these surfaces for the entire plantation estate averaged 27.4 m^3 ha^{-1} yr^{-1} for the 300 Index and 30.4 m for Site Index. Surfaces showed wide regional variation in this productivity, which was attributable mainly to variation in air temperature and root-zone water storage from site to site.

Introduction

In New Zealand *Pinus radiata* D. Don is the most widely distributed commercial forestry species covering an estimated 1.8 million hectares. Plantation forests comprise 6% of New Zealand's total land area and *P. radiata* contributes 91% of the national plantation estate (NZFOA, 2005). In addition to the important contribution of wood and wood fibre to the New Zealand economy, the sequestration of carbon by forest plantations, given New Zealand's commitment to the Kyoto protocol (UNFCCC, 1998), is extremely important. Given the economic and environmental importance of the *P. radiata* species, mapping the spatial distribution of forest productivity is of considerable use in determining the site suitability for conventional forestry, carbon sequestration, or renewable energy.

Modelling *P. radiata* productivity and developing spatially representative maps is a complex task, especially at the national extent. Multiple linear regression techniques have been used in a number of studies to determine the major environmental contributors of New Zealand *P. radiata* productivity and site quality (Jackson and Gifford, 1974; Hunter and Gibson, 1984; Woollons *et al*., 2002; Watt *et al*., 2005, 2008). One of the major limitations of most productivity models is that thematic spatial representation is not possible because the dependent variables (from which predictions are made) are only available as point estimates. However, given the recent proliferation of spatial surfaces describing a diverse range of environmental variables (e.g. Leathwick *et al*., 2002a,b, 2003; Tait *et al*., 2006), development of such spatial models is now not only possible, but also provides a robust method of estimating productivity. Using such surfaces, Palmer *et al*. (2009) recently developed spatial predictions of *P. radiata* productivity using a range of techniques. It was found that regression analysis using partial least squares (PLS) provided the most accurate predictions of forest productivity at locations where observational data were sparse. However, regression kriging (RK) was found to provide more accurate predictions where data were abundant. Regression kriging is likely to yield more robust estimates of productivity than PLS for the current estate because sample plot density within New Zealand plantations is typically high.

Using surfaces previously developed by regression kriging the objective of this study was to determine national and regional mean values of Site Index and 300 Index for the current *P. radiata* plantation estate.

Methods

300 Index and Site Index development

300 Index and Site Index values were calculated for 1,764 locations extracted from the permanent sample plot (PSP) system. PSP data were screened for sites that would adversely influence the integrity of the dataset. Exclusions included Nelder (spacing), oversowing (legume N), disturbance (forest floor removal), and fertiliser (P, N, and K) trials. Control plots within these trials were retained. The initial screening also found a general increase in 300 Index with year of stand establishment, with stands established in the 1930s being typically ~25% lower than those established in the 1980s, while site productivity indices derived from trees younger than seven years of age were unreliable. As a result we excluded PSP data obtained from stands established prior to 1975 and those stands younger than seven years of age. PSPs with plot history data inadequate for estimating the 300 Index were also excluded. The productivity indices were calculated for the 1,764 PSP locations across New Zealand. All variables were projected to a New Zealand map grid projection with a New Zealand geodetic datum, NZGD1949.

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Geographic information system (GIS) data representing environmental and climatic data

For the 1,764 sites where 300 Index and Site Index values were calculated, GIS surfaces representing independent variables covering environmental, climatic and edaphic factors were extracted. Variables included air temperature, soil water balance, terrain attributes, and surfaces related to landuse and soil nutrient status.

Regression modelling

Stand data were analysed using the multivariate method partial least squares (PLS) regression. The SAS (Version 9) PLS procedure was used, with the observations separated randomly into model (n = 1,146) and test (n = 618) datasets for cross validation purposes. Figure 1 shows the PSP locations across New Zealand for the model and test sites. The test dataset locations were withheld from all further map prediction procedures and were used subsequently to determine model prediction bias and precision.

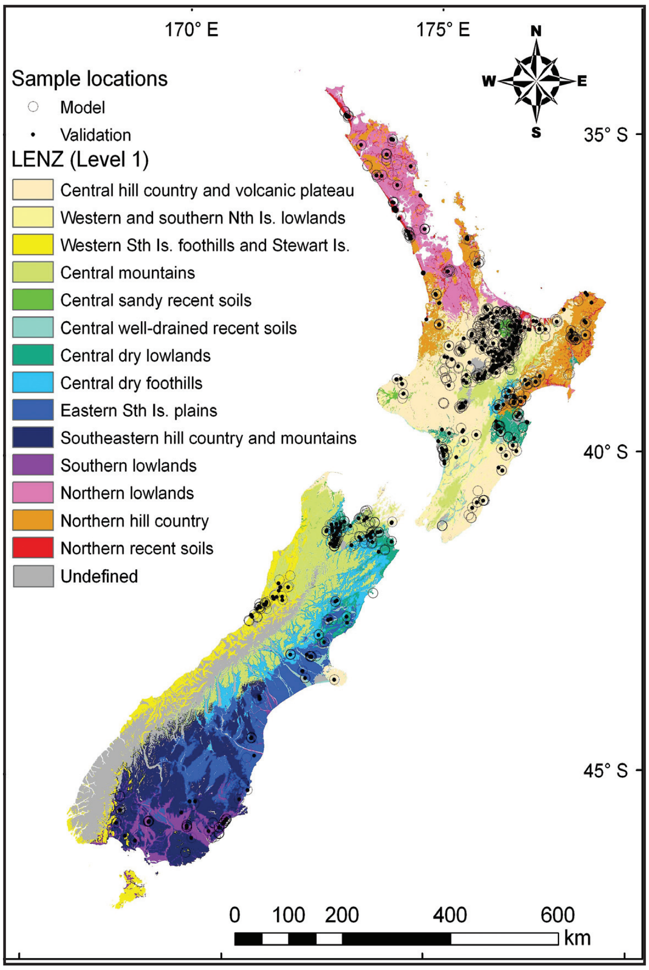

Figure 1. Distribution of PSP sites used to model Pinus radiata *productivity and the withheld sites randomly selected for model validation superimposed over the fourteen most general classes (level 1) of Land Environments for New Zealand (LENZ). Figure 1 was reproduced from Watt et al. (2010).*

Improving model predictions using geostatistics

A geostatistical spatial interpolation technique called kriging was used to improve model predictions. This kriging involved developing a surface from the residuals of the regression modelling. The residual is the difference between the measured and modelled value at each site. Kriging the residuals allowed us to develop a map of the 'unexplained' portion of the 300 Index and Site Index data. The 300 Index and Site Index residual surfaces were added back to the original regression model surface, improving the variance explained by another ~12% (Table 1).

Validation

Data from 618 sites withheld from the modelling process were used to provide robust validation statistics. This allowed us to test the regression kriging model we had developed with independent data not used in the modelling process (Table 1). The coefficient of determination (R^2) statistic tells us how much of the variance was explained by correlation with independent variables. The root-mean-square error (RMSE) statistics, which is in the same units as the response variable, indicates the average error of the prediction. Lower values of RMSE indicate a better fit.

Results

Model accuracy

Spatial predictions were accurate, accounting for 61% and 70% of the variance for 300 Index and Site Index, respectively (Table 1). The RMSE values were relatively low for both 300 Index and Site Index (Table 1).

Table 1. Validation statistics showing the coefficient of determination (R^2) and root-mean-square error (RMSE) for 300 Index and Site Index surfaces developed using the partial least squares (PLS) and regression kriging (RK) techniques.

Prediction techniques	300 Index		Site Index	
	R^2	RMSE (m^3 ha^{-1} yr^{-1})	R^2	RMSE (m)
PLS	0.48	4.22	0.59	3.13
RK	0.61	3.65	0.70	2.65

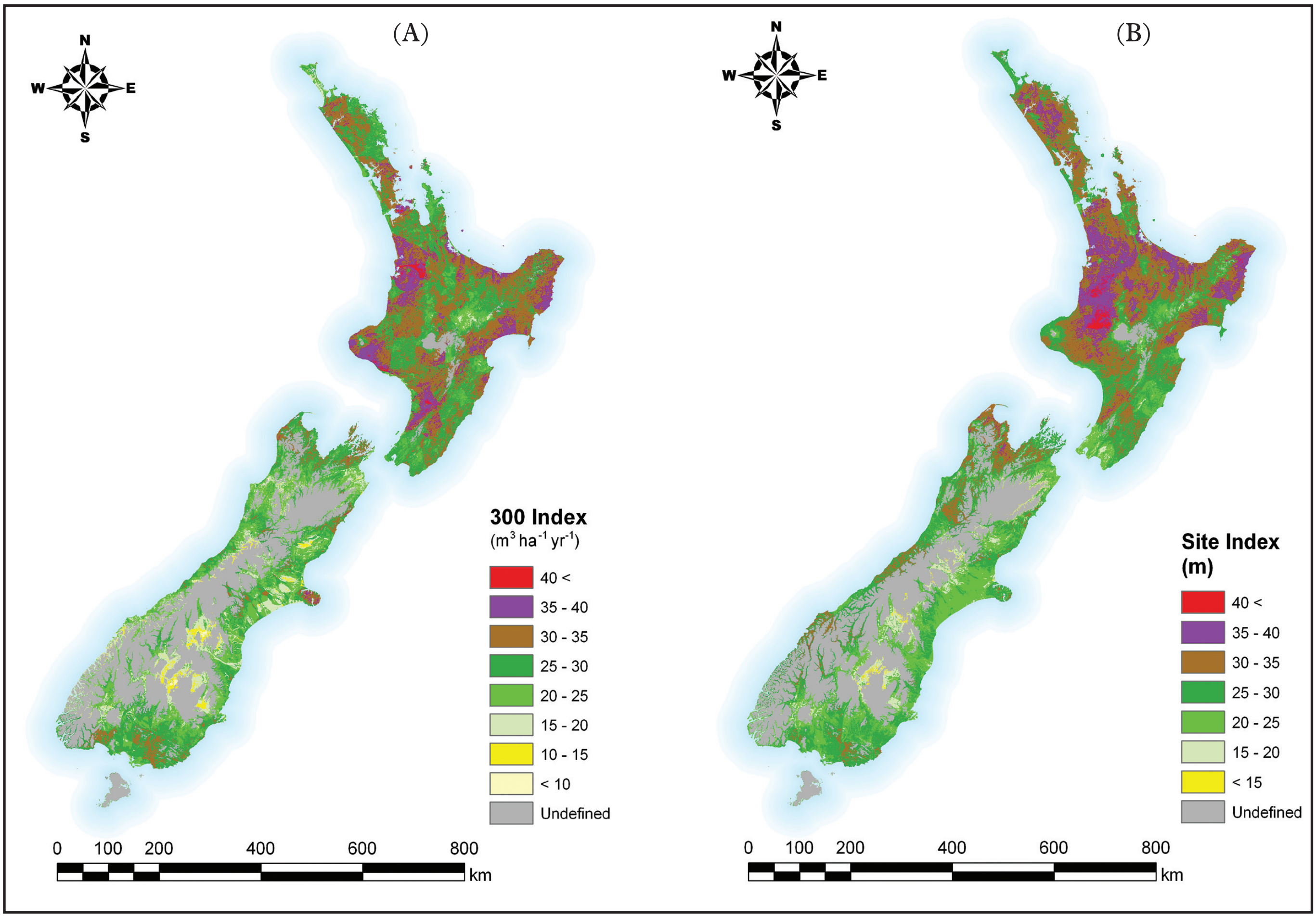

Figure 2. Map of New Zealand showing spatial variation in predicted (a) 300 Index and (b) Site Index. Figure 2 was reproduced from Palmer et al. (2009). See Appendix 1 and 2 for full size graphics.

National maps for 300 Index and Site Index

Spatial variation in 300 Index and Site Index using the model described here was primarily related to air temperature and soil water balance (data not shown). Consequently, predictions of both 300 Index and Site Index increased from the cooler, temperate Southland region to optimum values found at mid-latitudes in the North Island, before declining further north, particularly in the sub-tropical climates of Auckland and Northland. Increases in productivity also occurred in regions with high average root-zone water storage (e.g. Southland) and were reduced in drier areas such as the Canterbury plains (Figure 2).

Predicted plantation productivity

Over the entire plantation estate, the predicted Site Index averaged 30.4 m. The predicted 300 Index averaged 27.4 m^3 ha^{-1} yr^{-1}, which, assuming a mean rotation length of 28 years, translates into a total stem volume of 767 m^3 ha^{-1}. As there are typically 15% breakages in harvesting and approximately 10% of stands are unstocked, this corrected volume translates into a mean merchantable stem volume of 575 m^3 ha^{-1}.

Surfaces showed wide variation in regional averages for productivity across the New Zealand plantation estate (Table 2). For 300 Index, the predicted values were highest in Hawkes Bay (31.3 m^3 ha^{-1} yr^{-1}),Gisborne (32.2 m^3 ha^{-1} yr^{-1}), and Taranaki (31.2 m^3 ha^{-1} yr^{-1}) regions and lowest in Otago (23.6 m^3 ha^{-1} yr^{-1}), West Coast (23.3 m^3 ha^{-1} yr^{-1}), and Canterbury (22.2 m^3 ha^{-1} yr^{-1}) regions. Predicted Site Index values were highest in Gisborne (33.2 m), Waikato (32.6 m), and Taranaki (32.5 m) regions and lowest in Southland (25.5 m), Otago (24.7 m), and Canterbury (24.1 m) regions (Table 2).

(See Table 2 over page)

Model implications and applications

The regression kriging technique used here combines the accuracy of the regression prediction technique (partial least squares), over areas with low measurement density, with the accuracy of ordinary kriging in areas with high to medium measurement density. Regression analysis allowed us to develop relationships with local environmental and landform information (for example, air temperature and soil water balance) and then transfer this information to areas with little or no known productivity information. The

Table 2. Area weighted average, standard deviation (stdev), and range for predicted 300 Index and Site Index for Pinus radiata *forests identified using Land Cover Database 2.*

		300 Index (m^3 ha^{-1} yr^{-1})		Site Index (m)	
Region	Ha	Mean (stdev)	Range	Mean (stdev)	Range
Auckland	48,382	27.4 (4.75)	17.3-44.1	30.9 (2.86)	18.9-38.5
Bay of Plenty	268,848	27.2 (4.19)	14.3-41.9	31.9 (3.82)	16.1-41.0
Canterbury	96,984	22.2 (5.93)	8.2-38.7	24.1 (3.39)	13.5-33.8
Gisborne	151,505	32.2 (2.90)	20.4-44.4	33.2 (3.49)	15.6-42.6
Hawkes Bay	145,875	31.3 (4.03)	13.5-41.9	30.9 (3.41)	15.7-38.6
Manawatu-Wanganui	134,154	28.3 (4.03)	14.1-45.5	30.3 (4.66)	13.5-46.3
Marlborough	70,570	26.8 (3.42)	10.8-36.6	28.6 (2.75)	13.5-34.3
Nelson	10,543	26.3 (2.12)	17.1-33.0	29.6 (1.77)	20.7-35.5
Northland	176,737	26.8 (4.89)	13.9-38.9	31.7 (3.63)	19.6-40.4
Otago	105,503	23.6 (2.90)	6.9-34.4	24.7 (2.48)	13.5-33.1
Southland	60,578	25.6 (3.37)	12.0-34.7	25.5 (3.10)	13.5-33.2
Taranaki	25,519	31.2 (4.04)	17.9-42.6	32.5 (2.53)	19.6-39.9
Tasman	97,123	25.8 (2.80)	14.2-37.0	31.3 (2.71)	13.5-38.2
Waikato	327,740	27.5 (3.58)	15.8-47.2	32.6 (2.89)	19.1-43.0
Wellington	67,382	27.6 (2.67)	16.1-40.1	27.2 (3.35)	15.0-35.8
West Coast	41,617	23.3 (3.58)	7.7-33.8	28.2 (2.37)	16.7-35.3
New Zealand	1,829,060	27.4	6.9-47.2	30.4	13.5-46.3

*Modelled data were constrained to ensure predictions were not made below the bounds of actual data by excluding from analysis all sites with a Site Index value <13.5 m.

kriging component within the regression kriging technique added additional predictive power (gains in R^2 of ~12% were demonstrated here) to partial least squares through spatial interpolation of the unexplained variance from the regression analysis. This spatial relationship is based on the idea that properties that are closer together are likely to be more similar than properties further apart. Therefore prediction certainty will increase in regions, including the volcanic plateau of the central North Island and the Nelson area, where greater productivity observational densities occur. Although not as accurate as a partial least squares model in areas with sparse data, regression kriging does retain a reasonable level of prediction accuracy, and outperforms pure kriging techniques in areas with a low density of data.

The wide variation in predicted productivity shown here was mainly attributable to variation in air temperature and water balance. Previous research using these PSP data provides an insight into the form of relationships between productivity and these variables (Watt *et al*., 2010). Both Site Index and 300 Index increase with air temperature reaching optimum values at mean annual air temperatures of approximately 13°C, before declining at temperatures above this. Within New Zealand these optimum temperatures occur around coastal Bay of Plenty, Waikato, and Gisborne. Productivity has also been shown to increase with the fraction of available root zone water storage from mean annual values of 40% in dry regions to optima reached at 88-89% of the maximum available water, which are close to field capacity for most of the year (Watt *et al*. 2010). Above this optima there is little decline in productivity. Consequently, regions with the highest productivity were moderately warm, wet regions, such as Gisborne, Waikato, and Taranaki, whereas the cold, dry regions of Canterbury and Otago generally had the lowest productivity.

Acknowledgements

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Appendices

Appendix 1 and Appendix 2 over the page are enlarged versions of the maps in Figure 2.

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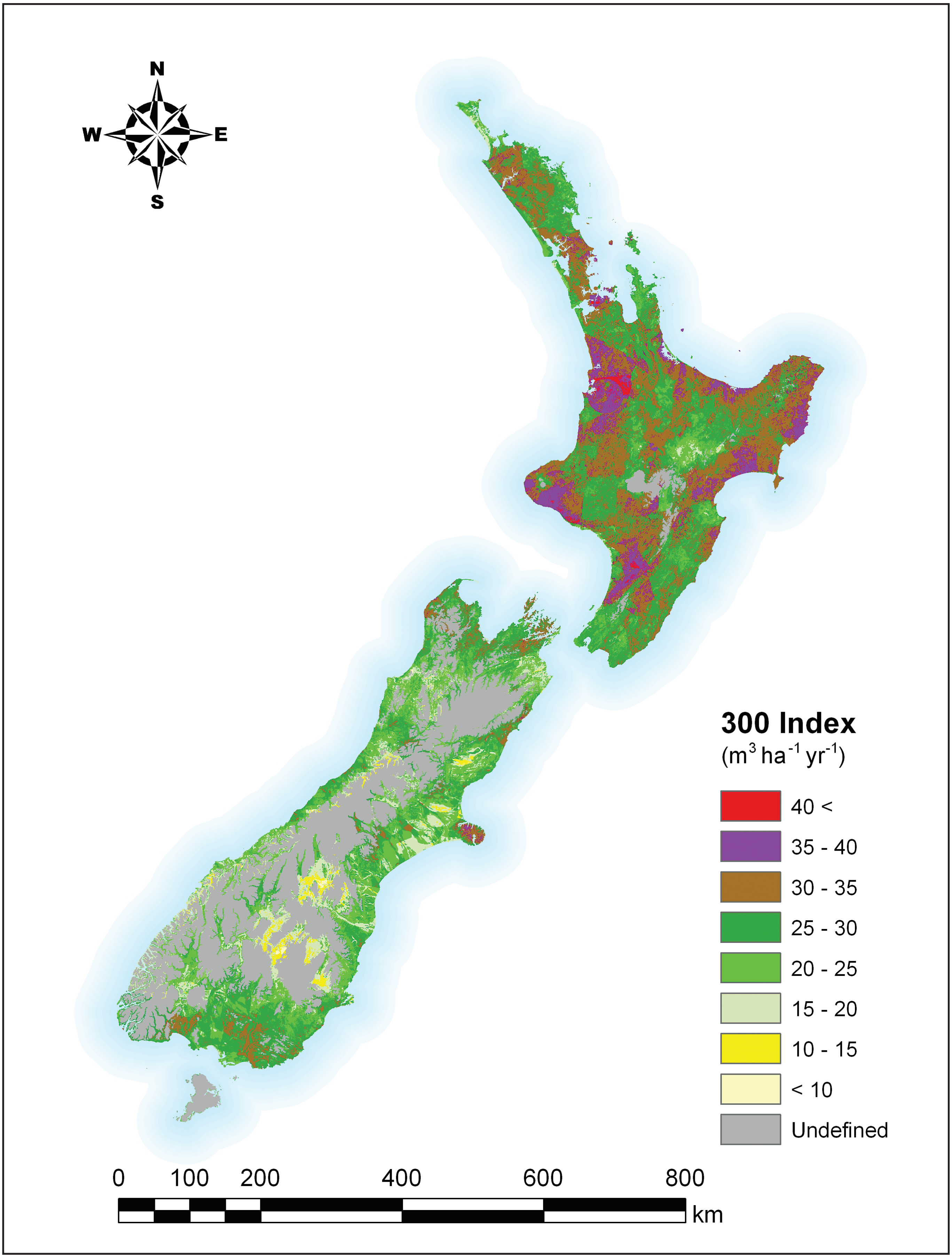
Appendix 1. Map of New Zealand showing spatial variation in predicted 300 Index. Figure was reproduced from Palmer et al. (2009).



Appendix 2. Map of New Zealand showing spatial variation in predicted Site Index. Figure was reproduced from Palmer et al. (2009).