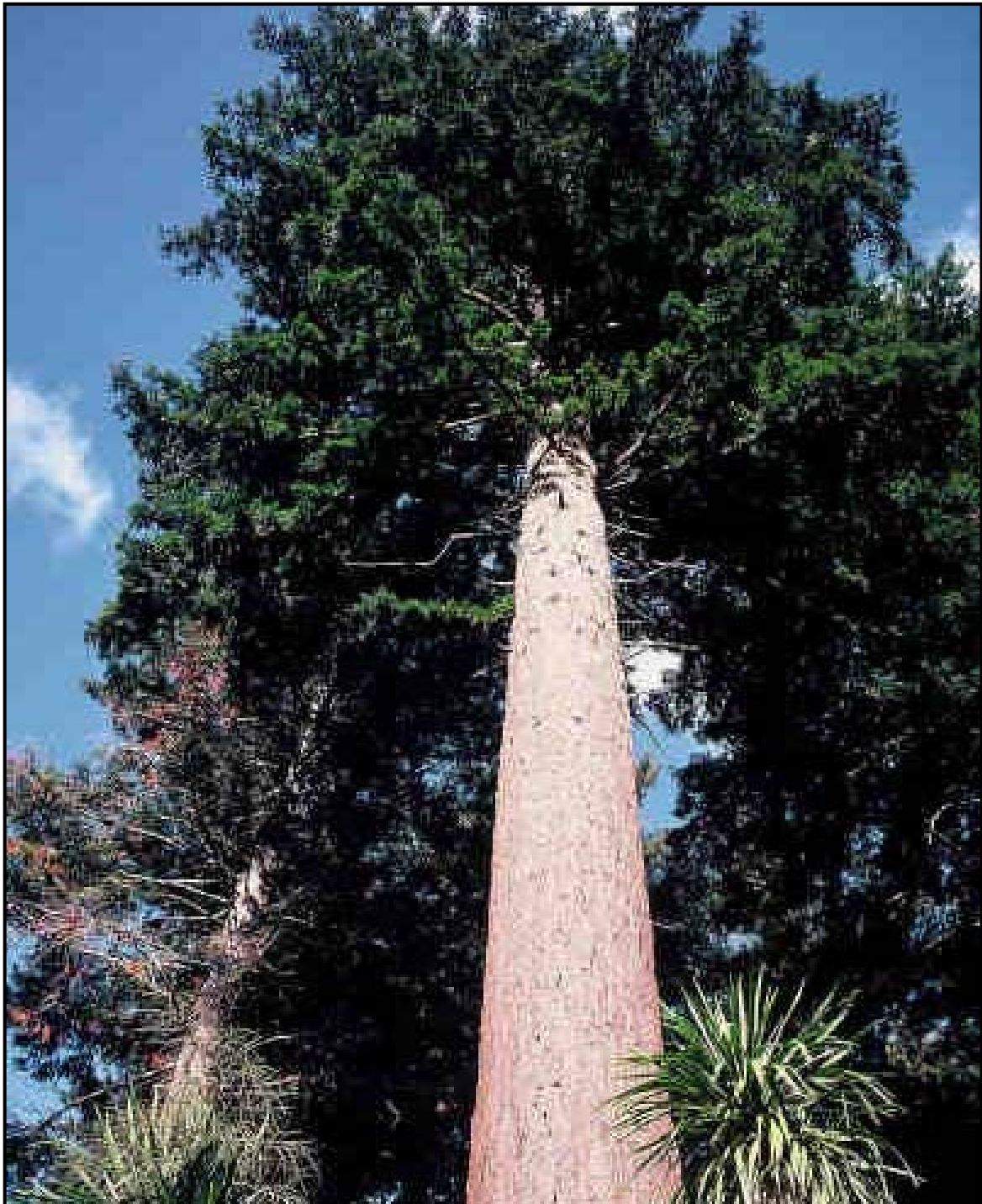


PREDICTING THE SPATIAL DISTRIBUTION OF *SEQUOIA SEMPERVIRENS* PRODUCTIVITY IN NEW ZEALAND

David J. Palmer, Michael S. Watt, Mark O. Kimberley, Heidi S. Dungey



Front cover: Coast redwood (planted approximately 1900-1910) situated on the northern boundary of Scion alongside Te Ngae Road opposite Ngapuna Shops (Photograph from the National Forestry Library).

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Abstract

Permanent sample plot data was extracted from a national *Sequoia sempervirens* (D. Don) Endl. dataset and used to develop multiple regression models for 400 index and site index using independent variables obtained from interpolated climate surfaces and a national ancillary soil phosphorus map. Site index was defined for this species as the height of the 100 largest diameter trees per hectare at breast height age 40 years. The 400 index was defined as the stem volume mean annual increment at breast height age 40 years for a reference regime of 400 stems ha⁻¹. The final 400 index model accounted for 76% of the variance in the data. Independent model variables for the 400 index include mean spring air temperature, subsoil acid soluble phosphorus, and mean summer vapour pressure deficit, with these variables respectively accounting for 55, 16 and 5% of the variance. The final site index model explained 82% of the data variance using mean annual daily temperature and mean summer vapour pressure deficit, with the variables accounting for 71, and 11% of the variance, respectively. A one-at-a-time validation procedure indicated final models were relatively unbiased, and accurate.

Partial response curves show a positive relationship between 400 index and mean spring air temperature, and acid soluble phosphorus, and a negative linear relationship with summer vapour pressure deficit. For site index, partial response curves show a positive linear relationship with mean annual daily temperature, and a downward facing parabolic relationship with summer vapour pressure deficit, that reached an optimum site index at 0.53 kPa. Maps illustrating the spatial variation in 400 Index and site index for *S. sempervirens* across New Zealand are provided.

Keywords: national scale modelling, New Zealand plantation forestry, productivity model, redwood; *Sequoia sempervirens*, spatial modelling

1. Introduction

Sequoia sempervirens or coast redwood naturally occurs within a narrow coastal belt from southernmost Oregon to the south Monterey County, California. Frequent summer fogs are a feature of this coastal belt and provide a humid atmosphere, which is considered a governing factor in its natural distribution (Knowles and Miller, 1993). The species is a hexaploid (Ahuja and Neale 2002), and has been shown to have more diversity within natural populations than between populations (Rogers 2000). Selfing has been recorded to be high in some instances, but manifests after plantation establishment rather than in the nursery (Libby et al. 1981).

In New Zealand, *S. sempervirens* was first planted on any scale between 1860 and 1870, and first planted in state forests around 1900 (Knowles and Miller, 1993). While some stands have been very impressive, many have had poor performance and survival, related to siting, establishment and seed source (Miller and Knowles 1993, Young 1983). Recently there has been renewed interest in this species (Cown and McKinley 2008) because more than 95% of old-growth coast redwood has now been set aside in public holdings in California (Stuart 2007, Cown 2008). This leaves an opportunity for New-Zealand-grown timber to compete with the second-growth coast redwood resource. The emergence of an emissions trading scheme (Anon 2009) and the likelihood of attaining carbon credits for forests has spurred interest in establishing *S. sempervirens* over the longer-term (Turner et al. 2008).

Research on *S. sempervirens* in New Zealand has a long history, but has not always been well supported (e.g. Colbert and McConchie 1983, Vincent 2001) and much remains unpublished. With renewed interest in planting, however, there is an increased need to clarify the value and growing systems for planted forests in New Zealand. Identification of key factors driving productivity of *S. sempervirens* and effective siting models are a critical part of understanding how to best to grow this species. Spatial extrapolation of these models would provide growers with useful information on siting. The recent development of spatial surfaces describing a diverse range of environmental (Leathwick et al., 2002a, b, 2003) and climatic data (Tait et al., 2006), has meant that the development of spatial models covering large areas is now possible. From a management perspective these spatial models represent a major advance, as the maps that can be produced provide very detailed information of how productivity varies at a fine resolution across the landscape.

Using values of *S. sempervirens* productivity obtained from the New Zealand permanent sample plot database, the objectives of this study were to (i) develop a multiple regression model of *S. sempervirens* site index and 400 Index using independent variables obtained from national extent ancillary maps and interpolated surfaces and (ii) using this model develop 400 index and site index surfaces for New Zealand.

2. Materials and methods

2.1 Data acquisition and preliminary screening

Stand level data for *Sequoia sempervirens* plantations were extracted from the New Zealand Forest Research Institute Permanent Sample Plot system (Pilar and Dunlop, 1990). Extracted data were examined for sites that could adversely influence the integrity of the dataset. This process included the screening of trees from coppicing ensuring the oldest sample was represented and trees younger than 15 years were discarded. Remaining plot data were averaged to a 100 m² grid to align with the resolution of the available environmental information leaving a total of 23 plots available for modelling. Although the final data covers a wide environmental range across New Zealand sub-tropical areas in northern regions of the North Island were not represented (Fig. 1).

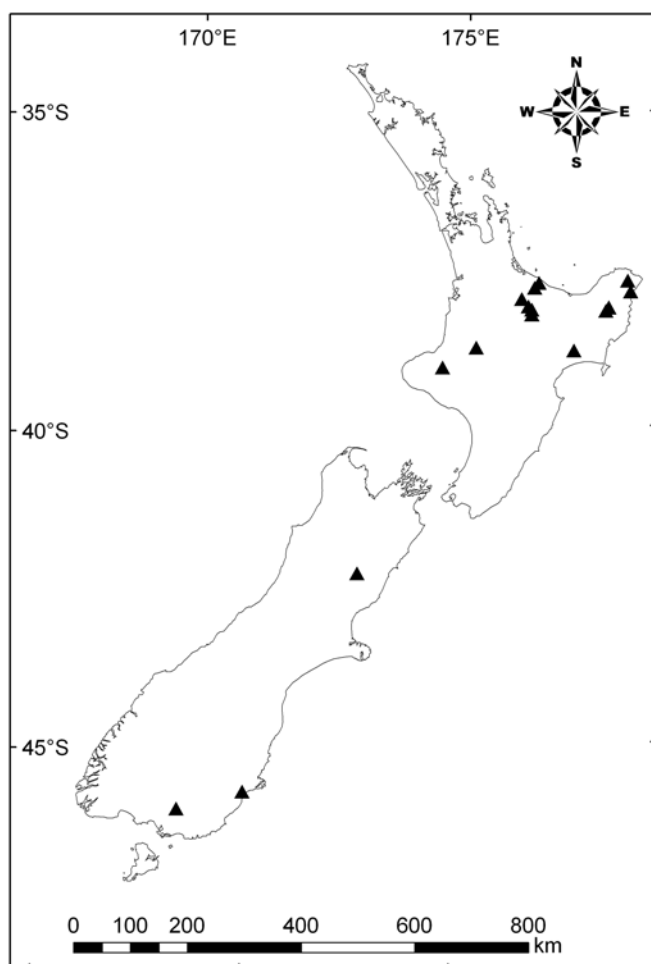


Figure 1. Map showing the location of the permanent sample plots used in this study.

2.2. Tree dimensions

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

This model was used to derive site productivity estimates for each permanent sample plot measurement. Site index was derived from measurements of age and MTH using the MTH model. Site Index (SI), an index of height growth, is defined for this species as MTH at BH (breast height, 1.4 m) age 40 years (i.e., 40 years after attaining a MTH of 1.4 m, which typically occurs at about age 3 years). An index of basal area growth, $BA_{40/400}$ was derived from measurements of age, stocking and BA using the BA model. $BA_{40/400}$ is defined as the BA at BH age 40 years for a stand growing at 400 stems ha^{-1} . The 400 index, an index of stem volume productivity, and defined as the under-bark stem volume mean annual increment ($m^3 ha^{-1} yr^{-1}$) at BH age 40 years, was then derived from SI and $BA_{40/400}$ for each plot using the following method. Firstly, it was found using the stem volume function that a typical redwood stand at BH age 40 years and 400 stems ha^{-1} stocking has an under-bark stem volume of $BA \times MTH / 3.82 m^3 ha^{-1}$. The 400 index was therefore calculated as $BA_{40/400} \times SI / 3.82 / 40$.

2.3. Independent variables

Spatial datasets used to model the 400 index and site index included a wide range of environmental, biophysical, and climatic data. The final 400 index model used the climate variables mean spring temperature, mean summer vapour pressure deficit (Mitchell, 1991; Leathwick et al., 2002a; Tait et al., 2006), and subsoil acid soluble phosphorus (Leathwick et al., 2002b; 2003). Subsoil acid soluble phosphorus was included in the model as a categorical variable. For this variable the categories included in the surface were very low, low, moderate, high, and very high, respectively, defined as 0-7, 7-15, 15-30, 30-60, and 60-100 mg P/100g. Site index used mean annual daily air temperature and mean summer vapour pressure deficit. Mean annual daily air temperature was calculated from $(2 T_{max} + T_{min})/3$, where T_{max} and T_{min} are mean monthly estimates of daily minimum and maximum temperature, respectively. Independent data were extracted from these datasets for each of the permanent sample plot locations.

2.4. Data analysis

Multiple regression models were constructed using the general linear model procedure in SAS (SAS Institute, 2000). Variables were introduced sequentially into the model starting with the variable that exhibited the strongest correlation, until further additions were not significant or did not improve the overall model R^2 . Variable significance was determined manually using an F -test, with the significance tested for each variable addition against the residual sum of squares from the previous model. Variable selection was undertaken manually one variable at a time, to ensure that non-linear relationships and relationships with categorical variables were identified, from residual plots, and correctly incorporated into the model.

For the final models residuals were plotted against independent variables and predicted values to determine model bias. A one-at-a-time cross validation was undertaken to determine model stability. The cross validation process excluded the first plot as a single-element test set and fitted the model over the remaining sites. This process was iterated for each site, generating validation data. Predicted values for the 400 index and site index were then plotted against their respective actual values to assess bias (Fig. 2). Model accuracy was examined using the coefficient of determination (R^2) between predicted values and actual 400 index and site index.

Digital surfaces were developed for the 400 index and site index using the final SAS regression models and the GIS platform ArcInfo™. Arc macro language (AML) was used in association with the ArcInfo™ *Grid* module to calculate spatial surfaces using the SAS modelled intercept, regression coefficients, and their independent variables. Independent data within the spatial models were also constrained with the 400 index surface limited to a lower mean spring temperature of 9 °C to ensure that projections were not made too far beyond the bounds of the data. As there were no high, and very high values of acid soluble phosphorus represented in the dataset, extrapolated spatial values of 400 Index for these categories were conservatively set to values estimated for the medium category. For site index the mean annual daily temperature was limited to a lower value of 10.6 °C and mean summer vapour pressure deficit constrained between 0.42 and 0.77 kPa. Sites beyond the range of these bounds were displayed as undefined.

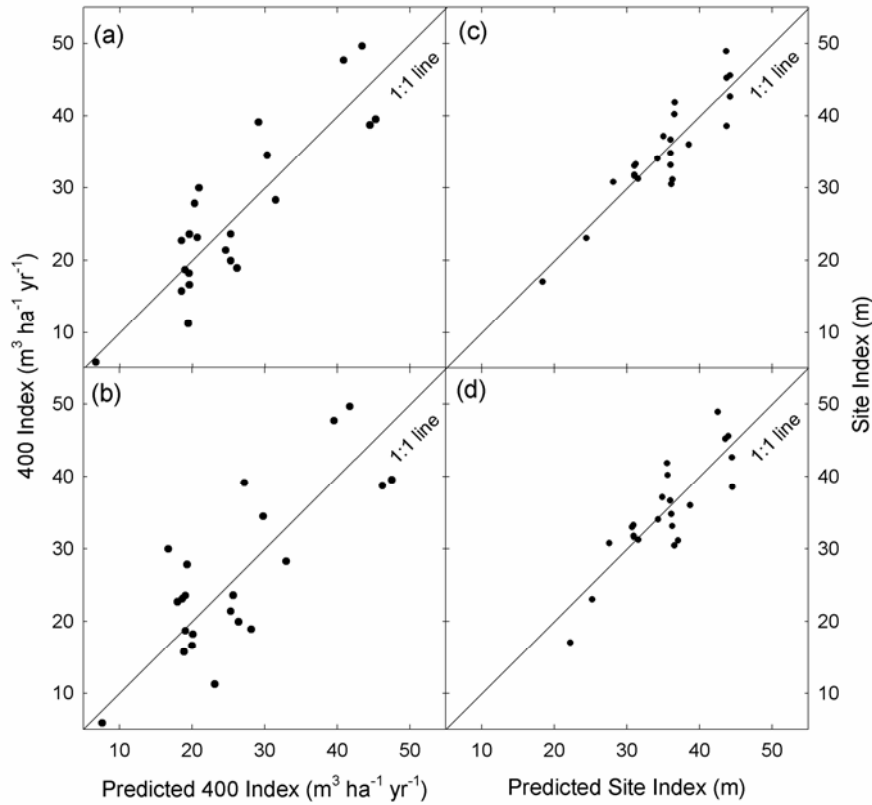


Figure 2. Relationship between predicted and actual 400 index for (a) the fitting and (b) validation datasets. Also shown is the relationship between predicted and actual site index for (c) the fitting and (d) validation datasets.

3. Results

Rainfall ranged four fold across sites from 684 to 2,988 mm yr⁻¹. Mean annual air temperature and mean daily solar radiation varied substantially across sites ranging from 9.9 to 14 °C and 12.4 to 15.3 MJ m⁻² day⁻¹, respectively (Table 1).

The 400 index model included mean spring air temperature (T_s), sub-soil acid soluble phosphorus (P), and mean summer vapour pressure deficit during summer (D). The final model formulated using these variables accounted for 76% of the variance in 400 index. The terms T_s and P were both highly significant ($P < 0.001$) with partial R^2 values of 0.55 and 0.16, respectively. Although D was marginally insignificant ($P = 0.07$) this variable was included in the model as it was considered physiologically sound, reduced model bias and substantially increased model precision (partial $R^2 = 0.05$).

Table 1. Range in mean annual air temperature, mean daily solar radiation, and total annual rainfall for the permanent sample plots.

Variable	Range
Mean annual air temperature (°C)	9.9-14.0
Mean total daily solar radiation (MJ m ⁻² day ⁻¹)	12.4-15.3
Mean total annual rainfall (mm year ⁻¹)	684-2,988

The final model for site index included mean annual daily air temperature (T_a) and mean summer vapour pressure deficit (D). The variable D was also fitted as a downward facing parabola that reached an asymptote at a D of 0.53 kPa. The final model formulated using these variables accounted for 82% of the variance in site index. Both T_a and D were highly significant ($P < 0.01$), with partial R^2 values of 0.71 and 0.11, respectively. Summary of statistics for the final predictive models of the 400 index and site index for *Sequoia sempervirens* were withheld for reasons of confidentiality.

Residuals for the final models of site index and 400 index were normally distributed and exhibited little apparent bias with predicted values (Fig. 3a and 4a). Residuals also exhibited little apparent bias with independent variables used in the 400 index and site index models (Figs. 3 and 4). The results from one-at-a-time validation indicated that the final models from both models were relatively unbiased, and accurate, with the predicted values accounting for 61% and 74% of the variance in the actual 400 index and site index, respectively (Fig. 2).

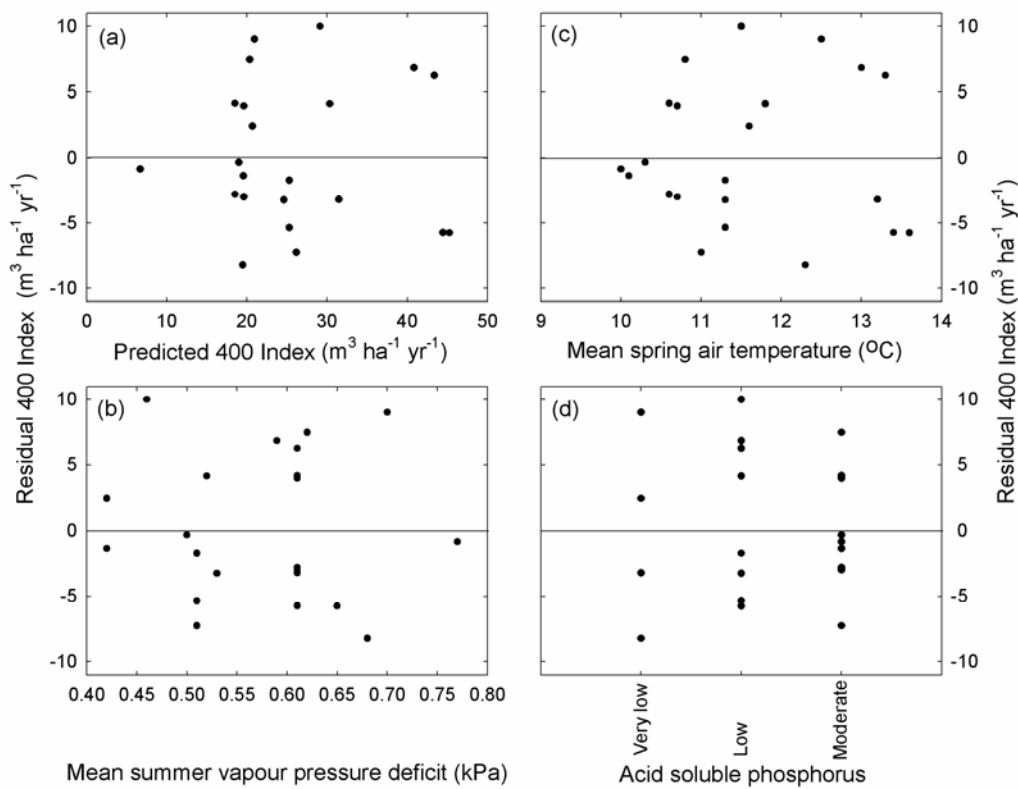


Figure 3. Plot of residual values against (a) predicted 400 index, (b) mean summer vapour pressure deficit, (c) mean spring air temperature, and (d) acid soluble phosphorus.

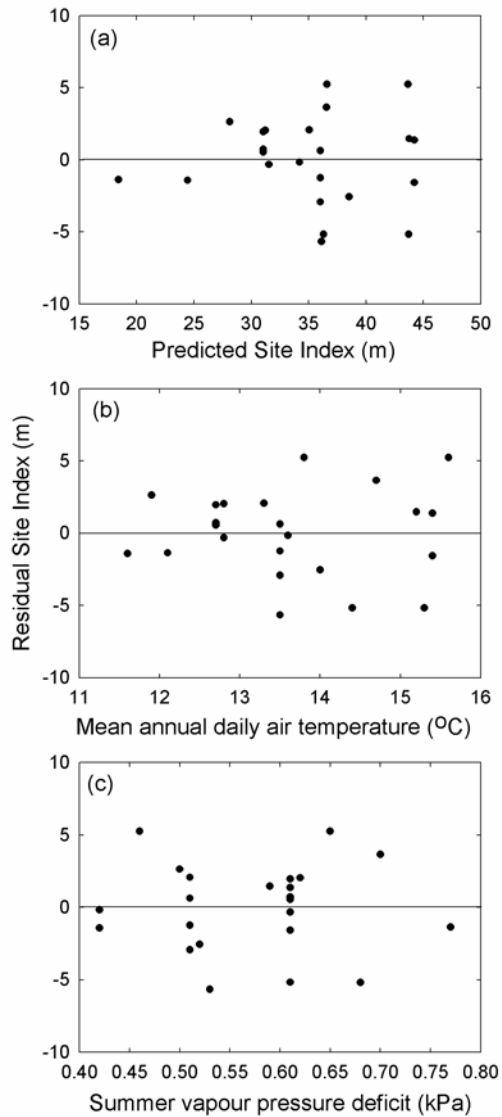


Figure 4. Plot of residual values against (a) predicted site index (b) mean annual daily air temperature, and (c) mean summer vapour pressure deficit.

To assess the functional forms of the independent variables, partial response curves were generated for models of 400 index (Fig. 5) and site index (Fig. 6). The 400 index was positively and linearly related to mean spring air temperature (Fig. 5a), and exhibited a negative linear relationship with summer vapour pressure deficit (Fig. 5b). The categorical independent variable acid soluble phosphorus was positively related to 400 index predicting respective values of 15, 26, and 30 $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ for the very low, low and moderate classes (Fig. 5c). The strong influence of temperature was clearly shown in the productivity map (Fig. 7a) with 400 index values diminishing, with increasing latitude and at elevated inland regions in the main axial ranges, and the central North Island.

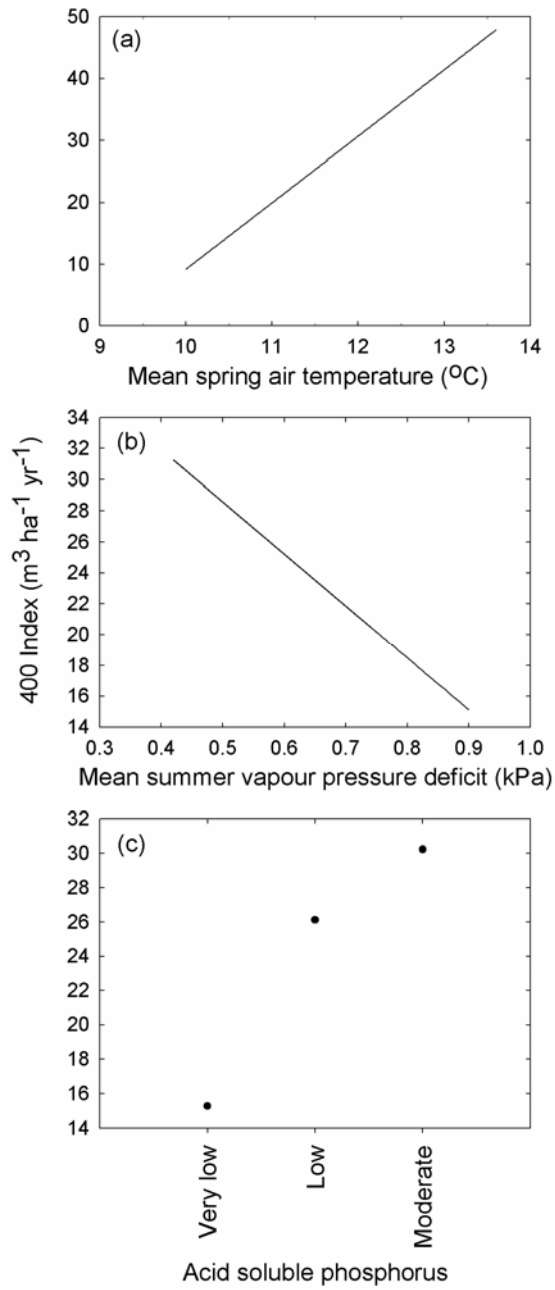


Figure 5. Partial response curves of 400 index for (a) mean spring air temperature, (b) mean summer vapour pressure deficit, and (c) acid soluble phosphorus. When each partial response curve was generated all other variables in the model were held constant at mean values.

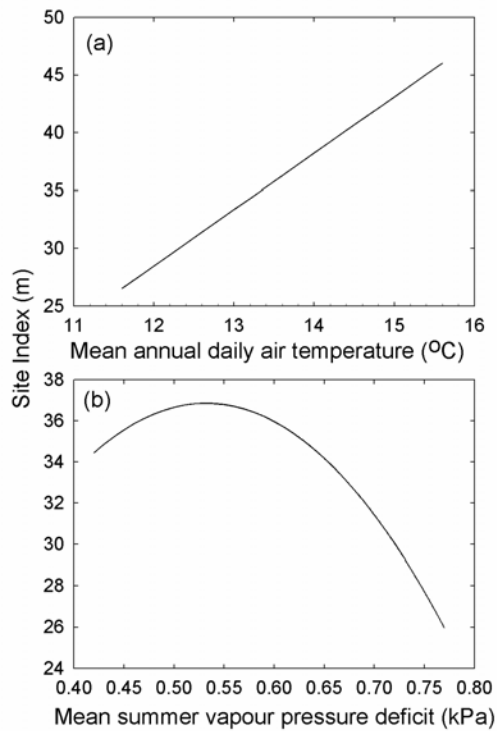


Figure 6. Partial response curves of site index for (a) mean annual daily air temperature, and (b) mean summer vapour pressure deficit. When each partial response curve was generated all other variables in the model were held constant at mean values.

Partial response curves for site index show a positive, linear relationship with mean annual daily air temperature (Fig. 6a). The relationship between site index and mean summer vapour pressure deficit, was modelled as a downward facing parabola, with an optima reached at 0.53 kPa (Fig. 6b). The site index surface clearly demonstrates the strong influence of air temperature with values showing a general increase from south to north, and declining from warmer coastal sites inland towards frost prone, higher elevation sites (Fig. 7b).

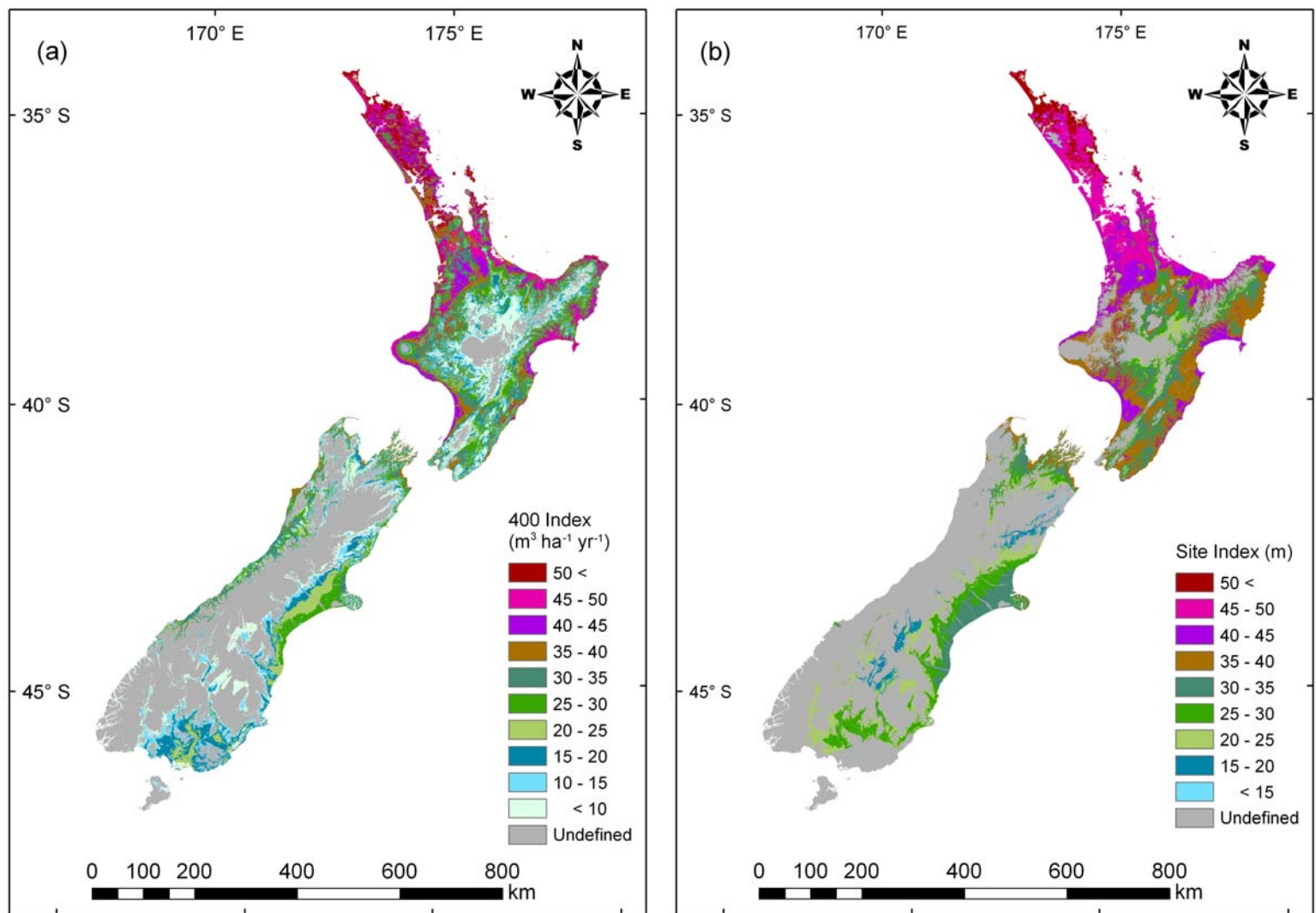


Figure 7. Productivity surfaces for *Sequoia sempervirens* describing (a) 400 index and (b) site index across New Zealand.

4. Discussion

The productivity models and maps developed here considerably advance our understanding of how environment regulates productivity of *Sequoia sempervirens*. This study clearly highlights the importance of air temperature as a determinant of productivity for the species, with this variable accounting for 55 and 71% of the respective variance in 400 index and site index. The accuracy and lack of bias of the developed models provides confidence in the spatial projections and highlights the utility of thematic spatial layers as driving variables in the development of productivity models.

The dominance of air temperature as a driving variable is consistent with productivity models developed for other plantation species (Palmer 2008; Watt et al., 2009) and is also sound from a physiological point of view. Although the quantity of radiation intercepted controls the maximum growth attainable, air temperature is a primary determinant of the amount of intercepted radiation that can be utilised by the plant (Monteith, 1977). The positive relationship often found between tree growth and air temperature (Watt et al., 2005, 2008, 2009) is thought to be principally driven by the lengthening of the growing season (Lieth, 1973). The importance of such lengthening of the growing season was demonstrated recently by Kerkhoff et al. (2005), who showed that net primary production (NPP) expressed as NPP per month of growing season was virtually invariant with air temperature.

The negative relationship between vapour pressure deficit and productivity has a physiological basis. Considerable process-based research has shown increases in vapour pressure deficit induce reductions in both stomatal conductance (Watt et al., 2003) and growth (Landsberg and Hingston, 1996). This relationship is embodied in the widely used and generally applicable process-based model 3PG (Landsberg and Waring, 1997) which uses an exponential decay relationship to model the decline in utilisable radiation and growth with increasing vapour pressure deficit.

Mean annual increment was found to be significantly related to the class level variable subsoil acid-soluble phosphorus. One limitation of this categorical variable is that it does not account for subtle variations in soil fertility within New Zealand (see Watt et al., 2008) that can be accommodated using continuous variables. Further research should therefore focus on the development of spatial layers for soil chemical properties such as soil C:N ratio and total phosphorus that have previously been found to be significantly correlated to productivity for a range of plantation species (Watt et al., 2008). Use of layers for continuous variables describing soil fertility is likely to improve predictions of productivity for this species.

The maps show very high productivity for Northland regions. These high values should be interpreted with some caution as the models were not developed using data from these regions. Although it is reasonable to expect productivity will be enhanced similarly by high temperature at different locations, it should be noted that Northland soils may be of lower fertility compared with other New Zealand soils. It is likely that subsoil acid-soluble phosphorus does not fully capture the influence of this low fertility on 400 index. It is also worth noting there is no fertility related variable for site index. Further research should therefore focus on validating the model described here against plot data from Northland.

In conclusion, these results highlight the utility of thematic spatial layers as driving variables in the development of productivity models. Models developed from these layers are likely to improve in the future as more variables, such as soil chemical properties, become available. This approach greatly reduces model development cost. The development of detailed maps from these models will provide invaluable decision support for determining optimal sites for plantation species such as *Sequoia sempervirens*.

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