

Precision Forestry Research Project – Final Report

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Introduction

Estimates of productivity and factors limiting productivity are critical for forest growers to make optimum silvicultural investment decisions and design regimes to maximise the value of every hectare of their estates, but existing productivity layers from national models or current/past rotation data are not detailed enough for site specific management decisions. Monitoring of crops and site quality evaluation at high resolution in order to optimise forest management has been dubbed “precision forestry”, and borrows ideas from “precision agriculture”.

Precision agriculture combines geographical positioning systems (GPS), geographical information systems (GIS), remote sensing, site evaluation, and computer-controlled variable rate applications of treatments such as seed spacing, weed control or fertilisation by machines. These features of precision agriculture have analogues in forestry, but precision-forestry may be extended to operations and processes beyond those used in precision agriculture.

Decisions about species choice, site preparation, weed control, fertilisation, genotypes, tending regimes, and harvest planning are all likely to be affected by more precise knowledge of site characteristics and site productivity. Moreover, high resolution estimates of site features and productivity can improve average estimates for large areas commonly regarded as stands by forest managers.

Four technologies are available for providing high resolution estimates of site and crop features that enable precision forestry across landscapes:

- 1) GIS layers that represent spatially explicit estimates of soils, topographic, and climatic features.
- 2) Remote sensing of tree dimensions via aerial photography, satellite imagery and LiDAR technology.
- 3) Estimation of tree dimensions on a mechanical harvester head equipped with a GPS system and appropriate electronic measurement devices.
- 4) Hybrid physiological and mensurational modelling of forest productivity that exploits GIS layers describing soils, topography and climate in order to predict radiation-use efficiency and estimates of underlying site productivity.

Dimensions of trees measured through (2) and (3) above are often regarded as estimates of underlying site productivity, however, they are very rough and potentially biased estimators of site productivity. Tree dimensions are influenced not just by site productivity but also by tree genotypes and management activities such as site preparation, tending, weed control and pest management. Hybrid physiological and mensurational modelling therefore provides us with a measure of site productivity that is independent of these other influences, and that is why it is an integral part of a precision forestry management programme.

The project described here had an overall goal to combine (1) and (4) above in order to generate estimates of forest productivity at a 15 x 15 m resolution across large forest estates. These have been delivered as raster layers in GeoTiff format. The steps involved were as follows:

1. Evaluate the quality of weather records available from the National Institute of Water and Atmospheric Research, and find ways to localise them within forest estates.
2. Check the precision and bias of commonly available GIS layers that represent digital terrain models.
3. Use the best available estimates of site and climatic inputs to estimate radiation-use efficiency at the locations of PSPs within forest estates.
4. Calibrate models relating radiata pine site index and 300 index to radiation use efficiency using PSP data, taking into account other features that might improve model estimates, such as aspect and slope.
5. Run the radiation use efficiency model within each pixel of a 15 x 15 m raster across estates, and then apply the calibration model to generate layers describing variation in site index and 300 index at high resolution across estates.
6. Generate layers at the same high resolution that describe factors limiting productivity across entire forest estates.

This report describes these steps in detail, and finishes with a discussion of outcomes and future steps for this research programme.

Evaluation of weather data estimates

Eco-physiological modelling of forest production relies heavily on local meteorological data in order to calculate constraints of photosynthesis, and we need to clearly identify the precision and bias associated with sources of such data.

A typical eco-physiological or “hybrid” model of forest growth and yield exploits a linear relationship between intercepted radiation and forest net primary productivity (Montieth 1972, 1977). The slope of the relationship has been labelled “quantum efficiency” and it is influenced by temperature, soil moisture status, vapour pressure deficit (VPD), soil nutrition, and plant physiological age. The idea of reducing maximum achievable quantum efficiency with modifiers that represent these influences is that basis of the 3-PG model (Landsberg et al. 1997). Modifiers vary between 0 and 1 and are generally calculated using models of sub-processes such as water balance models or predictions of the impact of vapour pressure deficit on stomatal conductance. In order to work effectively, sub-models require accurate inputs of meteorological data, particularly rainfall, daily maximum temperature, daily minimum temperature, VPD, and daily global or (if available) photosynthetically active radiation.

Eco-physiological models have been made to operate at a variety of temporal scales (McMurtrie et al. 1983a, b; McMurtrie et al. 1990; McMurtrie et al. 1992), but for management purposes hybrid models of forest production are likely to be best employed with a monthly time step (Mason et al. 2007; Mason et al. 2011a).

The objectives of the study described here were to:

- 1) Determine the precision and bias of available estimates of meteorological data for particular points in the New Zealand landscape by comparing the estimates with measurements at independent meteorological stations.
- 2) Identify any adjustments that might be made using other information, such as elevation, that might improve estimates for those points.

Three alternative estimates of weather data were available:

- 1) Long-run average weather estimates over decades, for instance, averages on a 0.5° grid from Bioclim, and radiation estimates documented by Leathwick et al. (1998).
- 2) Data from the nearest available meteorological station, adjusted for differences in elevation, latitude and distance from the sea. Such adjustments might be made using simple adiabatic adjustments or using equations reported by Norton (1985).
- 3) Estimates from the National Institute of Water and Atmospheric Research's (NIWA) "Virtual Climate Station Network" (VCSN) (Tait et al. 2006; Cichota et al. 2008), a grid of points at approximately 5 km spacing across New Zealand where daily estimates of weather variables are modelled. These can also be adjusted to localise them.

Option (1) was considered to be an inferior option, because the layers are coarse and also long-run averages are unlikely to correlate with observed growth rates as well as weather patterns that occurred during years when trees in plots were growing. Moreover, although the study has not been published, an evaluation of outcomes with the 3-PG model using long-run averages has been found to provide an extreme estimate of growth rather than the average of a range of simulations using variable weather patterns (Cristian Montes pers. comm.). Nonetheless, averages from Bioclim were briefly examined during the calibration stage of the study described here.

9 independent meteorological stations were used to evaluate how well estimates from nearest meteorological stations and the VCSN network compared with measurements at specific points in the landscape, and how estimates could be localised.

Method

Nine meteorological stations were established in association with forest experiments (Figure 1). They all recorded rainfall, temperature, relative humidity, wind speed and global radiation on a half-hourly time step with sensors operating every few seconds. Seven of them employed ONSET equipment supplied as a package with the HOBO U30-NRC-SYS-B Weather Station. This system employs a HOBO U30 solar powered logger, a HOBO S-LIB-M003 Silicon Pyranometer Smart Sensor, and standard ONSET temperature, rainfall and wind sensors. One station employed the same sensors but with a HOBO H21-002 battery powered micrologger. The ninth station was a Delta-T Devices WS-GP1 compact weather station with a solar powered logger. All stations were mounted on tripods on flat terrain that was unsheltered by trees or local topography. Table 1 lists the stations.

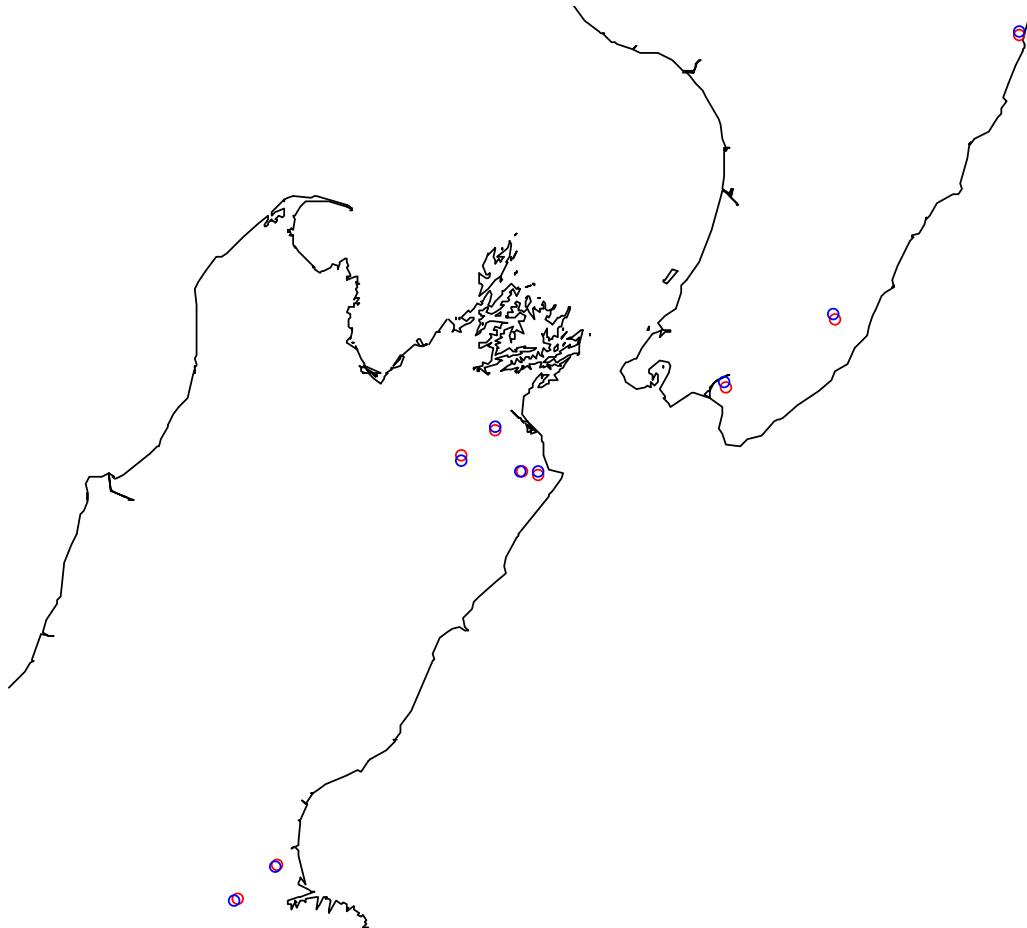


Figure 1 – Locations of independent meteorological stations (red circles) and the nearest NIWA virtual climate station network points (blue circles).

The National Institute of Water and Atmospheric research operates meteorological stations throughout New Zealand, with a higher spatial frequency for some measurements than others. Spatial frequency is very high for rainfall, somewhat less high for temperature, and low for radiation measurements. The closest stations to our experimental stations that covered the same time period were selected for each type of measurement, and their data was downloaded from the NIWA web site. These data are provided as a free service to the community. Locations of the stations are shown in table 2.

NIWA staff interpolate between meteorological stations to provide daily estimates of weather at 5 km by 5 km grid points throughout New Zealand (Tait et al. 2006), and this is known as the virtual climate station network (VCSN). The nearest grid points to our stations were selected and their data were kindly supplied to us by Dr Andrew Tait, Principal Scientist with the National

Climate Centre. The locations of these grid points are shown in Figure 1, and the distances between our stations and the points are shown in table 1.

Table 1 – Meteorological stations, their locations, locations of the virtual climate stations points closest to them, and distance between them

Station	Latitude	Longitude	Altitude (m)	Sea distance (km)	VCSN Latitude	VCSN Longitude	VCSN No.	VCSN Altitude (m)	VCSN Sea Distance (km)	Distance between (m)
Avery	-41.7376	174.124	62	5	-41.725	174.125	29662	71	6	1399
Lawson	-41.7226	174.0321	172	12	-41.725	174.025	30161	136	13	648
Dillon	-41.6503	173.677	281	40	-41.675	173.675	27528	427	38	2752
Cuddon	-41.539	173.8693	53	21	-41.525	173.875	27539	28	19	1625
Atkinson	-41.3496	175.2407	60	5	-41.325	175.225	27120	10	4	3032
JNL Ngaumu	-41.046	175.8764	241	14	-41.025	175.875	27805	218	16	2344
McNeil	-39.7892	176.9706	282	2	-39.775	176.975	30574	146	3	1623
Rolleston	-43.6182	172.3461	46	6	-43.625	172.325	21315	52	6	1859
Harewood	-43.4668	172.5887	19	7	-43.475	172.575	19949	22	8	1433

Table 2 – NIWA stations used for local station estimates of temperature, rainfall and radiation

Station	Temp station number	Distance to temp station (km)	Rainfall station number	Distance to rainfall station (km)	Radiation station number	Distance to radiation station (km)
Lawson	4420	9.4	4420	9.4	12430	25.5
Avery	4420	1.5	4420	1.5	12430	29.7
Dillon	36106	17.3	4319	14.3	36106	17.3
Cuddon	4326	1.8	4326	1.8	4326	1.8
Atkinson	21938	16.5	2665	3	21938	16.5
JNL Nguamu	31857	15.4	2613	14.2	37662	17.3
McNeil	3017	19.2	3017	19.2	2980	37.7
Rolleston	17603	10	4880	3	17603	10
Harewood	4843	5.1	4843	5.1	4843	5.1

Data from all sources were summarised by year and month.

Mean daily maximum and minimum temperature estimates from NIWA were localised to our stations in two ways: a) An adiabatic adjustment was made based on the difference between NIWA estimate point elevations and our station elevations, and b) equations predicting long run monthly temperature means from elevation, latitude and distance from the sea (Norton 1985) were employed for both our station locations and the NIWA estimate point locations and the difference was added to the NIWA station estimates.

NIWA estimates were compared with meteorological data recorded at our stations in three ways:

1. Tables of correlations were prepared between alternative NIWA estimates and actual recorded estimates of monthly weather statistics.
2. Graphs of observed versus estimated meteorological statistics were prepared with points coloured and labelled by station.

3. Graphs of residuals versus predicted values, differences in elevation, and distances between our stations and NIWA estimate points were prepared.

Results

Temperature

Table 3 shows correlations between observed temperatures, VCSN estimates, and nearest NIWA station estimates. Correlations tend to be high, and the most frequently best transformations to local conditions were achieved by using Norton's (1985) equations, although a simple lapse calculation was slightly, but not significantly better for maximum temperature from VCSN points. Correlations were higher with VCSN estimates than with nearest station estimates. While the raw minimum temperature was slightly more highly correlated with observed temperature, Norton's equations may become particularly useful even for minimum temperature when stations and observed points differ greatly in distance from the sea.

Table 3 – Correlations between observed mean daily maximum and minimum temperatures averaged by month, and estimates from either VCSN points or from nearest NIWA meteorological stations, including some alternative step-out transformations

Type	Maximum	Minimum
Raw VCSN	0.9731	0.9752
Lapsed VCSN	0.9816	0.9671
Norton VCSN	0.9812	0.9722
Raw NIWA station	0.9553	0.9142
Lapsed NIWA Station	0.9697	0.8951
Norton NIWA station	0.9723	0.9125

Figures 2 and 3 show plots of observed temperature versus raw temperature and the best adjusted temperature, while Figure 4 shows residuals for the best estimates of observed temperatures. Even with adjustments there is clear evidence of bias with station, but generally the bias is not too severe in magnitude.

Plots of residuals versus a) distances between estimate points and stations, and b) differences in elevation between estimate points and station points were created. Residuals of raw maximum VCSN and nearest NIWA station estimates were correlated with elevation difference, but adjusted estimates were less clearly correlated with elevation difference. Residuals of raw VCSN estimates tended to have a higher variance with distance, but not those of adjusted estimates, nor did NIWA estimates vary with distance.

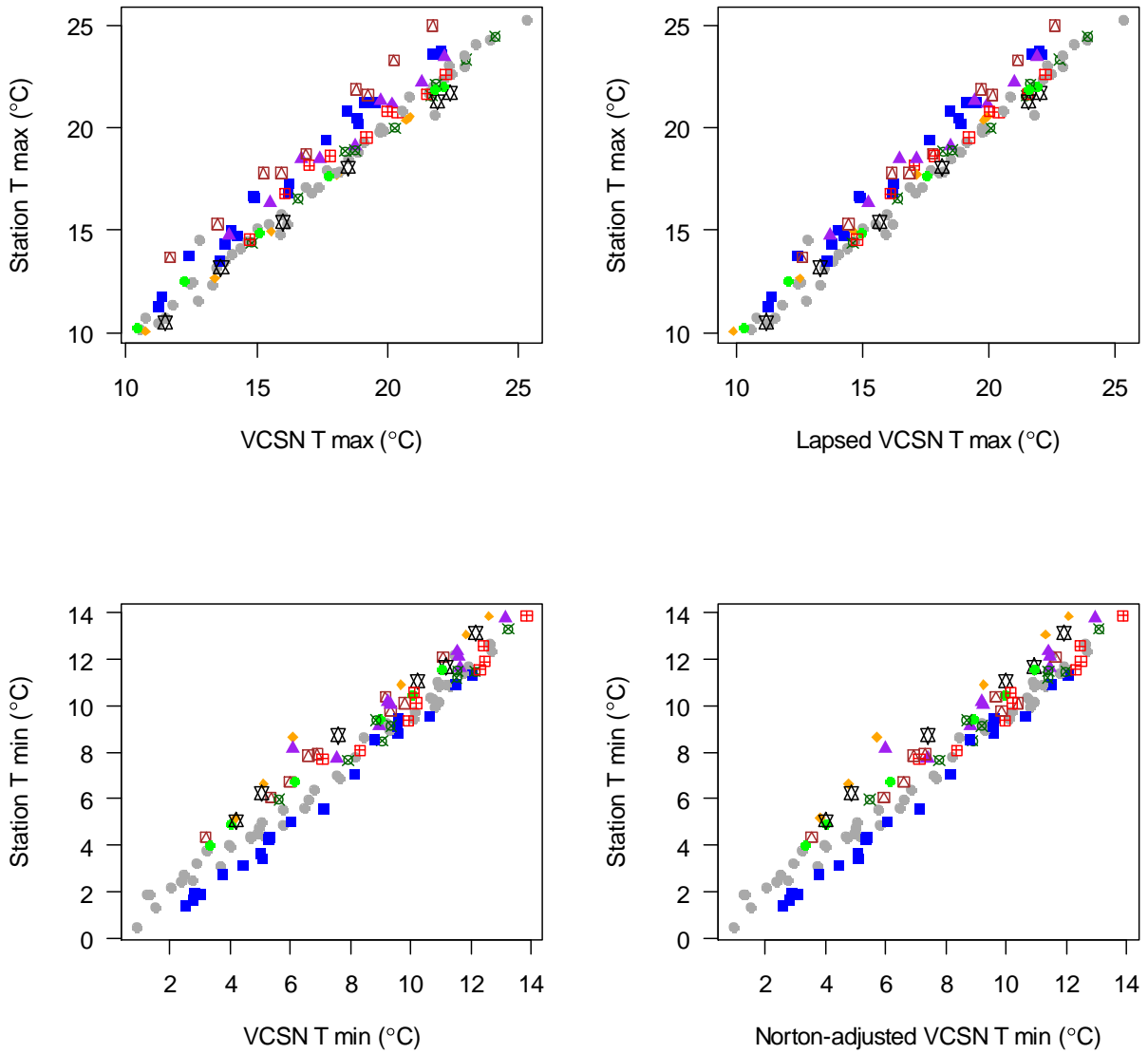


Figure 2 – Observed monthly average daily maximum temperature versus raw VCSN (top left) and lapsed VCSN (top right) estimates. Observed monthly average daily minimum temperature versus raw VCSN (bottom left) and lapsed VCSN (bottom right) estimates. Colours and symbols show different observed meteorological stations.

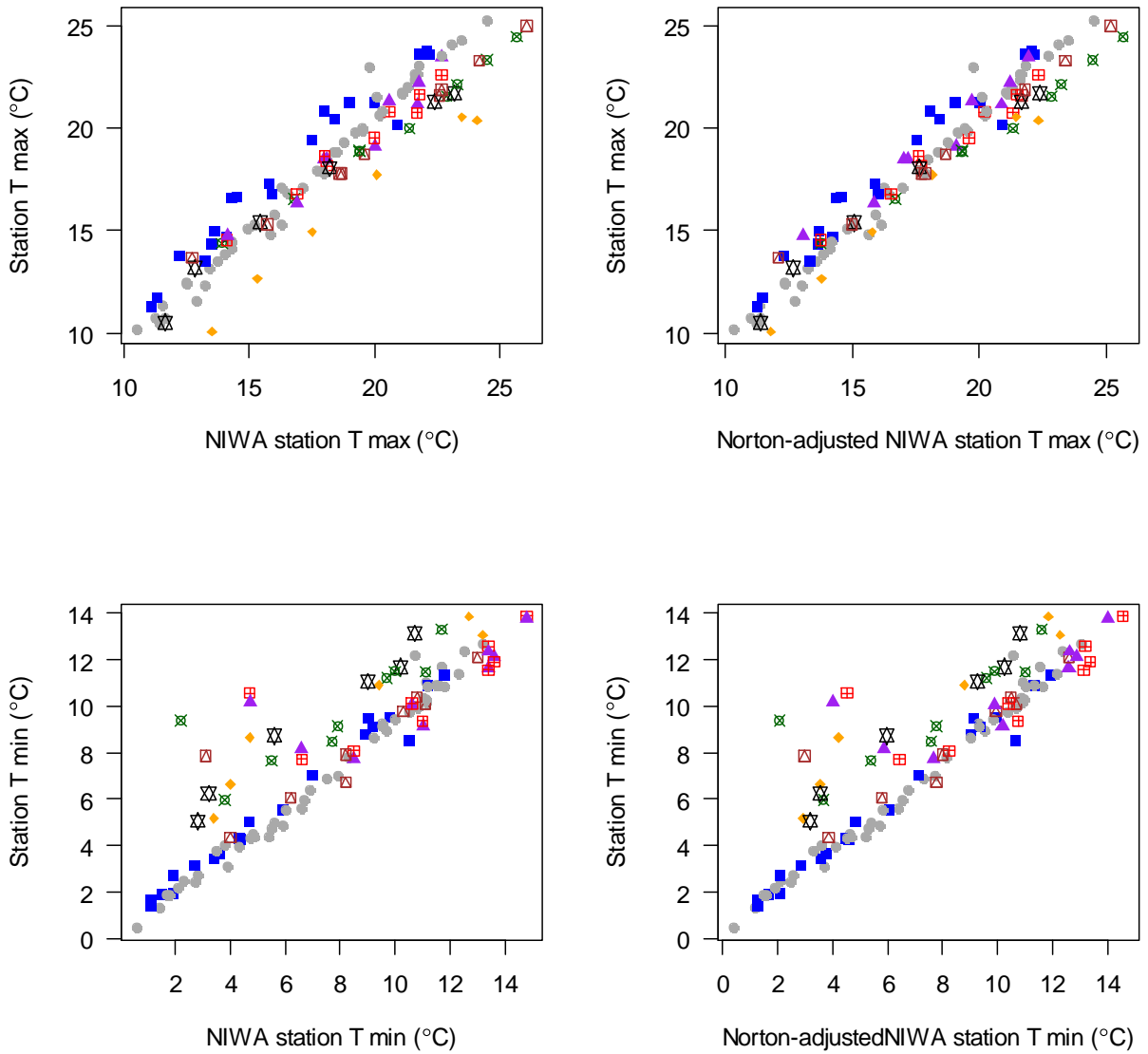


Figure 3 – Observed monthly average daily maximum temperature versus raw NIWA (top left) and Norton-adjusted NIWA (top right) nearest station estimates. Observed monthly average daily minimum temperature versus raw NIWA (bottom left) and Norton-adjusted NIWA (bottom right) nearest station estimates. Colours and symbols show different observed meteorological stations.

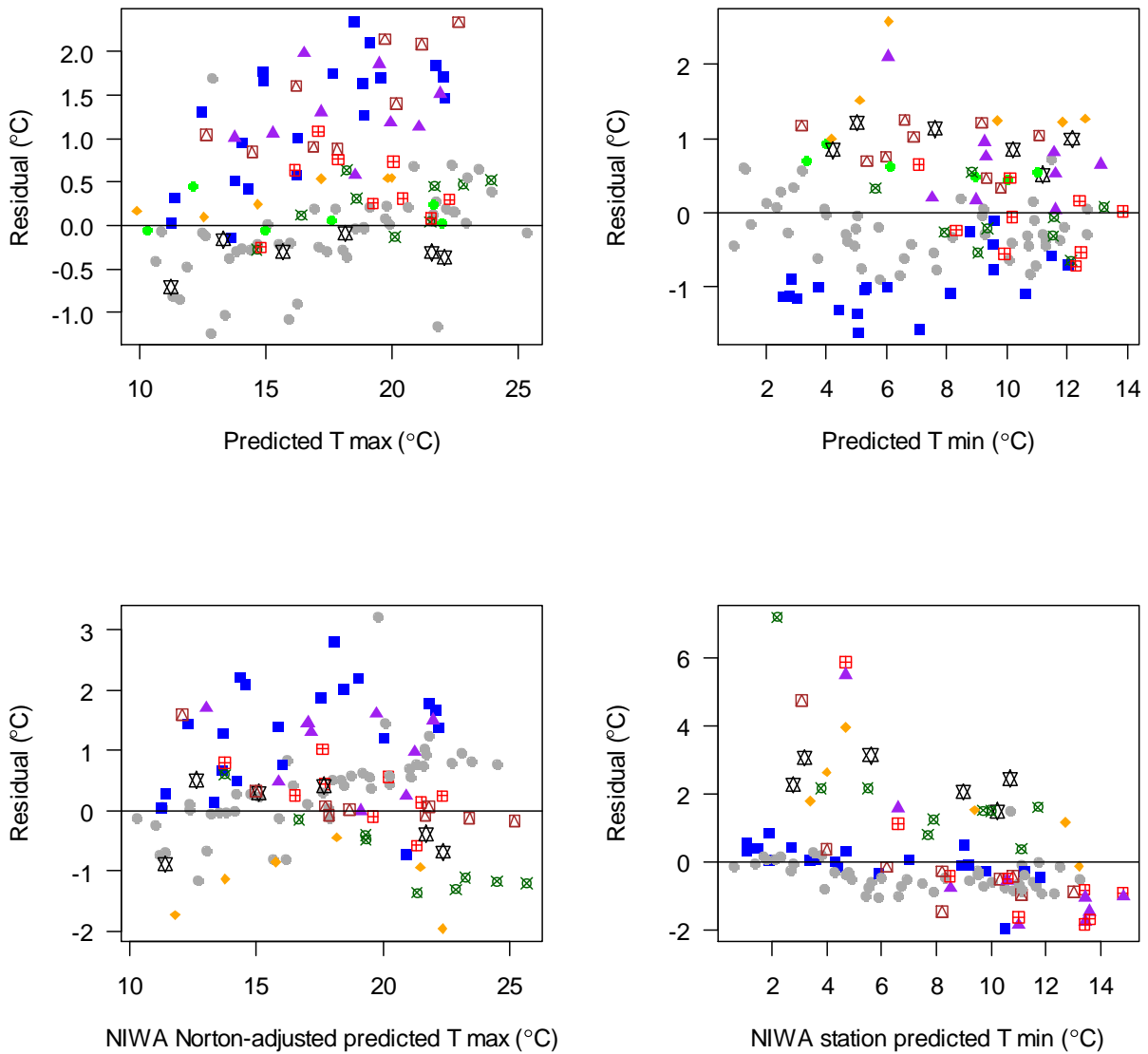


Figure 4 – Residual plots for a) lapsed VCSN estimates of maximum temperature (top left), b) raw VCSN estimates of minimum temperature (top right), c) Norton-adjusted nearest NIWA station estimates of maximum temperature (bottom left), and d) nearest NIWA station estimates of minimum temperature (bottom right)

Radiation

Correlations between observed radiation and VCSN average monthly radiation was 0.9914, while that with radiation from the nearest NIWA meteorological station was 0.9928 (Figure 5).

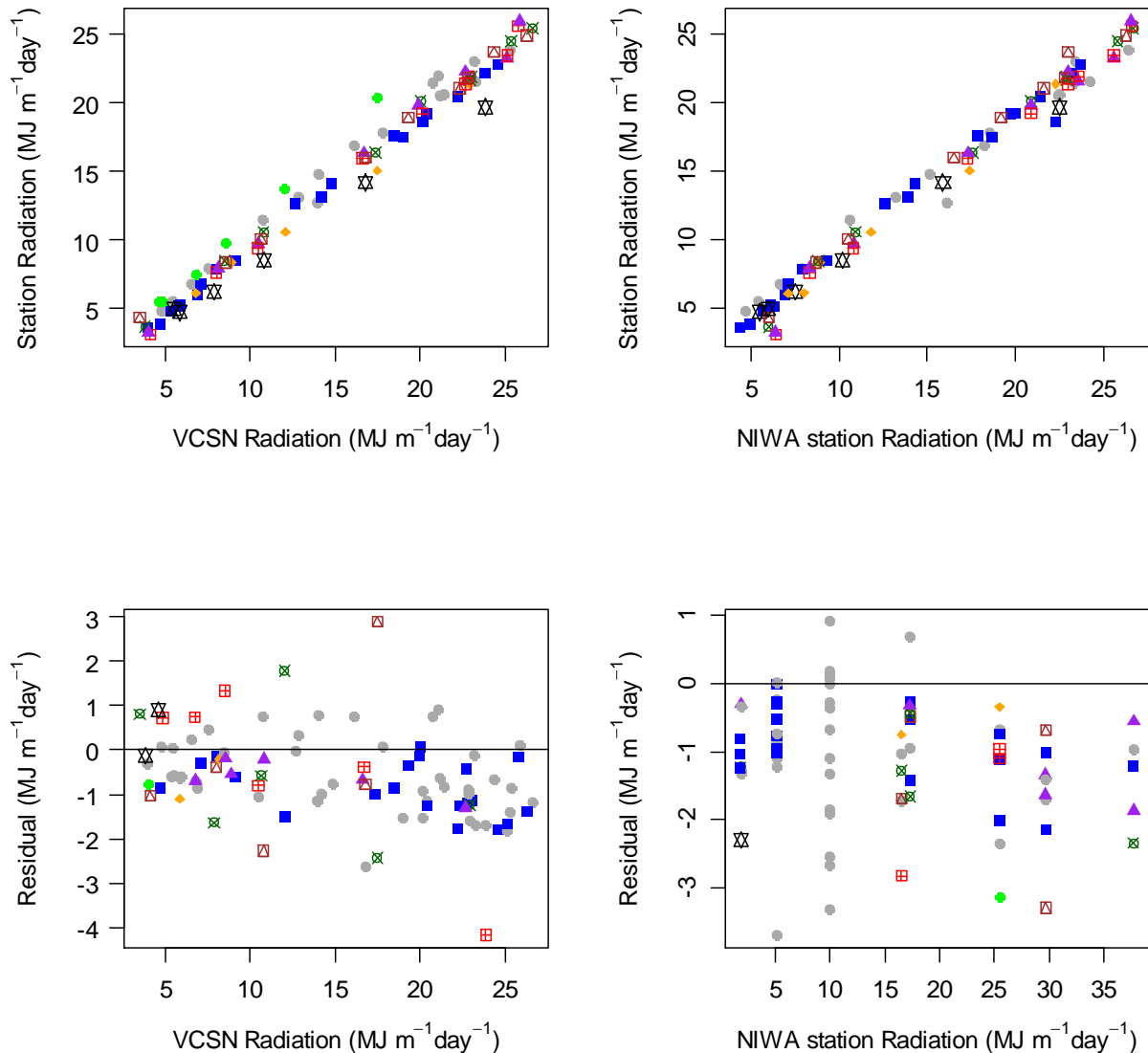


Figure 5 – Monthly average observed radiation versus VCSN estimates of radiation (top left), Monthly average observed radiation versus nearest NIWA station radiation (top right), residuals of VCSN radiation estimates versus predicted value (bottom left), and residuals of nearest NIWA meteorological station estimates of radiation versus predicted value (bottom right).

Residuals increased with distance between our stations and estimate points. Note also that despite having a higher correlation with observed values, the nearest NIWA station estimates were biased overall.

Rainfall

Correlations between observed rainfall and estimated rainfall were 0.916 and 0.801 for VCSN points and nearest NIWA rainfall station respectively (Figure 6). As expected the residuals were highly heteroscedastic. There was also a small tendency for residuals to increase with distance between our stations and VCSN points, but distance to NIWA rainfall stations appeared to matter little.

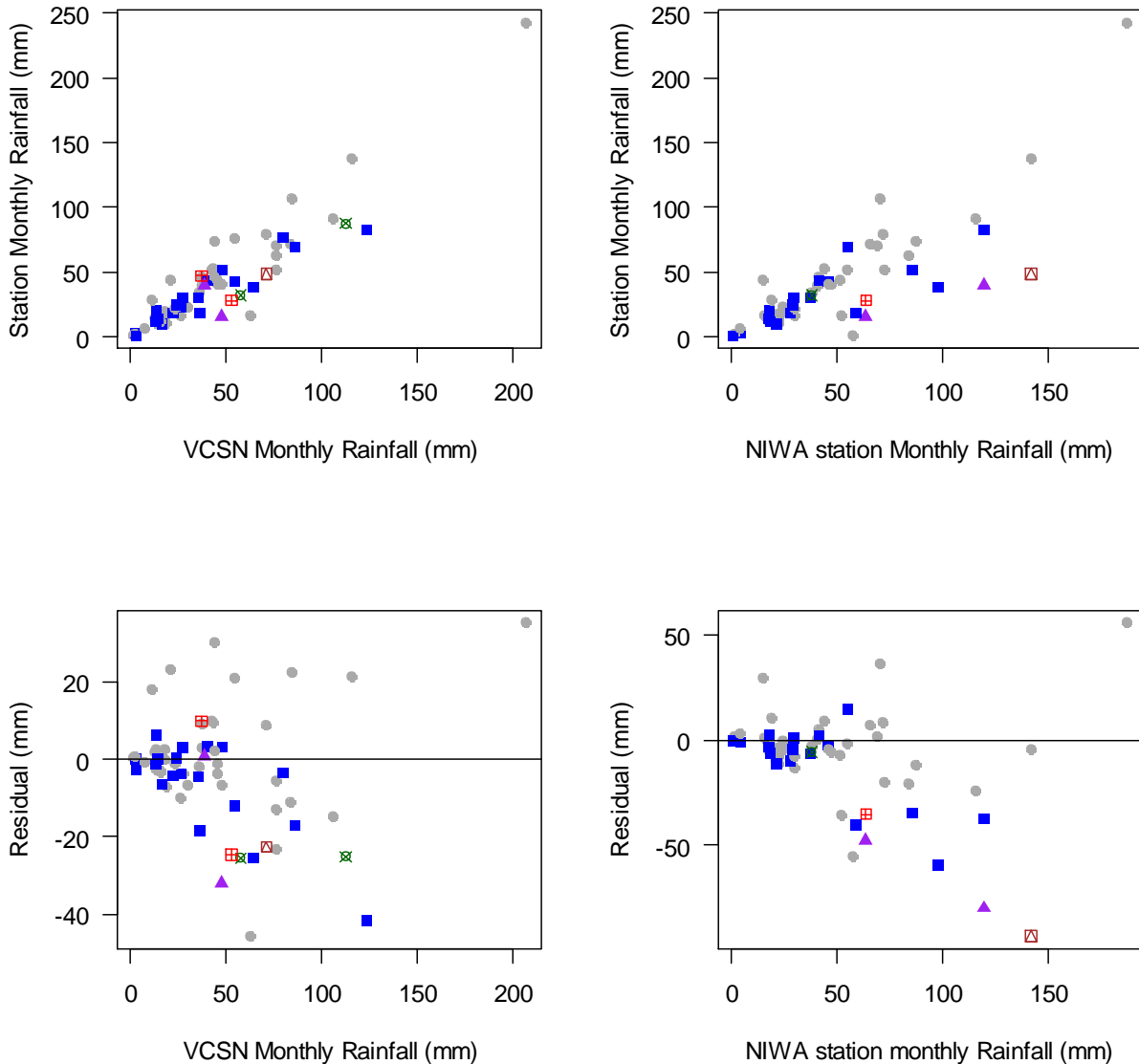


Figure 6 – Observed average monthly rainfall versus VCSN estimates (top left), observed average monthly rainfall versus nearest NIWA station estimates (top right), residuals of VCSN rainfall estimates versus predicted values (bottom left), and residuals of nearest NIWA rainfall station estimates versus predicted values (bottom right)

Vapour pressure deficit

The correlation between average monthly vapour pressure at our stations and VPD estimated at VCSN points was 0.83 (Figure 7), with a tendency towards higher variance and bias with decreasing relative humidity. There were no clear patterns of residuals with distance to VCNS point nor with elevation difference.

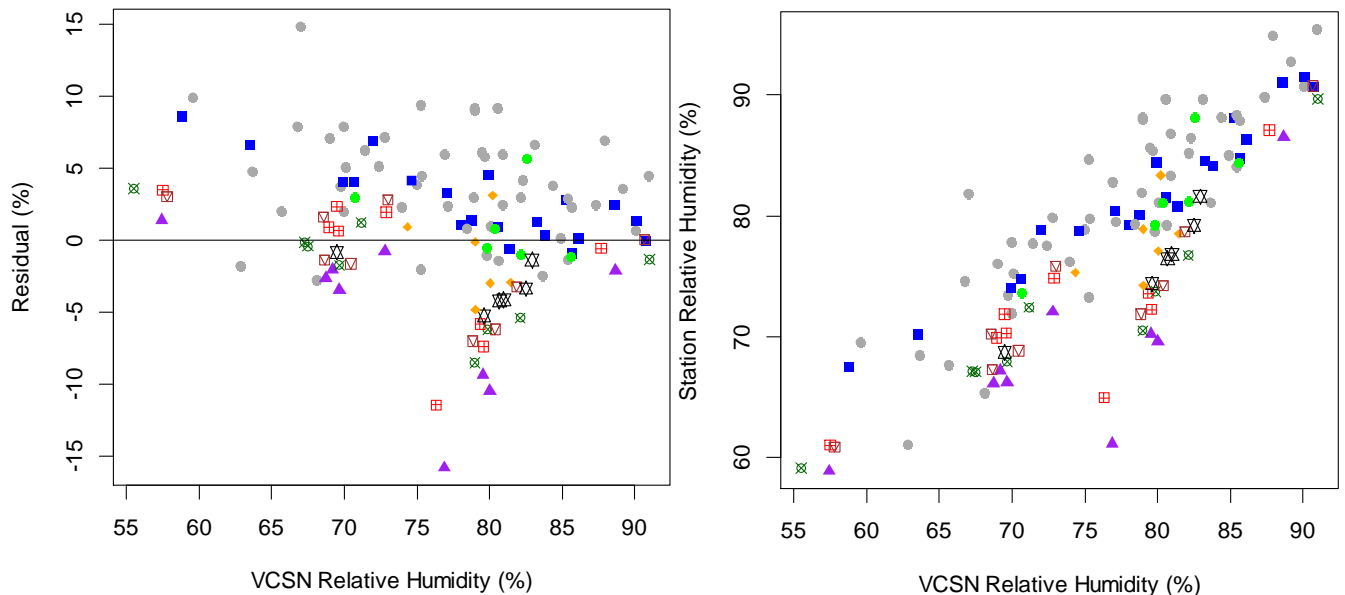


Figure 7 – Observed monthly average relative humidity versus VCSN estimates (right), and residuals versus predicted values (left)

Discussion and conclusions

Clearly the VCSN offers advantages over nearest NIWA station estimates of variables that we require for eco-physiological modelling of forest growth for all variables examined in this study.

Errors of most variables were relatively small and estimates would be tolerable for our modelling efforts, although they will add to errors of estimates of our models.

Rainfall was the most poorly estimated variable, and in some cases the error may become very important in our models, particularly in dry areas where water supply is the dominant factor influencing growth. NIWA has far more rainfall stations than stations that measure other variables and clearly NIWA's preoccupation with rainfall measurements is justified as rainfall appears to be far more local than other variables.

The overall bias of NIWA station estimates of radiation is troubling, but may reflect particular locations of our stations and NIWA radiation stations given the small numbers of our stations and the relatively low numbers of NIWA radiation stations.

There was a tendency for both VCSN and NIWA station estimates to be biased with respect to individual stations and as expected, this bias was often related to distance between our stations and the estimate points. Adjustments of temperature using simple lapse adjustments for elevation differences or Norton adjustments for elevation, distance from the sea and latitude often reduced temperature estimate bias, particularly for maximum temperatures. Minimum temperatures are quite well estimated from VCNS points and local adjustment offered little, if any improvement in estimates.

Evaluation of digital elevation models

Establishing accurate estimates of global position, elevation, slope, and aspect is essential for simulating plant growth across landscapes. LiDAR is generally assumed to be extremely accurate, but other sources of digital elevation estimates are available, such as the 25 m cadastral TOPO50, and a 15 m reworking of the same GIS layer. These latter two estimates are available nationwide, while LiDAR estimates are available for only portions of New Zealand.

Method

We compared estimates of elevation, slope and aspect derived from the following sources for an area of highly variable topography within the Blakely Pacific Estate:

- 1) 25x25 m digital elevation model (DEM) from TOPO50
- 2) 15x15 m DEM
- 3) LiDAR 0.025 points m⁻² = 40x40 m
- 4) LiDAR 0.05 points m⁻² = 20x20 m
- 5) LiDAR 0.01 points m⁻² = 10x10 m
- 6) LiDAR 0.5 points m⁻² = 2x2 m

We compared these sources with LiDAR at 1 point m⁻². Residual values were calculated and plotted against predicted values.

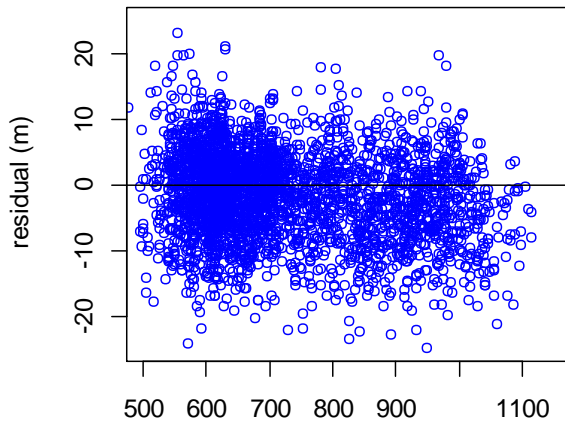
The digital elevation models (DEM) were used to derive slope and aspect surfaces using the Spatial Analyst toolbox in ArcGIS 10.2 (ESRI, Redlands, CA). In some cases, a digital elevation model needed to be produced from contour shapefiles prior to deriving slope and aspect surfaces. To achieve this, the tool 'Topo to Raster' from the Spatial Analyst toolbox was used. DEMs were all resampled to a 15 m spatial resolution, a value shared by corresponding slope and aspect surfaces. Initial DEM resolution ranged from 2 m to 15 m.

Results

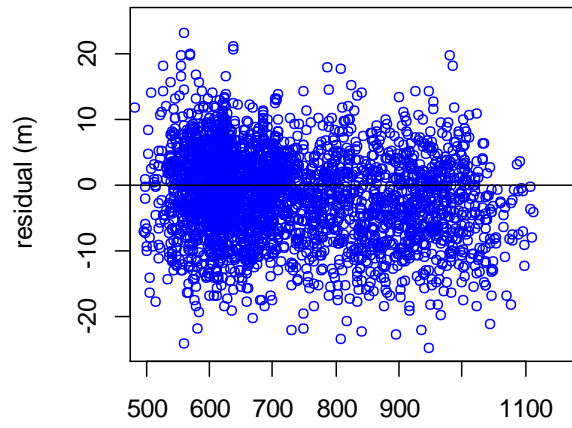
Results showed that in general, even the lowest resolution LiDAR was superior to the cadastral GIS layers. Higher resolution LiDAR resulted in some improvement, but the difference was not as marked as between the cadastral layers and the lowest resolution LiDAR. This is shown as a series of residual plots.

Elevation

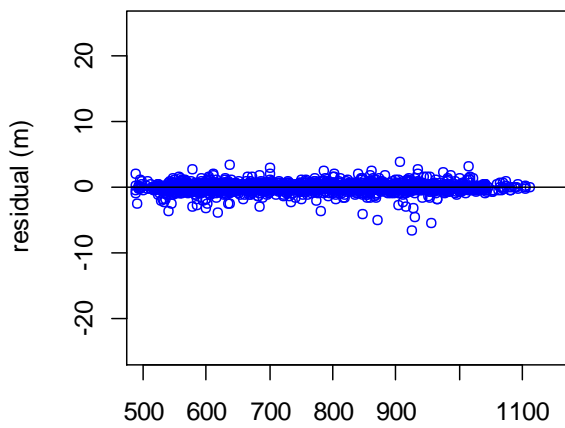
Elevation errors for the cadastral layers were generally + or – 15 m, while those for the lowest resolution LiDAR were mostly within 2 m (Figure 8).



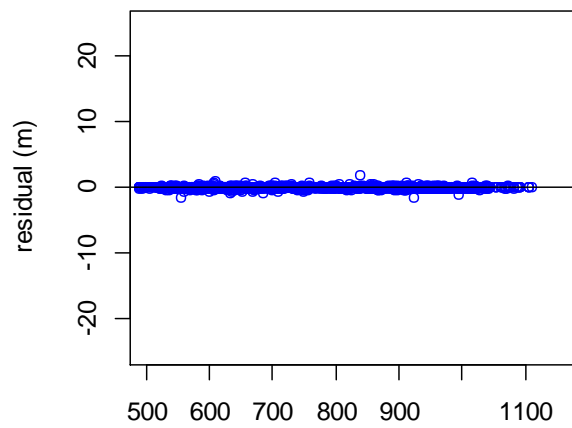
25x25 m elevation from TOPO50 map series (m)



15x15 m elevation from TOPO15x15 map series (m)



40x40 m elevation from LIDAR (m)



2x2 m elevation from LIDAR (m)

Figure 8 – Residual elevations for a) TOPO50 map series (top left), b) TOPO 15 x 15 map series (top right), c) 40 x 40 m LiDAR (bottom left) and d) 2x2 m LiDAR (bottom right)

Slope

Slope was very badly influenced by inaccuracies in the two cadastral layers, but was reasonably well estimated in the LiDAR layers (Figure 9).

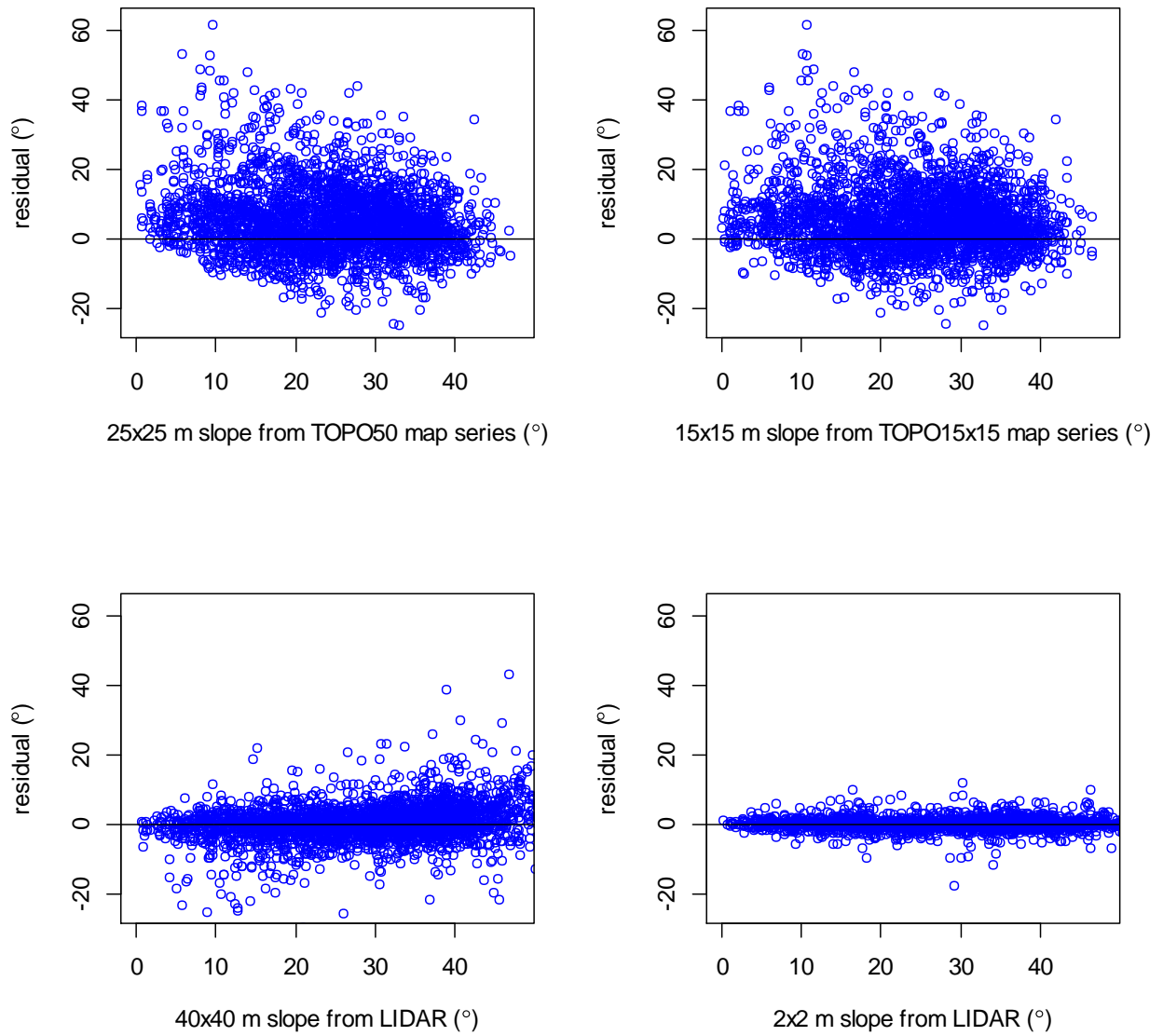


Figure 9 – Residual slopes from a) TOPO50 map series (top left), b) TOPO15x15 map series (top right), c) 40x40 m LiDAR (bottom left) and d) 2x2 m LiDAR (bottom right)

Aspect

Aspect estimates from the cadastral layers were at least as poor as slope estimates (Figure 10)

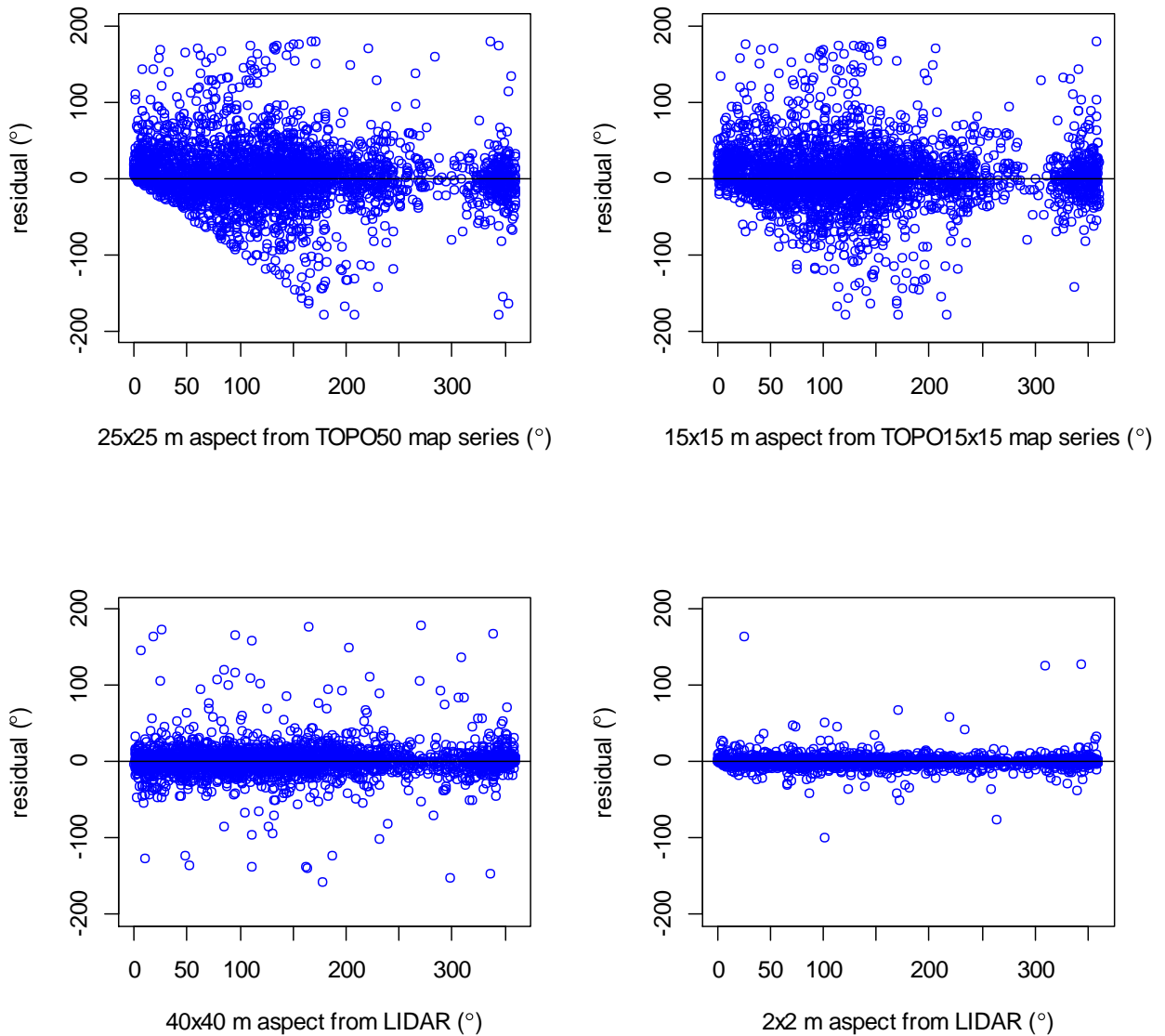


Figure 10 – Residuals of aspect from a) the TOPO50 map series (top left), b) the TOPO15x15 map series (top right), c) 40x40 m LiDAR (bottom left) and c) 2x2 m LiDAR (bottom right)

Discussion

Cadastral layers may be adequate if all one wishes to know is elevation, but they provided very poor estimates of slope and aspect; their estimates of slope and aspect could not be expected to provide good estimates of effects of those features on productivity. This may be due to poor northing and easting registration of those layers.

LiDAR may be essential if we wish to include aspect and slope in our model calibrations.

Estimating radiation-use efficiency at permanent sample plot locations

Permanent sample plot (PSP) summaries were provided by three companies, Kaingaroa Timberlands Ltd., Nelson Forests Ltd. and Blakely-Pacific (NZ) Ltd.. Permanent sample plots used for testing outputs of the radiation-use efficiency model had to have been planted after 1972, because VCSN summaries were not available before that date, and were restricted to those with measurements after age 10 (13 for Kaingaroa TL) so that they would reasonably represent site quality (Table 3).

Table 3 – Summary of PSPs used from each company

Company	No. PSPs	Site index range (m)	300 index range (m³/ha/yr)	Estimate age range (years)	Elevation range (m)
Kaingaroa T L	1115	20 - 43	11 - 39	13 - 23	112 - 812
Nelson Forests L	175	24 - 36	15 - 45	10 - 23	60 - 672
Blakely Pacific L	75	21 - 38	18 - 43	10 - 21	190 - 499

Estimate ages in each PSP were chosen so that they would be as close to 20 years (the site index age) as possible.

PSPs in Kaingaroa Timberlands Ltd.'s estate were very numerous and unevenly distributed, and so for calibration purposes a subset was randomly selected with a constraint that no more than four PSPs would be in any one compartment. The calibration set comprised 408 PSPs. The remainder were available for model validation.

Weather data were assembled from the closest VCSN point to each PSP covering the period from time of planting to the measurement age, and the data were summarised by month.

Elevation, slope and aspect estimates were estimated for each PSP from the best available source. For Kaingaroa Timberlands Ltd. LiDAR data were used, while for Nelson Forests Ltd. a 6 m contour layer developed by Craig Brown was used. Craig's layer included LiDAR for some portions of the estate. For Blakely Pacific Ltd. the NZ 15x15m DEM was used.

Soil type and potential rooting depth were estimated for each PSP from the Fundamental Soil Layer provided by Landcare Research. These layers are very low resolution (Figure 11), and it is clear that poor access to accurate local soil data limits the utility of the water balance model.

Potential radiation use efficiency was simulated for each PSP using object-oriented R coding developed by Euan Mason (Mason et al. 2007; Mason et al. 2011a). An outline of the functions used is given below.

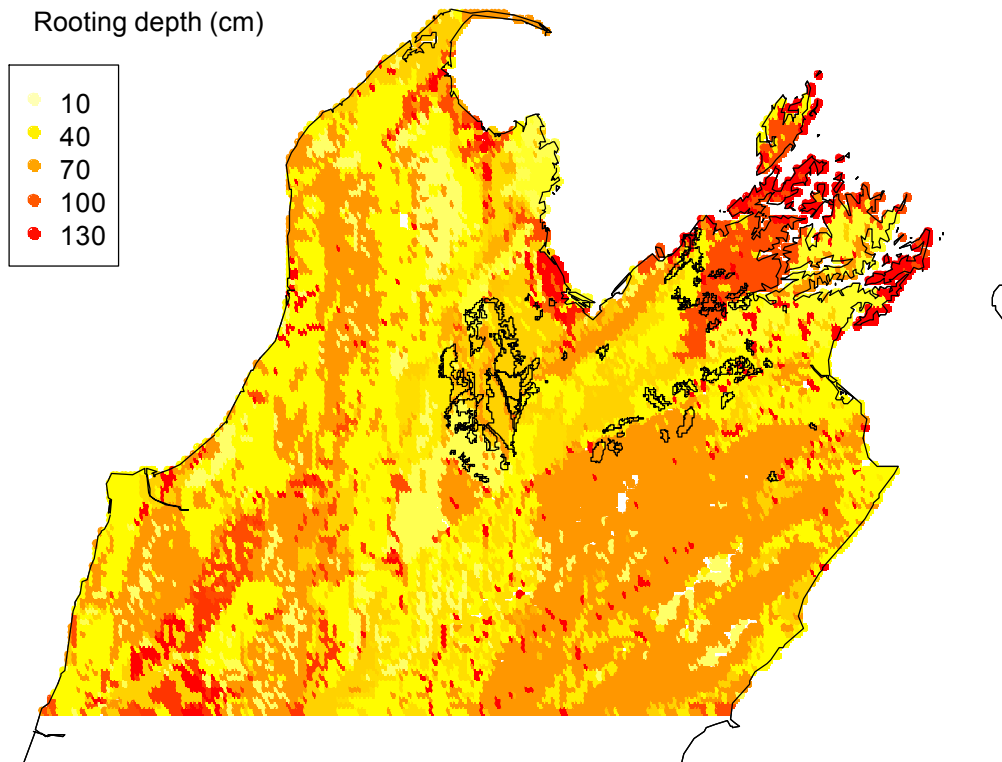


Figure 11 – Potential rooting depths estimated from the fundamental soil layer for the top of the South island of New Zealand. It is clear that the information is at very low resolution

A water balance model was created for each plot that was identical to that used in 3-PG (Landsberg et al. 1997). A leaf area index model was required for the water balance, and based on LAI measurements in Canterbury (Pinjuv et al. 2006) a simple exponential model was assumed with an asymptote of 6.5 that was reached by approximately age 15 (details are available on request). The soil water modifier used for light sums was also identical to that used in the 3-PG model. Monthly weather and LAI estimates were assembled as related tables in a database, and then a water balance model was run over the years since planting in each plot, using a monthly time step. Maximum stomatal conductance was assumed to be 0.02 m/sec and maximum boundary layer conductance was assumed to be 0.2 m/sec (Landsberg, pers. comm.).

Vapour pressure deficit (VPD) was estimated from mean daily maximum and minimum temperatures by assuming that vapour pressure deficit was 0.5 times the saturated vapour

pressure at the maximum temperature minus saturated vapour pressure at the minimum temperature.

A VPD modifier was used that is identical to that used in the current version of the 3-PG model. It was represented as:

$$f_D = e^{-0.05VPD} \quad (5)$$

where in (5) VPD=vapour pressure deficit. This modifier was also used to calculate stomatal conductance from maximum stomatal conductance in the water balance model.

A temperature modifier, also identical to that used in the 3-PG model was based on the minimum, optimum and maximum temperatures for photosynthesis as:

$$f_T(T_a) = \left(\frac{T_a - T_{min}}{T_{opt} - T_{min}} \right) \left(\frac{T_{max} - T_a}{T_{max} - T_{opt}} \right)^{\frac{(T_{max} - T_{opt})}{(T_{opt} - T_{min})}} \quad (6)$$

where in (6)

$f_T = 0$ if $T_a \leq T_{min}$ or $T_{max} \leq T_a$, and T_{min} , T_{opt} and T_{max} were the minimum, optimum and maximum air temperatures for net photosynthetic production. T_a was the mean temperature for each month. The minimum, optimum, and maximum temperatures for photosynthesis were assumed to be 6, 22 and 35 degrees respectively (Walcroft et al. 1997).

The radiation sums for each month were multiplied by the temperature modifier, and sums from time of planting to the beginning and end of each interval in the dataset were created. The radiation sum was therefore:

$$R_T = \sum_{t=1}^T R_t \min[f_\theta f_D] f_k \quad (7)$$

where in (7)

R_T = modified radiation sum over the growing period for the PSP

R_t = the total global radiation sum for month t

f_θ = the soil water balance modifier

f_D = the vapour pressure deficit modifier (equation 5)

f_k = the temperature modifier (equation 6) for month t.

We would have liked to add a nutrient fertility modifier to the analysis, but as outlined in the appendix, we have been unable to find any GIS layers relating to soil nutritional fertility that offer improvements.

In addition, separate model runs were calculated using Euan Mason's software accounting for the geometric influences of aspect and slope on radiation as proposed by Tian et al. (2001), based on Revfeim (1978):

$$H_s^* = H_s[R_d(1 - K_r) + f_b K_r + 0.12(1 - f_b)] \quad (8)$$

Where in (8) H_s^* = global radiation received on a surface with an orientation α and slope β , f_b is a “slope reduction factor” = $1 - \frac{\beta}{180}$. R_d = direct radiation proportion of that on a flat surface with a given aspect and slope, calculated as:

$$R_d = \left[\frac{\sin(\varphi)}{\sin(\varphi^*)} \right] \left[\frac{d_d - \sin(d)\cos(e_e)\cos(g)}{\cos(\omega_s^*)} \right] \left[\frac{1}{\omega_s - \tan(\omega_s)} \right] \quad (9)$$

Where in 9:

$$d_d = \frac{(h_1 - h_0)}{2} \quad (10)$$

$$e_e = \frac{(h_1 + h_0)}{2} \quad (11)$$

$$g = \sin^{-1}[\sin(\beta)\sin(\alpha)\sec(\varphi^*)] \quad (12)$$

$$\varphi^* = \sin^{-1}[\sin(\varphi)\sin(\beta) - \cos(\varphi)\sin(\beta)\cos(\alpha)] \quad (13)$$

$$\omega_s^* = \cos^{-1}[\tan(\varphi^*)\tan(\delta)] \quad (14)$$

Where in (11) h_1 and h_0 are sunrise and sunset hour angle on an arbitrary slope. The model published by Erbs et al. (1982) was used to calculate the proportion of diffuse radiation in global horizontal radiation (K_r):

For $\omega_s \leq 1.4208$ and $0.3 \leq K_t \leq 0.8$

$$K_r = 1.391 - 3.560K_t + 4.189K_t^2 - 2.137K_t^3 \quad (15)$$

For $\omega_s > 1.4208$ and $0.3 \leq K_t \leq 0.8$

$$K_r = 1.311 - 3.022K_t + 3.427K_t^2 - 1.821K_t^3 \quad (16)$$

Where in (16) K_t = the proportion of global horizontal radiation to extra-terrestrial radiation $\left(\frac{H_s}{H_0}\right)$.

Calibration of radiation use efficiency model using PSPs

The radiation use efficiency software produced sums of potentially useable radiation in MJ/m² over the periods in which trees grew in PSPs, and so calibration was required in order to enable predictions of site index and 300 index (Kimberley et al. 2005). These were conducted for each estate separately and then using all PSPs combined. Only Kaingaroa Timberlands Ltd. and Nelson Forests Ltd. had enough PSPs and wide enough coverage to allow local calibrations, and so global calibrations were used for the other two estates.

Calibrations took the form of multilinear regressions with modified productivity indices as dependent variables, and modified radiation sums as well as other potentially important independent variables.

As a guide to the effectiveness of these calibrations, Palmer et al. (2010) modelled site index and 300 index of radiata pine across New Zealand, and achieved smallest root mean square errors (RMSEs) of 2.65 m and 3.65 m³/ha/yr respectively. Watt et al. (2015) used LiDAR measures of tree heights and environmental variables to estimate site index and 300 index in Kaingaroa Forest, achieving smallest RSMEs of 1.4 m and 2.45 m³/ha/yr respectively. The best way to compare models predicting the same thing is to use standard errors, and RSMEs are very closely related, generally being slightly smaller than standard errors.

There is a tendency for people to judge predictive models using R² values, but this is misleading when alternative models are tested using different data sources. For instance, two models can have the same standard error and vastly different R² values if the ranges of dependent variables differ. Forest managers should be concerned about errors of predictions rather than how much variation in the fitting dataset was explained. Standard errors will be reported in the results presented here, and the RMSEs quoted above can be used as a metric. It should be noted that we did not expect to achieve errors as small as those obtained from actually measuring trees with LiDAR (Watt et al. 2015).

Note also that productivity indices such as site index and 300 index have their own model errors when trees are measured to obtain them, and so some of the errors of prediction result from those model errors. Measurement of trees adds additional measurement device errors to the indices. Generally productivity indices will be best estimated when trees are measured at the index age.

Multi-linear models often require transformations to stabilise variance and make relationships linear. In the study reported here scaled power transformations were used:

$$x^{(\lambda)} = \begin{cases} (x^\lambda - 1) / \lambda & \lambda \neq 0 \\ \log(x) & \lambda = 0 \end{cases} \quad (17)$$

Where x is the variable being transformed, and λ is a parameter that varies usually between -2 and 5, providing a range of transformed shapes.

Pilot study in Nelson Forests Ltd.'s estate

A pilot study using Nelson Forests Ltd.'s PSPs revealed that:

- 1) Increasing the localisation and temporal relevance of weather estimates reduced the standard error of the model. So using long-run average climate estimates yielded a much poorer fit than weather in the years that trees actually grew, and localising weather variables using Norton's (1985) equations improved the fit markedly.
- 2) Improving the resolution of the DEM used for estimates brought out otherwise invisible effects of aspect and slope.
- 3) Simply adjusting the radiation on different aspects and slopes geometrically was too harsh a transformation, and so those effects were best incorporated statistically rather than as a process model. This may change in future after we characterise the impacts on monthly temperatures of radiation variation due to aspect and slope.
- 4) The soil water balance modifier made the model worse, and limitations of rainfall estimation plus potential rooting depth probably explain this, because the same water balance model and modifier has proven to be very effective when soil variables and rainfall are well estimated (Mason et al. 2007).
- 5) Using multiple VCSN points weighted by the inverse of distance to the point was less effective than simply using the nearest VCSN point.

Local models

Local models were constructed for the Kaingaroa Timberlands and Nelson Forests estates where PSP coverage was reasonably wide. They are summarised in table 4.

In all models modified radiation sums were by far the most significant variables and accounted for a large majority of explained variation in the models. In Kaingaroa, where site index is known to be strongly related to elevation (Mountfort 1979) modified radiation sums were more powerful predictors than elevation and removed elevation from the model.

Table 4 – Local models of productivity indices

Model	Independent variables	Standard error
KTL Site index	Temperature & VPD modified radiation sum Dummy variable for sandy soil Slope Local topex	1.9 m
KTL 300 index	Temperature & VPD modified radiation sum Dummy variable for sandy soil Slope Aspect (north to south) Local topex	3.5 m ³ /ha/yr
NFL Site index	Temperature modified radiation sum Aspect (north to south)	1.8 m
NFL 300 index	Temperature modified radiation sum Aspect (north to south) Mean water balance modifier	4.2 m ³ /ha/yr

Local topex is our invention that attempts to account for frost drainage on flat sites and exposure on sloping sites. It is the sum of differences between elevation of the point in question (in this case a PSP centre), and elevations of six equally spaced points 15 m from the centre point. Six points were used because raster pixels are hexagons and so each one has six adjacent pixels. On flat sites a highly negative local topex will indicate a local rise, less subject to frost than the surrounding area. On sloping sites a highly negative local topex would indicate an exposed site, such as a hilltop or a ridge. We found the expected interaction between slope and local topex.

For the Kaingaroa Timberlands Ltd. model we used a site index equation that was fitted by Ricardo Methol, a former PhD student of Euan's. Within plot standard errors were lower for this model than for van der Colff & Kimberley's (2013) model (Figure 12).

Models using combined datasets

PSP data were combined and models using all PSPs were fitted. Figure 13 shows the relationship between site index and temperature- & VPD-modified radiation sum for different companies' PSPs with point sizes representing the inverse of latitude. Clearly modified radiation sum and latitude interacted, and this was an important term in the model.

One small group of five plots in the Blakely Pacific estate showed extreme variability. These plots occupied highly fractured terrain and all had the same initial letters in their plot identifiers. It is possible that their geo-positions were poorly estimated and hence their elevations could have been in error. Clearly the plot locations need to be checked, but for the time being these plots were removed from the analysis.

Combined-data models are shown in table 5.

Table 5 – Combined-data models of productivity indices

Model	Independent variables	Standard error
Site index	Temperature & VPD modified radiation sum Latitude Dummy variable for sandy soil Aspect (north to south) Slope	2 m
300 index	Temperature & VPD modified radiation sum Latitude Slope Aspect (north to south) Local topex	4.3 m ³ /ha/yr

In both models slope and aspect interacted, as expected (Figure 14).

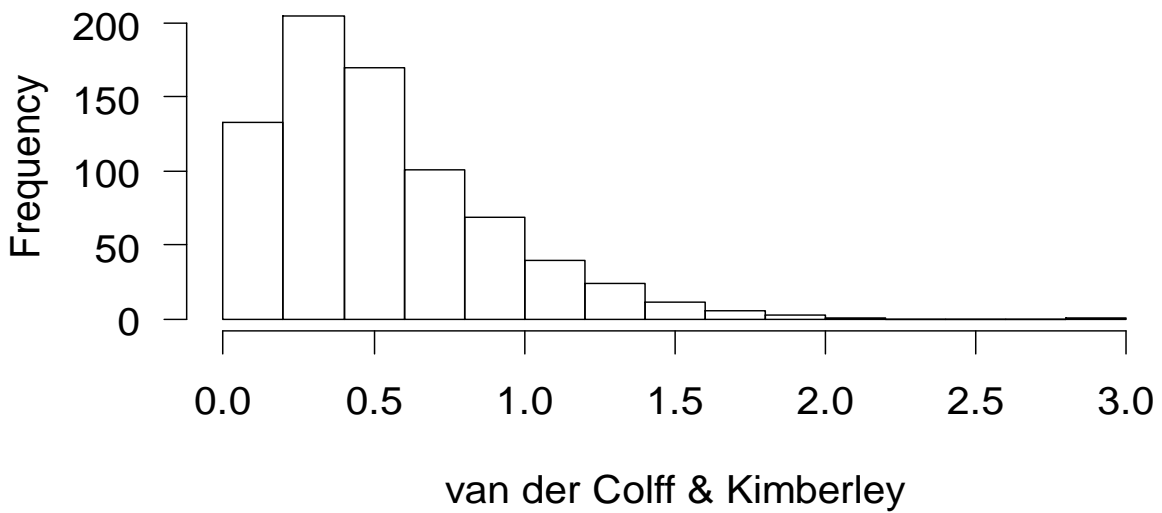
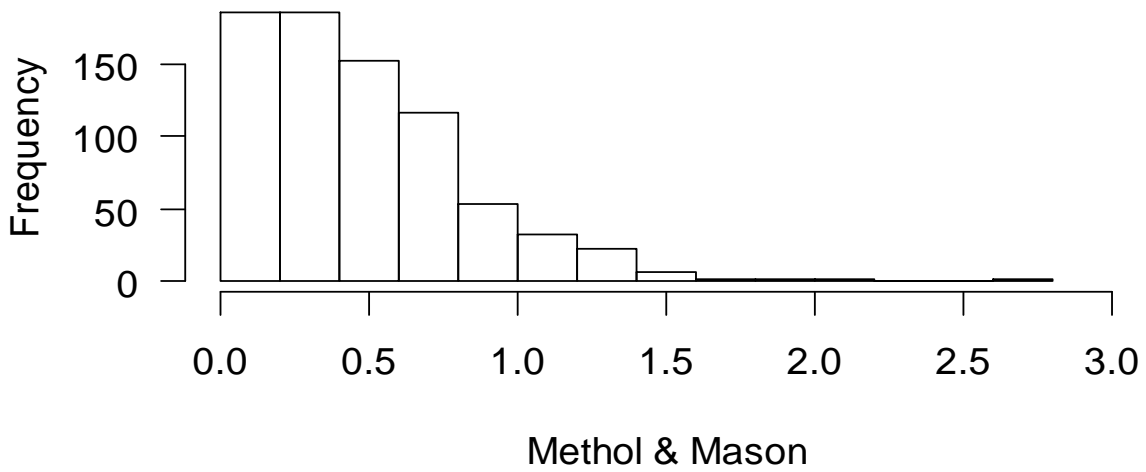


Figure 12 – Distributions of within plot standard errors (m) of site index prediction for Methol & Mason's model & van der Colff & Kimberley's model.

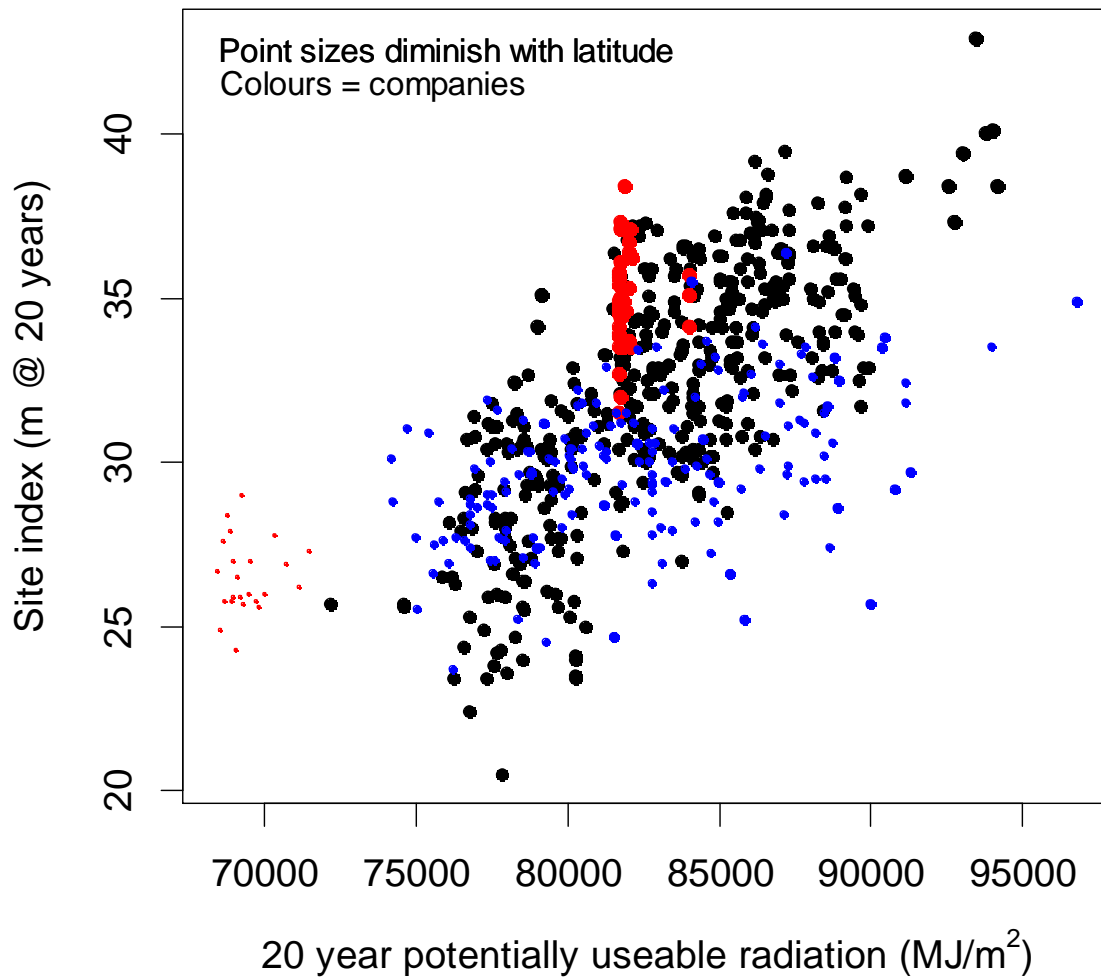


Figure 13 – Site index versus temperature- & VPD-modified radiation sum, by company and latitude. Black=Kaingaroa Timberlands Ltd., blue=Nelson Forests Ltd. & red=Blakely Pacific Ltd.

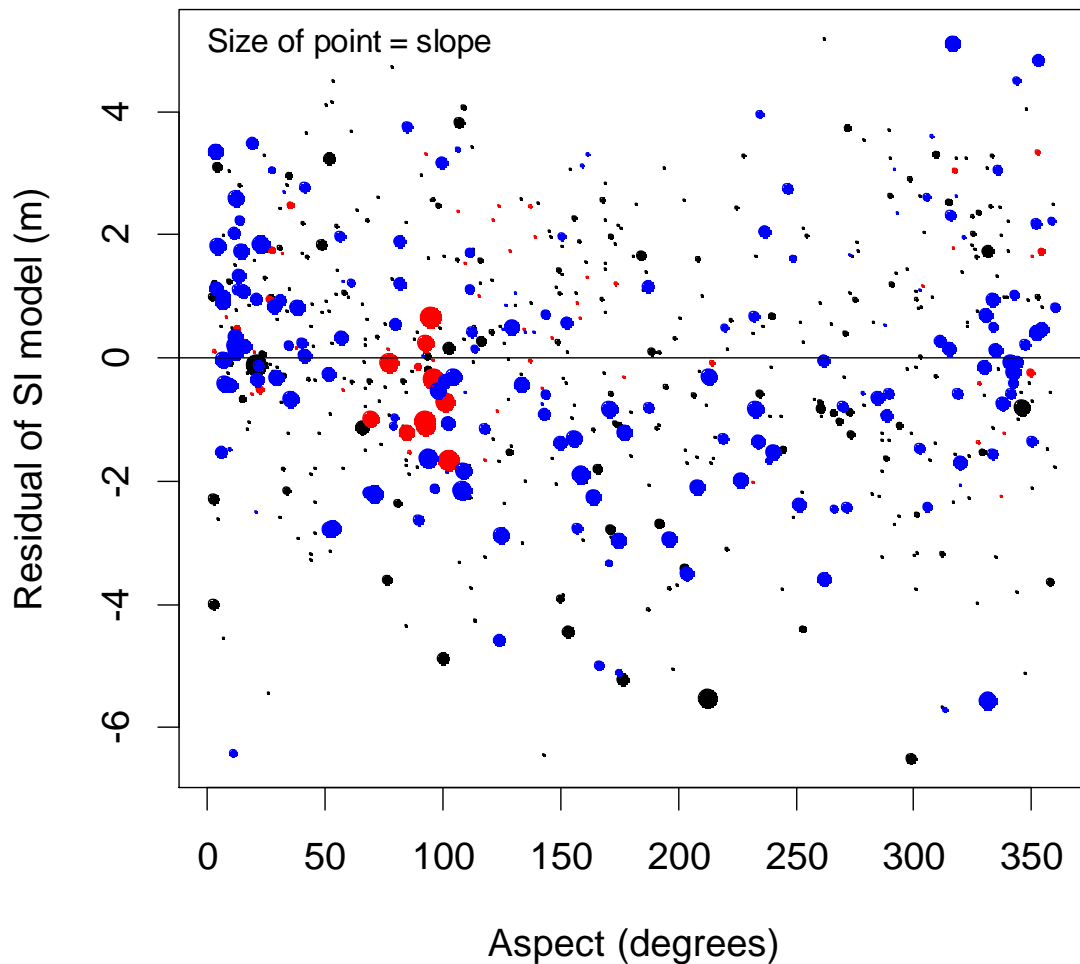


Figure 14 - Residuals of a model of site index using combined data that lacks slope and aspect, plotted against aspect and with point size indicating slope. Note that the U-shaped pattern is only evident for large slopes.

All fitted models showed very little residual bias and the combined models were unbiased with respect to company (Figure 15).

Models were now ready to be employed in the creation of raster layers showing estimated site index and 300 index across large forest estates.

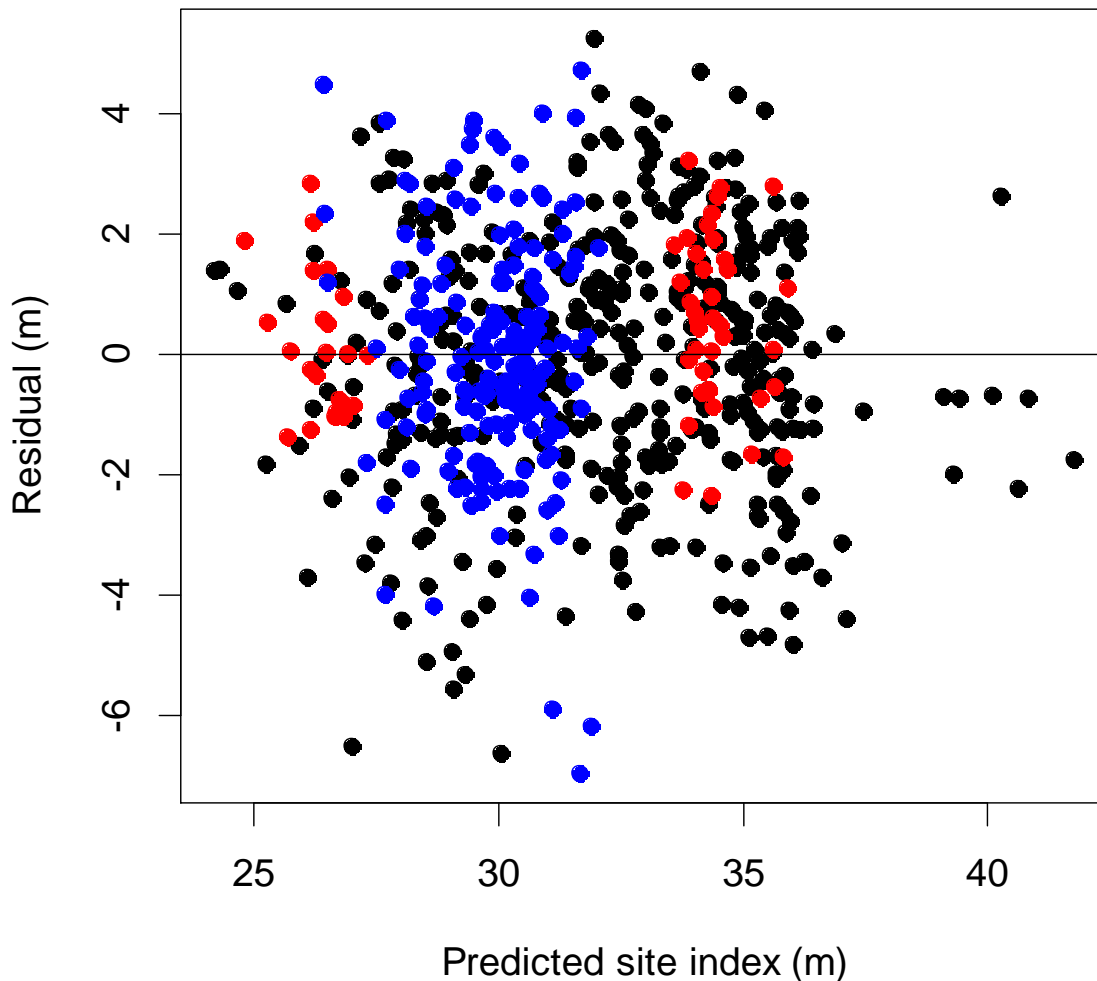


Figure 15 – Residuals versus predicted values for the site index model using combined data. Colours represent different company estates.

Independent validation of models using independent data

As some data had been randomly left out of the Kaingaroa Timberlands Ltd. dataset it was feasible to do some validation. These data could, in a few cases contain many plots within single compartments, and so they were sampled randomly to allow only four plots from any given compartment, yielding 94 validation plots with age>13. Models that could be tested with these data were the local models for the Kaingaroa Timberlands Ltd. estate, and the combined model used for Global Forest Partners Ltd. and Blakely Pacific Ltd.. The residuals were in a similar range to those observed during fitting, and relatively unbiased (Figure 16). There is a hint that the combined model for 300 index may be biased for very large predictions, but with three plots in that range we have too few to say for sure.

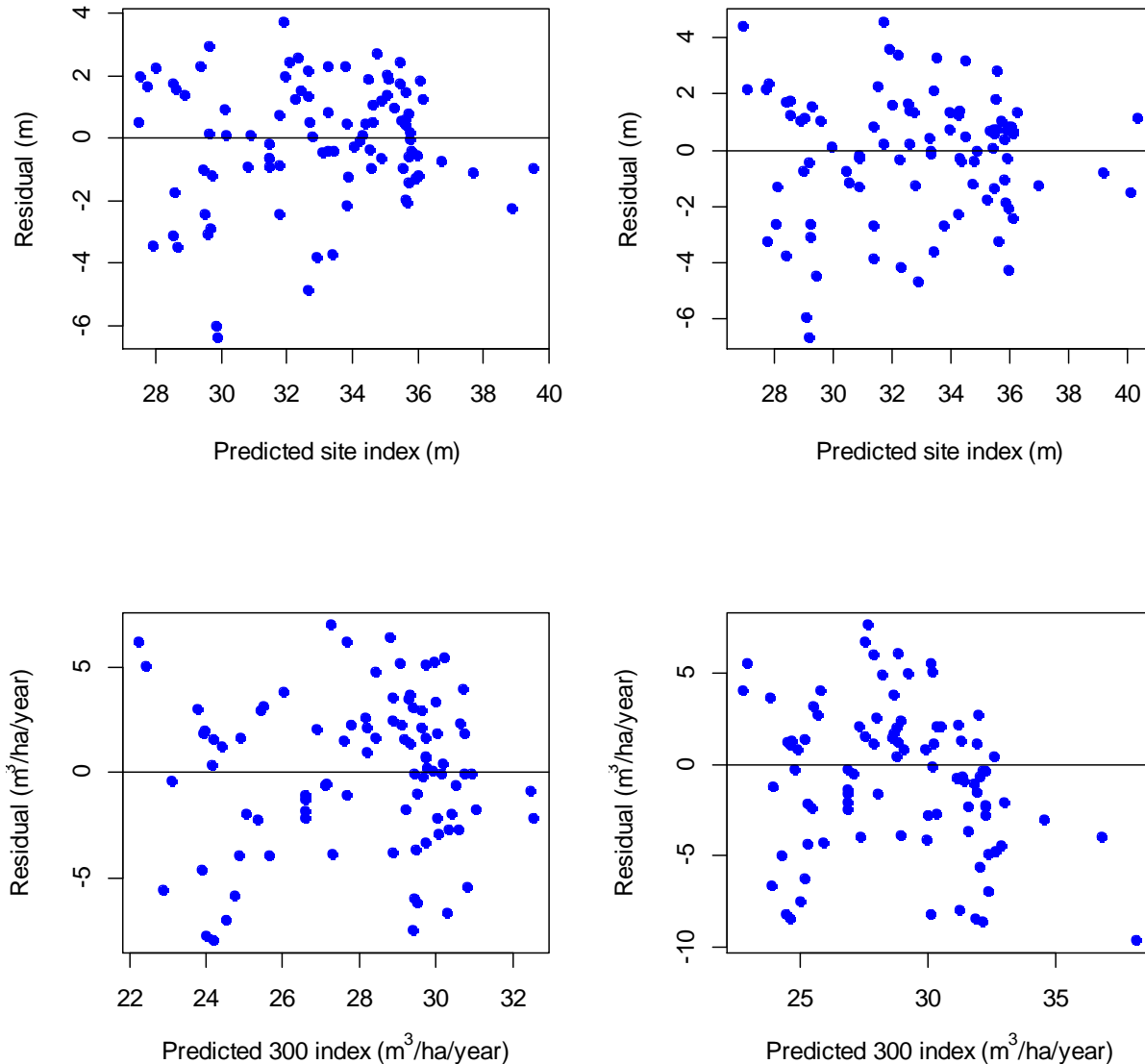


Figure 16 – Residuals of validation plots for the local Kaingaroa Timberlands Ltd. calibration models (left) and the combined data calibration models (right)

Creating raster layers for large forest estates

In order to create GIS raster layers showing distributions of productivity and site limitations across estates, we needed to assemble independent variables in pixels spaced at 15 m pixels across those estates. This involved an enormous number of pixels and physiological simulations across multiple years at each pixel. For instance, the Kaingaroa Timberlands' Ltd. estate contained over 9.8 million pixels. Some of the simpler input variables were calculated using ARC Info, however other, more complicated ones, such as modified radiation sums required a supercomputer. It was calculated that a fast desktop would require several months of continuous computing to complete the computations.

Weather used for simulations was from 2005-2015, providing the most up to date estimates of site productivity. Weather data was extracted from NIWA's VCSN stations closest to each 15 m pixel in each estate. For instance, Figure 17 shows the stations closest to points in the Kaingaroa Timberlands Ltd. estate.

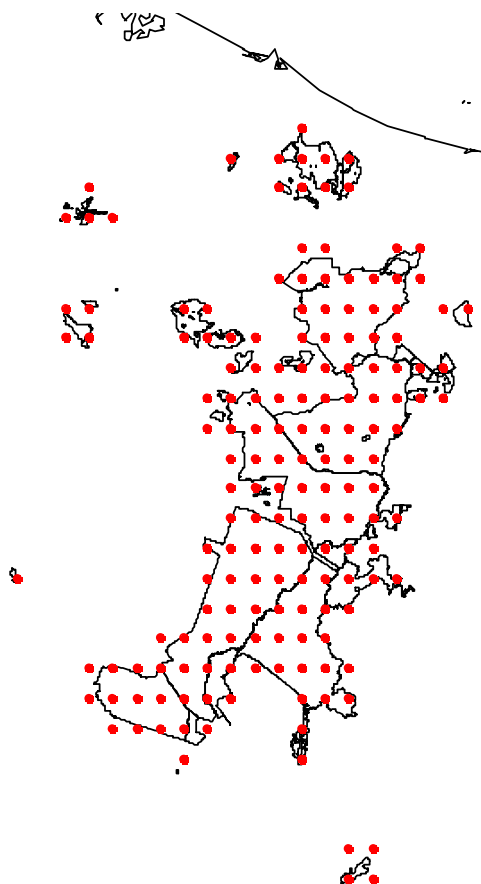


Figure 17 – VCSN points used for historical weather estimates across the Kaingaroa Timberlands Ltd. estate

Simulations were conducted at each pixel point using the University of Canterbury's IBM Power755 cluster, which contains 13 nodes each with 32 processors with 11 nodes accessible via Linux. All supercomputer simulations were performed in R running in Linux and using Euan Mason's hybrid modelling code in parallel processes.

Outputs from the supercomputer's parallel processes were reassembled on a single machine, estimates of productivity indices and of growth limiting factors were computed for each pixel,

raster layers were created in R, and then the layers were written to disk in GeoTIFF format. Examples of some of the raster layers are shown in Figures 18-23.

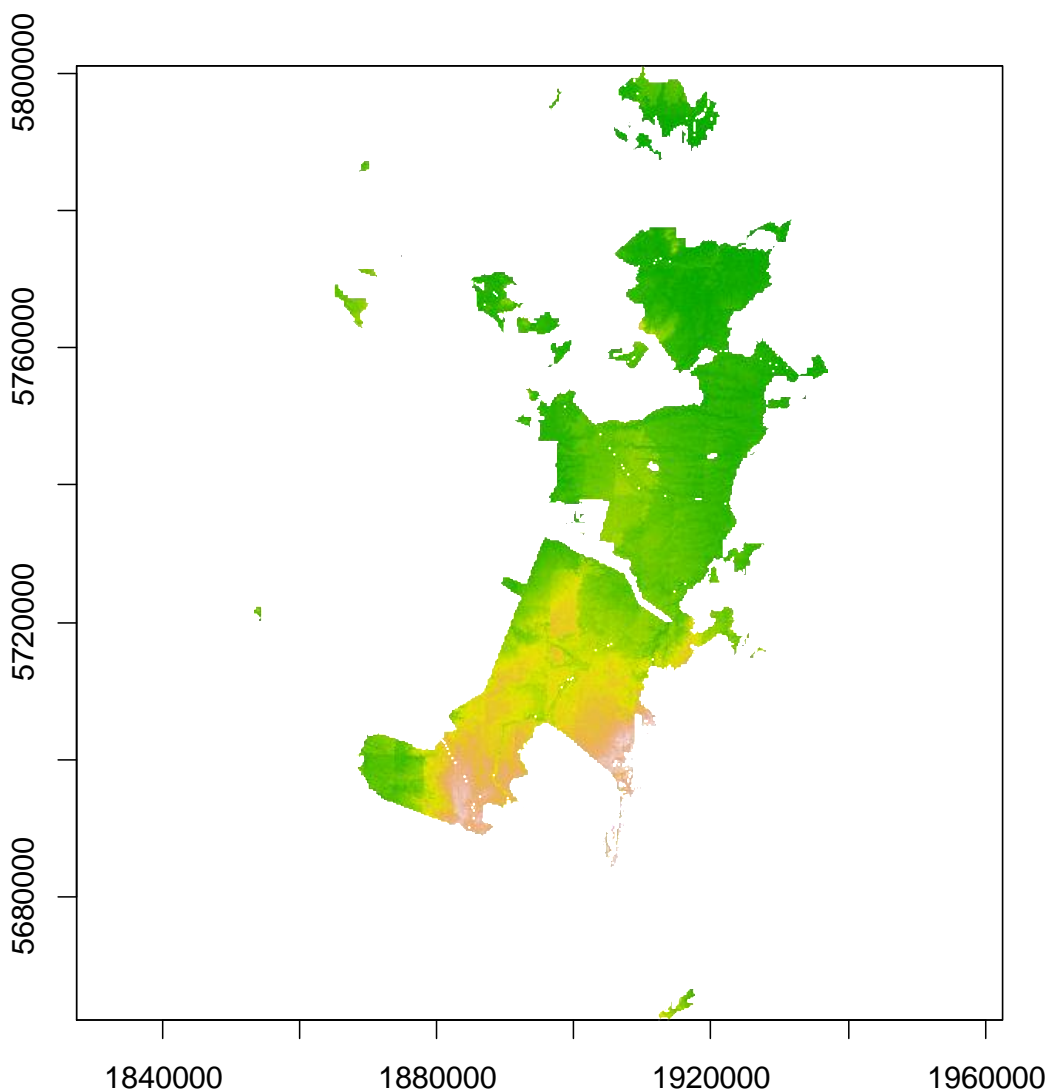


Figure 18 - Site index (MTH in m at age 20) distribution across the Kaingaroa Timberlands Ltd. estate. Green is higher site index. The raster comprises over 9.8 million pixels, each with a separate estimate of site index. The scale has been removed at the request of Kaingaroa Timberlands Management Ltd.

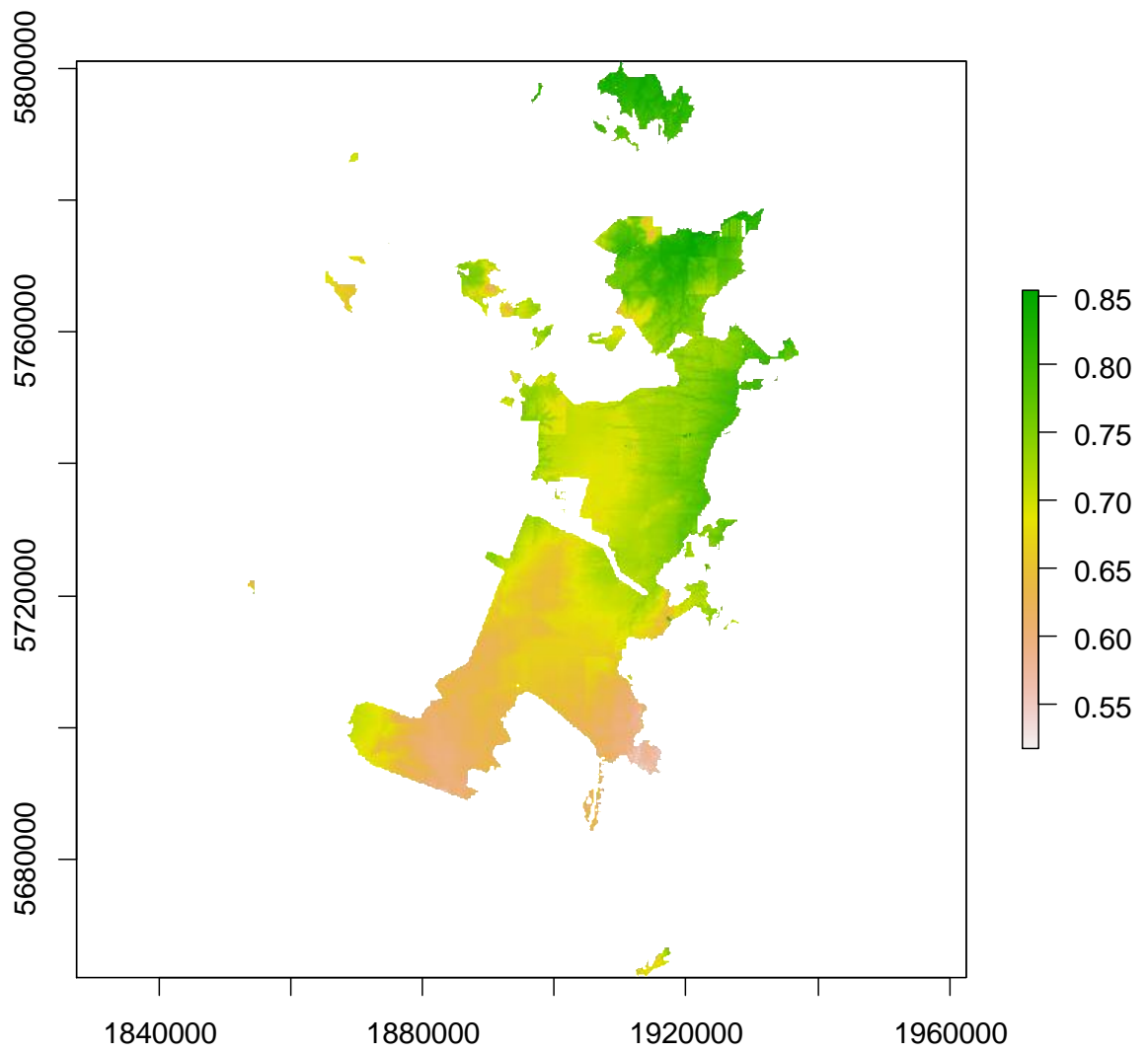


Figure 19 – Temperature limitations on photosynthesis, expressed as numbers from 0 (no photosynthesis) to 1 (no temperature limitations)

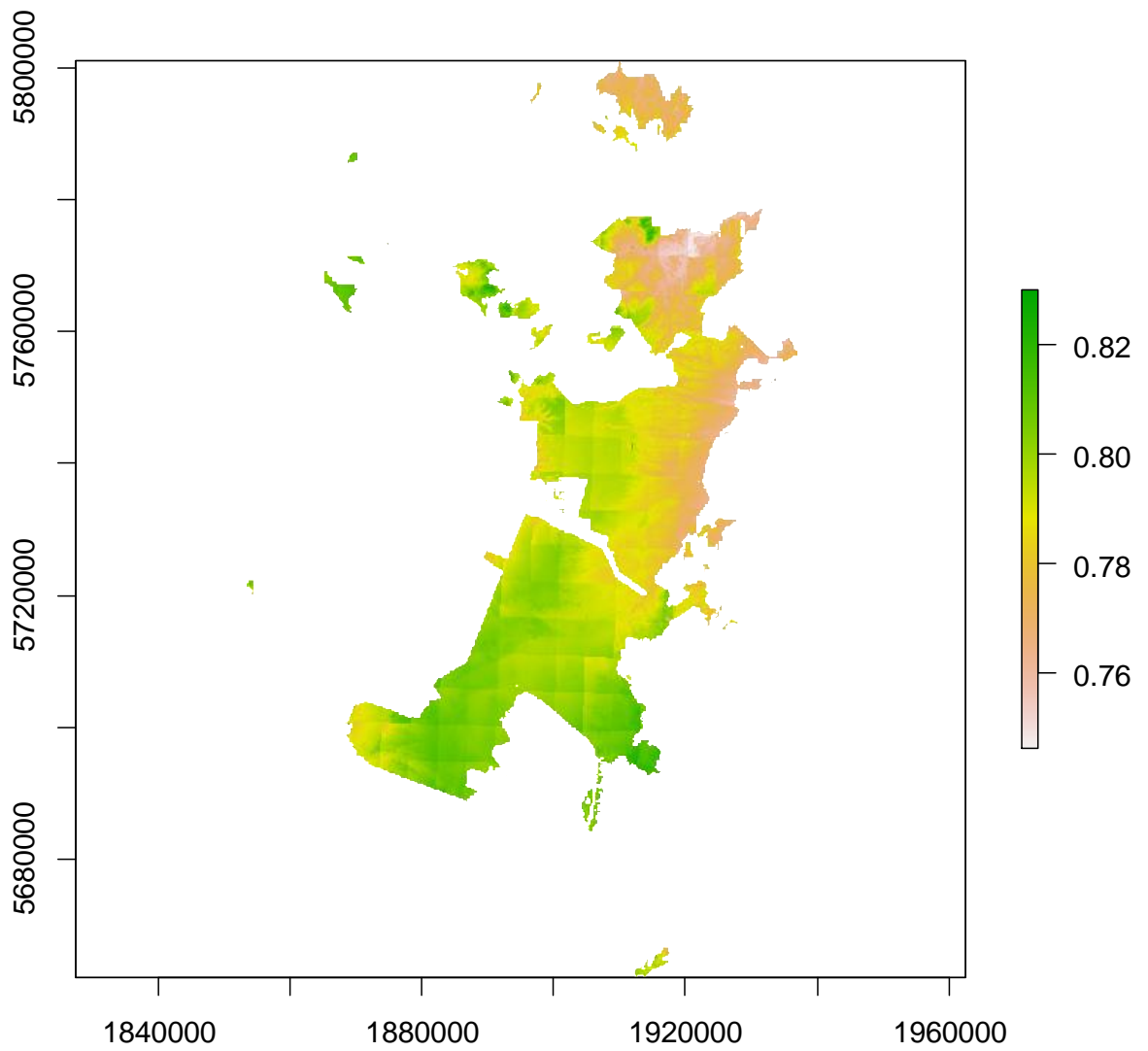


Figure 20 - VPD limitations on photosynthesis in the Kaingaroa Timberlands estate (1=no limitation)

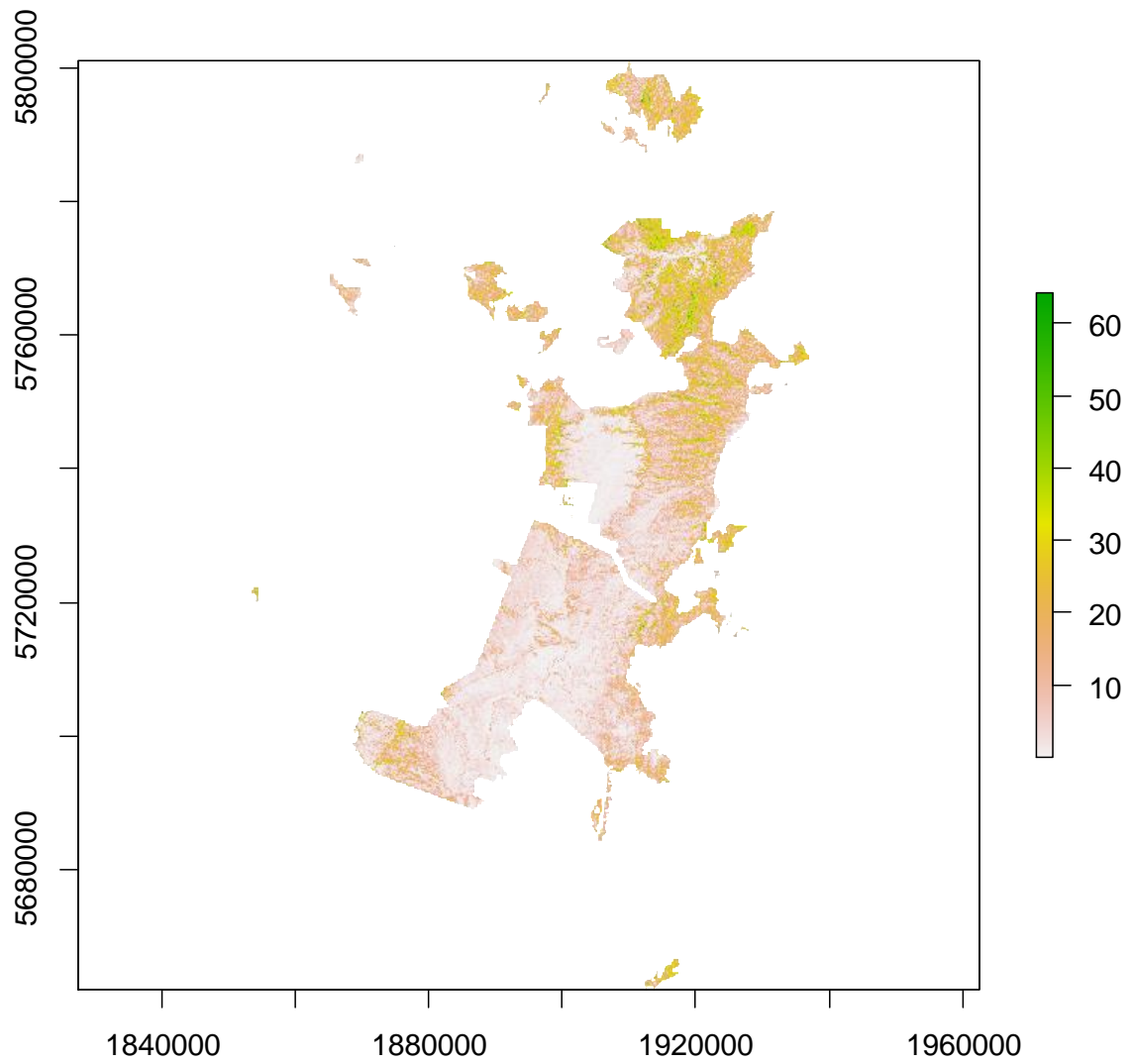


Figure 21 – Slope across the Kaingaroa Timberlands estate (degrees)

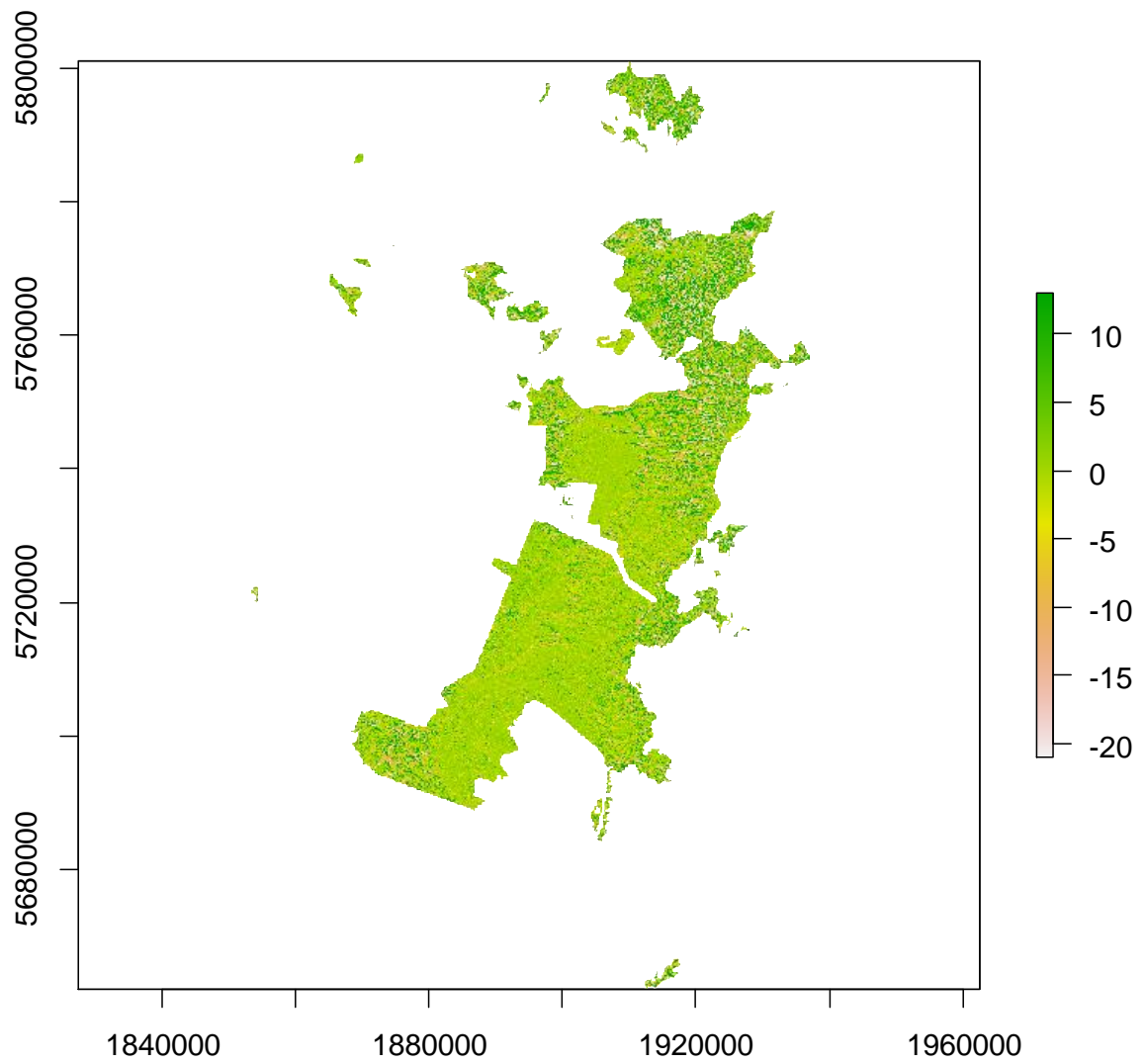


Figure 22 – Local topex across the Kaingaroa Timberlands estate. Negative values represent local mounds and positive values represent local depressions

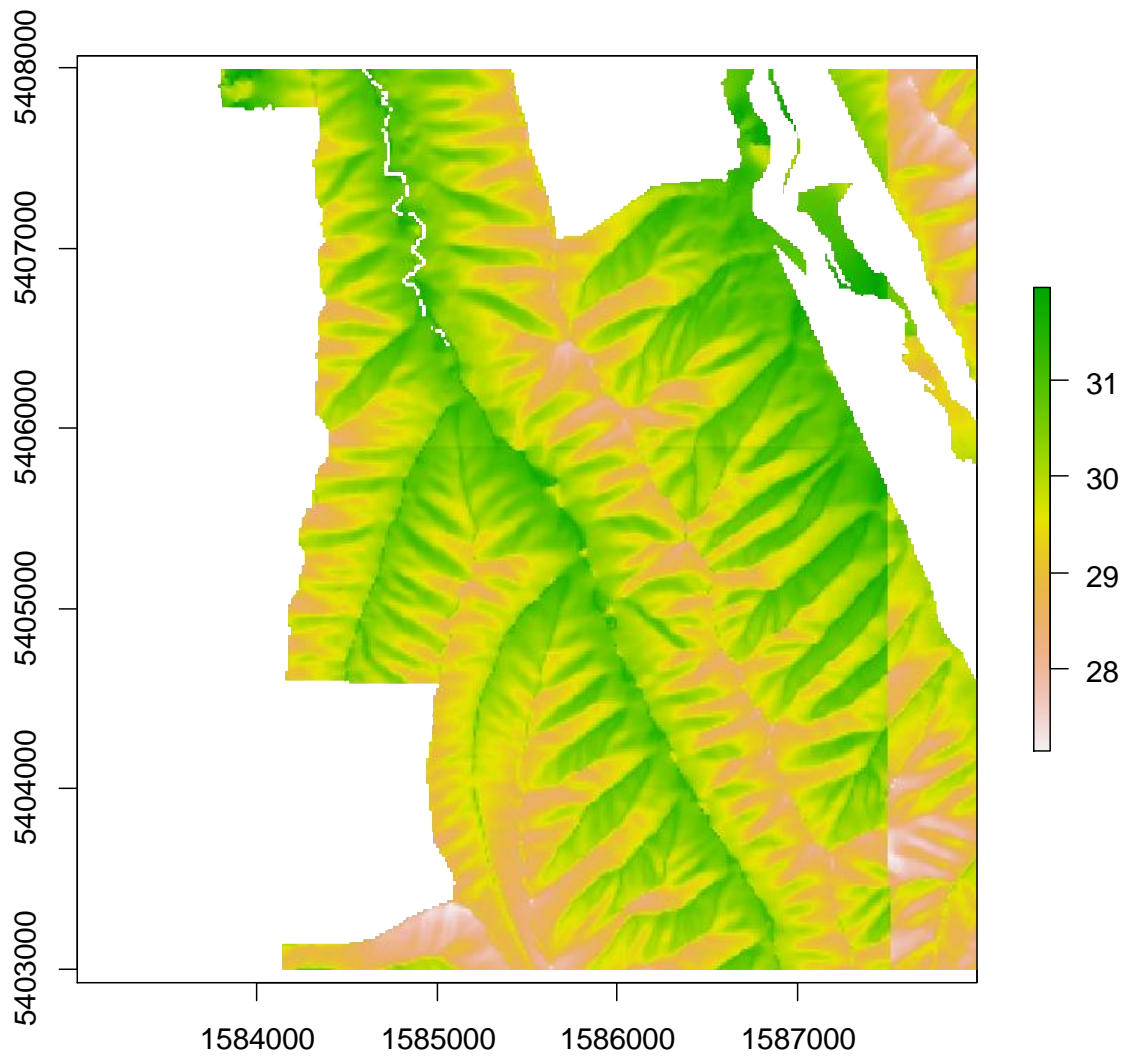


Figure 23 – A small section of the Nelson Forests Ltd. estate, showing impacts of topography on site index estimates. Higher site indices are at lower elevations and more northern aspects.

Figure 24 illustrates, using a small section of the Global Forest Partners Ltd. estate, how the slope*aspect interaction works.

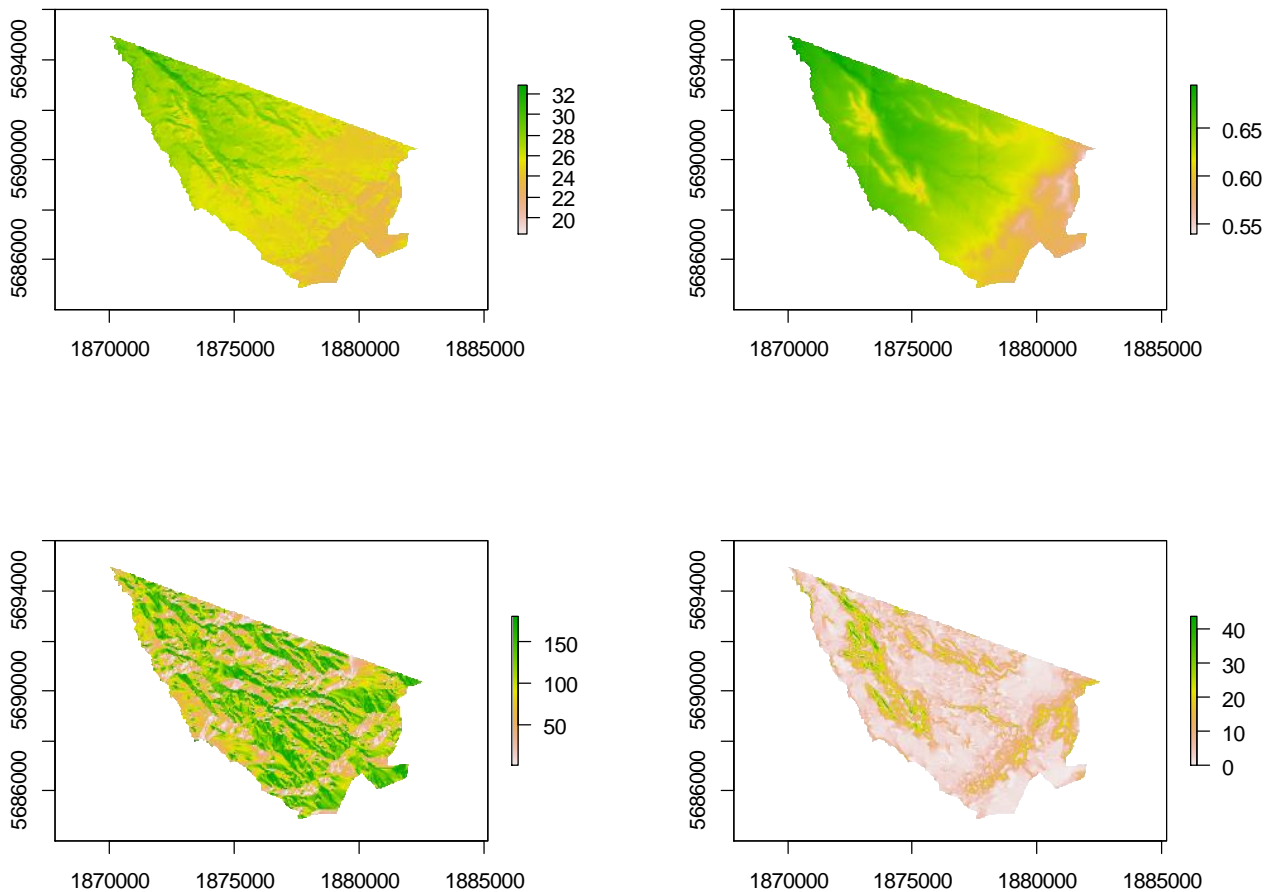


Figure 24 – An illustration of interacting limiting factors on a small section of the Global Forest Partners Ltd. estate. The top left graph shows estimates of 300 index. On the top right temperature limitations are shown. At bottom left the graph shows north-south aspect, with northerly sites at 180 degrees and southerly ones at 0. The bottom right graph shows slope. Note that northerly aspects only increase growth markedly when slope is high.

Discussion

The results described here offer managers unique tools for precision forestry; estimates of site productivity that are independent of genotype and silviculture. Other site quality assessments, such as measurements of trees with a harvesting head or estimates using LiDAR, in fact any estimates that depend firstly on measurements of tree dimensions, inevitably confound site quality, genetic and silvicultural influences unless these latter two factors are held constant. In order to make our estimates of site quality convenient we calibrated them using site index and 300 index measurements, but modified radiation sum estimates of site productivity were computed independently of any field of any field measurements of trees. This means represents a fundamental change in mensurational philosophy.

Conventional mensuration does not really follow a formal scientific method, but instead relies on a statistical approach first formalised by John Tukey (1977), called “Exploratory data analysis”.

The sequence of operations in exploratory data analysis is shown in Figure 25. As mensurationists we usually collect data, analyse it, formulate models and then make conclusions after fitting models to the data. However, the study reported here followed a pattern that followed a widely accepted philosophy of science formulated by Karl Popper (1935), with a flow shown in Figure 26. The idea is that with a hypothesis of how a process operates a model can be created which makes a prediction. Only then is data collected in an effort to refute the hypothesis. Our physiological model of constraints on light use was the hypothesis, and we used field data in or to try to refute it.

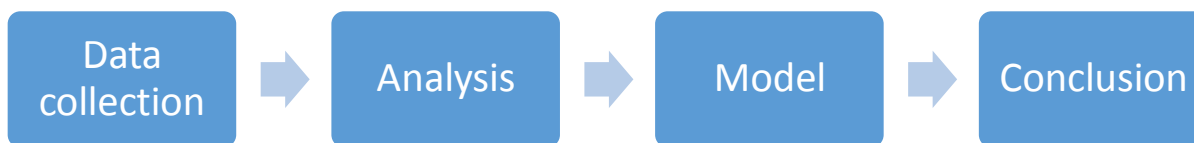


Figure 25 – Flow of operations in exploratory data analysis.

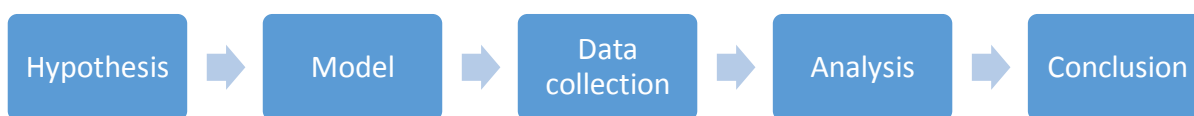


Figure 26 – Flow of operations for a scientist following Popperian philosophy

The implications for managers of this change are firstly that validation is less urgent. Validation of mensurational models is normally required because hypotheses are made using data and there is always a chance that what a dataset reveals is purely by chance. With *a priori* hypotheses findings are more secure. However, it could be argued that the calibration step in the study reported here requires some validation, and we agree. Initial validation can be initiated with data we didn't use for calibration, and this is confined to the Kaingaroa Timberlands estate.

Site features associated with soils featured in only a statistical fashion in the calibration models, and given the poor estimates of potential rooting depth and also local rainfall that we have this may be unsurprising. A limited study of SMap estimates (SMap is a reworking of the data used to construct the fundamental soil layer) suggested only modest, if any improvements from using this new soils vector layer. SMap is not yet available everywhere. The appendix contains a detailed consideration of options for nutrition fertility radiation use modifiers, but so far we have not found any that improve our calibrations. This is an important topic for future research.

Slope and aspect impact on solar radiation, which we have modelled, and on local temperature, which we have not yet modelled. So far, therefore, aspect and slope have been included as only statistical effects, and it is feasible, given temperature data that we are gathering in loggers on a range of different slopes and aspects, to attempt a function, process-oriented model of the impacts of slope and aspect. This is also an important subject for stage 2 of the project.

Raster layers were created using weather data between 2005 and 2015, and so they represent likely productivity given the most recent climate. It is feasible to run the supercomputer using weather data from previous epochs in order to gauge the impact, if any, of climate change. We are currently doing this at the request of Kaingaroa Timberlands Ltd..

We currently have three versions of the calibration models, two local ones for Kaingaroa Timberlands Ltd. & Nelson Forests Ltd., and one combined one that can be applied from North Canterbury to Northern Bay of Plenty, and it is important that their differences are understood.

Local models have slightly smaller standard errors and probably provide the best estimates of site index and 300 index. In particular, the local topex variable makes good sense in Kaingaroa where much of the land is flat and frost can retard initial growth where air drainage is poor (Menzies et al. 1982). The interaction between slope and local topex also makes good sense. A strong scaled power transformation means that a slight increase in slope from zero makes a large difference and the effect of increasing slope further is increasingly small. Similarly in Nelson Forests' estate where much of the land has slopes between 20 and 40 degrees, the effect of aspect turned out to be independent of slope and this is plausible but it may lead to some unusual effects on relatively small areas of flat land. The combined model offers some advantages for this latter land.

The combined model was calibrated using a data set that contained a much better balance of flat and sloping land, and so the interaction between slope and aspect was highly significant statistically. This is satisfying, but the standard errors of this model are a bit larger than for the local models, and the effect of latitude in that model requires explanation.

It is well known that tree shape varies with latitude in New Zealand, and that in Southland we tend to get shorter, fatter trees, all other things being equal. This alone may not explain the latitude effect in the combined model, but it probably contributes to it. The effect demands further study before we can confidently use in more widely than in the modelled ranges (see Table 3 for the ranges of site index and 300 index within which the models can be considered to be reliable).

The combined model is particularly suspect for Blakely Pacific Ltd.'s most southern forests, because below latitude -45 the company has no PSPs for radiata pine. Moreover, many of the predicted indices for Blakely Pacific's southern Forests were well below the limits of the calibration set (Figure 27), and it is likely that radiata pine will scarcely grow on those sites. Aaron Gunn says that many areas support Douglas fir.

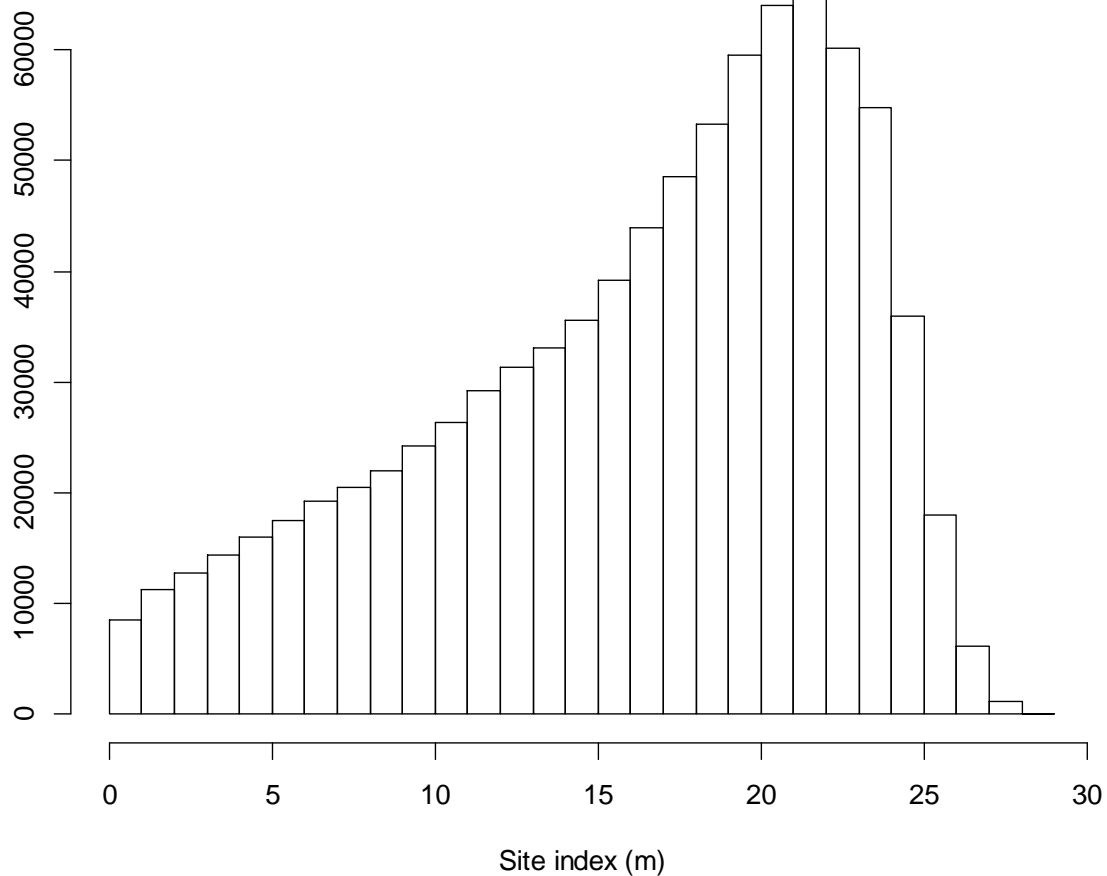


Figure 27 – Histogram of predicted site indices for Blakely Pacific’s southern forests. The graph shows frequencies of 15 m pixels after the combined calibration model was applied.

It would be feasible to run the physiological model for Douglas fir and then calibrate it using Douglas fir PSPs to provide rasters for Douglas fir productivity. This may be a useful next step, although extending the study to fully coherent hybrid growth and yield models may also be desirable.

The chosen strategy, of calibrating a physiological model to predict growth indices and then using the indices to run traditional mensurational growth and yield models adds errors. This approach means that the overall prediction error is the sum of:

- 1) Physiological model error
- 2) Growth index model errors
- 3) Growth and yield model errors and
- 4) Tree measurement errors

An alternative approach, running fully coherent hybrid models (Mason et al. 2007; Mason et al. 2011a), offers fewer errors:

- 1) Physiological model error
- 2) Growth and yield model errors and
- 3) Tree measurement errors

The coherent hybrid approach has been found to be more precise than traditional mensurational growth and yield models (Mason et al. 2011a) and it can also provide growth and yield models that incorporate impacts of climate change (Mason 2009) and also silvicultural treatments such as site preparation (Mason 2013). The example model from 2011 was made using site and climate data that was inferior to that used for the study reported here. A recent study by Cecilia Rachid Casnati, one of Euan Mason's PhD students at the University of Canterbury showed that much more substantial gains in precision were obtained using better site and weather data in Uruguay with these methods. This is clearly a prime option for the next stage of the study.

Raster layers provide a useable output from the first stage of the project, and we are very grateful for the involvement of staff from all companies involved. The research has revealed what can be gained by doing hybrid physiological/mensurational modelling at very high resolution, and has also identified some limits of available input data. We hope that participants will all be keen to take the work to stage 2, in which we can produce coherent hybrid growth and yield models, try a process-oriented model of the impacts of slope and aspect on local temperature, incorporate effects of nutritional fertility, evaluate impacts of climate change on forest productivity, and extend the work to other species.

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APPENDIX

Interim Report

Fertility modifiers for high resolution site productivity estimation for precision forestry using hybrid mensurational/physiological modelling

Horacio E. Bown & Euan G. Mason
February 15, 2016

INTRODUCTION

Background

Pinus radiata is the most outstanding and widely planted forest species in New Zealand and the Southern Hemisphere (Mead 2013). It represents 89% of the 1.8 million ha of plantation forestry area in New Zealand, and its predominance is explained by higher productivity ($> 20 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), greater adaptability to soil and environmental conditions, better response to tree breeding and silviculture, and better range in end-uses than most other forest species (Turner and Lambert 1986, Cown 1997). Such outstanding characteristics contribute to the success of the New Zealand forest industry that provides 1.1% of world timber consumption from only 0.05% of the global forest cover (N.Z.F.O.A. 2014).

Pinus radiata, once considered a low-quality timber, is now intensively tended and managed for a wide range of uses (MacLaren 1993). Additionally, tree breeding programmes have contributed to improve stem growth and form by up to 23 %, among other traits, and have led to the development of a widely used system of genetic improvement ratings (Vincent and Dunstan 1989). Clonal forestry, being practised at a moderate commercial scale in New Zealand, is envisaged to play an increasing role in the improvement of *Pinus radiata* for timber production and quality (Cown 1997, Sorensson *et al.* 1997, Sorensson and Shelbourne 2005). Increasing productivity of existing plantations at the global scale in order to fulfil current and future needs of wood for industrial and fuel consumption would require more intensive forest management and tree breeding strategies (Nambiar 1984, Turner and Lambert 1986). However unless nutrient and water requirements are optimized, the effects of intensive silviculture and tree breeding will not be realized (Webber 1978, Nambiar 1984, Turner and Lambert 1986, Raison and Myers 1992, Madgwick 1994). Because plantation forestry was historically relegated to land with low agricultural potential (Boomsma and Hunter 1990, Hunter and Smith 1996), fertilization has been an effective management tool permitting the New Zealand forestry sector to produce fast-growing radiata pine plantations in nutrient deficient areas (Mead and Gadgil 1978, Mead 2005a).

Major nutrient deficiencies noted in New Zealand comprise nitrogen, phosphorus, magnesium and boron, and localized deficiencies of potassium, manganese, copper, zinc and molybdenum have also been recorded (Will 1985, MacLaren 1993, Hunter *et al.* 1991, Mead 2005b). Severe nitrogen deficiencies are widespread in coastal sands, dredge tailings and generally where soils contain no or little organic matter or after topsoil removal such as skid sites and landings (Will 1978, 1985). Less severe nitrogen deficiencies with good fertilization responses have been noted in gley-podzols (pakihi soils) in Westland, undrained peats in Southland (Will 1978), eroded Moutere Gravel soils in Nelson (Mead and Gadgil 1978), podzolized sands and clays in North Auckland (Will 1978, 1985), and alluvial soils in Canterbury (Hunter *et al.* 1991). Marginal nitrogen deficiencies have been observed in other soils such as the central North Island pumice plateau where fertilization responses in growth have also been substantial (Will 1978, 1985).

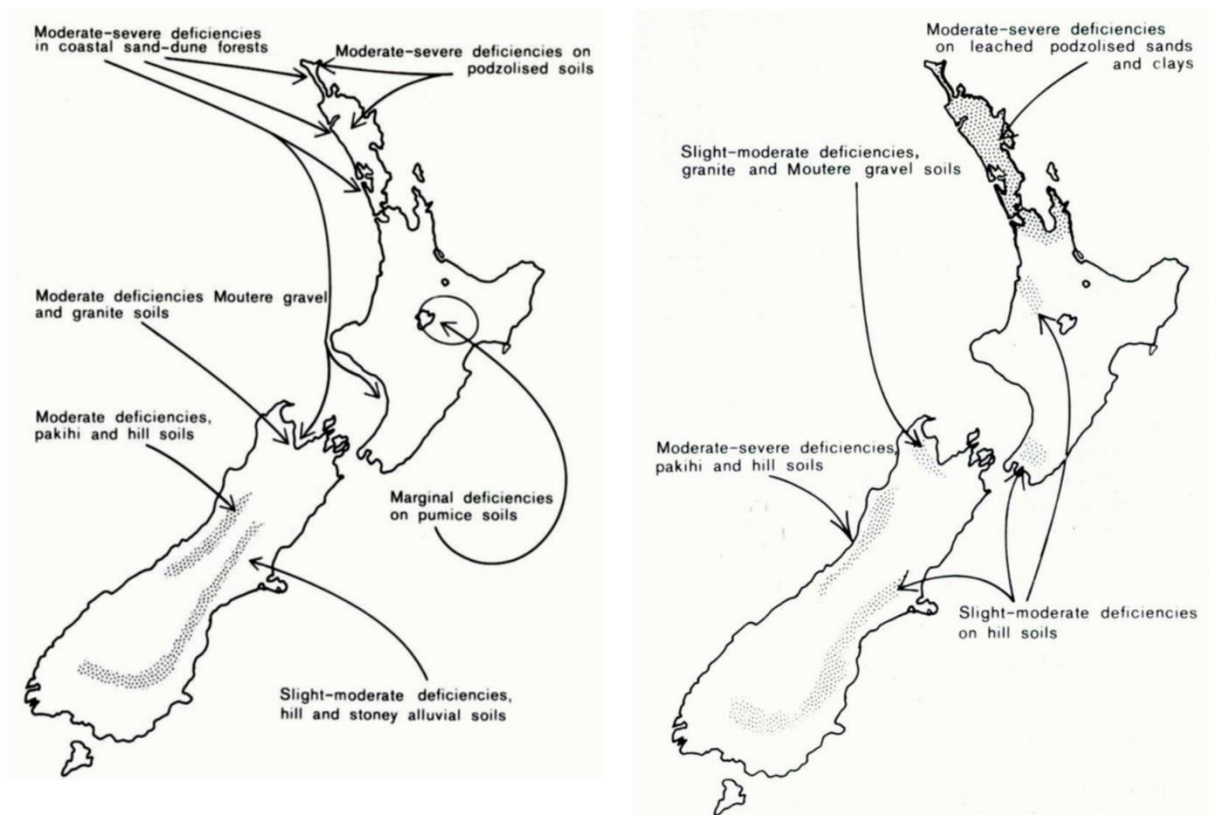


Figure 1. Major areas of nitrogen (left) and phosphorus (right) deficiencies in *Pinus radiata* forests in New Zealand. Source: Will (1985) p. 13,18.

Most New Zealand soils and their parental materials are low in phosphorus, and hence sustained agricultural and forest productivity are dependent on phosphate fertilizers (Will 1985). Moderate to severe phosphorus deficiencies have been observed in podzolized sands (e.g. Waipoua State Forest, Hunter and Graham 1983) and clay soils (e.g. Riverhead State Forest, Will 1965, Hunter and Graham 1982, 1983) in North Auckland and Northland, in the pakihī soils in Westland, leached granite soils (e.g. Kaiteriteri hills) and Moutere gravels in Nelson and rhyolitic and andesitic parent materials in the Coromandel Peninsula (Will 1978, 1985, Hunter and Graham 1983). Moderate phosphorus deficiencies have been noted in coastal Canterbury, whereas in most areas in north-east and inland Canterbury phosphorus levels are satisfactory (Hunter *et al.* 1991). Satisfactory levels of phosphorus are found in most soils where *Pinus radiata* grows on the pumice plateau region (Hunter *et al.* 1991).

Nutrient deficiencies are usually diagnosed by visual symptoms but more commonly by foliage analysis (Will 1985, MacLaren 1993, Madgwick 1994). Severe nitrogen and phosphorus deficiencies have been associated with foliage nutrient concentrations of less than 1.2 % and 0.12 % respectively (Will 1985, Turner and Lambert 1986). However the interpretation of foliage analysis, being clear-cut under severe nutrient deficiencies, remains largely uncertain at marginal levels as a predictive tool, probably because nutrients are highly dynamic both in the soil and within the tree (Turner and Lambert 1986, Landsberg and Gower 1997). Soil testing despite being widely used in agriculture has proved of limited use for identifying nutrient deficiencies in forestry (Will 1985, MacLaren 1993, Madgwick 1994). One noticeable exception has been the use of Bray extractable phosphorus (< 9 ppm) as indicative that phosphate fertilizer will be probably required soon after planting *Pinus radiata* in New Zealand (Will 1985).

Most nutritional problems in *Pinus radiata* plantations in New Zealand are now routinely solved using commercial fertilizers (Turner and Lambert 1986). Other methods of fertilization include the use of legumes to supply nitrogen, and the use of municipal, industrial and farm-waste water or sludge (biosolids) to supply water and nutrients (Mead 2005*b*). In young trees, deficiencies are usually corrected by applying fertilizers in a slot beside each tree, while in large trees aerial systems are usually preferred (Will 1985, MacLaren 1993, Mead 2005*b*).

Genetically improved trees on the basis of differential nutritional requirements may also potentially contribute to alleviate forest nutritional problems (Turner and Lambert 1986). Several studies have reported differences in nutrient use efficiency among *Pinus radiata* genotypes (Burdon 1976, Forrest and Ovington 1971, Knight 1978) but selection criteria for genetic improvement has not yet been defined (Turner and Lambert 1986). Additionally there is some controversy about whether some families that respond well to poor fertility sites will be less responsive under more fertile conditions, and this question is also extended to the interaction between nutrients and water (Turner and Lambert 1986). However Carson *et al.* (2004) showed that genotype \times fertility interactions in *Pinus radiata* are seldom significant, suggesting that selecting genotypes for better growth performance in poor fertility sites would not be substantially better than selecting for growth on all sites irrespective of nutrient availability. Responses to fertilization in nutrient deficient sites have been often large, particularly with nitrogen and phosphorus (Nambiar 1984, Hunter *et al.* 1986). For instance, Mead and Gadgil (1978) showed mid-rotation growth responses to nitrogen fertilization that often exceed $8 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ on fertile soils in the central North Island, while shorter-lived larger growth responses of up to $17 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ have been observed in less fertile sites in the Nelson region. Woollons *et al.* (1988) reported growth responses in basal area at mid-rotation of up to $6.2 \text{ m}^2 \text{ ha}^{-1}$ a few years after fertilization, and this response was enhanced and compounded over time in three out of four fertilization trials in New Zealand and Australia. The authors suggested that enduring responses to fertilization will be found in most sites in Australasia, but that in marginal sites periodic applications of fertilizers may be required to sustain early growth responses. The widespread use of fertilizers has been undoubtedly encouraged by the massive growth responses reported in a large number of research trials located since the 1950s in different soil, environmental and management conditions in New Zealand. However this large body of knowledge has been difficult to synthesize due to differences in methods and reporting practices (Madgwick 1994). Nambiar (1984) argues that practical solutions to many nutritional problems are known but that much of that knowledge is empirical, and that further innovation depends on a better understanding of the mechanisms underlying plant responses to shortages in site resources. The complexity of trees and tree-environment interactions has encouraged the development of multi-disciplinary research which has led to the development of physiological models as means to explore such systems (Sands and Mulligan 1990, Benson *et al.* 1992). This report is about nutritional modifiers to predict productivity of *Pinus radiata* plantations across the landscape in New Zealand. This is one among many components to be addressed within a greater framework for the project entitled "High resolution site productivity estimation for precision forestry using hybrid mensurational/physiological modelling" leaded by Professor Euan Mason at the University of Canterbury. The aim of the project is to provide estimates of productivity and factors limiting productivity so that forest growers can make optimum silvicultural investment decisions and design regimes to maximise the value of every hectare of their estate. The overall idea is to provide flexible algorithms to easily and rapidly provide layers of productivity and limiting factors across the landscape. The algorithms, programs and libraries need to be flexible enough so that future improvements could be easily performed in a short time.

This report aims at assessing alternative fertility modifiers for eco-physiological modelling of forest productivity within New Zealand. A fertility modifier is a value between 0 and 1 (i.e. a fraction, e.g. 0.59) that reduces the maximum productivity attainable for a given site as a result of nutrient limitations. As an example if the fertility modifier for a given site was 0.59 and the maximum potential productivity for that site was $600 \text{ m}^3 \text{ ha}^{-1}$ at age 25 years, then the corrected productivity would be $600 \times 0.59 = 354 \text{ m}^3 \text{ ha}^{-1}$ at age 25 years. This would be a static fertility modifier but we can also think about a dynamic fertility modifier that changes over time depending on weather, soil and plant conditions. In this report we will focus on static rather than dynamic fertility modifiers.

In the quest for fertility modifiers across the landscape we will face several problems. First, fertility modifiers are the most understudied aspect of physiological/hybrid modelling. Our poor understanding on how nutrients are used and stored by soils, microorganisms and plants is probably one of the reasons for this. Second, there is usually a poor correlation between soil physical and chemical properties and forest productivity. A general rule has not been developed and if developed, understandably, that rule would be full of exceptions. Third, layers of soil physical and chemical properties are based on extrapolations (e.g. through krigging) of data from soil pits which are usually sparse and more frequent in agricultural land. Four, the biophysical environment explains most of forest productivity (> 70%) leaving at the most a 30% to be explained by genetics, silviculture and fertility. All these aspects contribute to the so far lack of fertility modifiers for predicting forest productivity across the landscape.

The 3-PG framework

New hybrid mensurational and physiological models offer sensitivity to site and management practices at a scale that is linked with biological processes while preserving efficiency and precision obtained from parameterisation with data from permanent sample plots (Mason et al. 2007; Mason 2009; Mason et al. 2011b). Models built using these new techniques have been found to be more precise than traditional, time-based growth and yield models (Mason et al. 2011b), and yet they are sensitive to climate, site quality and management practices in a functional way.

Landsberg and Waring (1997), describe the construction of a mechanistic growth system that explicitly represents light use, called the 3-PG model. Local microclimatic conditions modify crop growth by mediating light use. Net primary productivity (NPP) of a plant canopy has been found to be directly proportional to light interception (Monteith 1977), and local microclimate that affects the slope of the relationship between intercepted light and NPP. There is reasonable support for a linear relationship in other studies (Grace et al. 1987; Dalla-Tea et al. 1991). The 3-PG model explicitly represents this principle for forest crops by calculating soil water, vapour pressure deficit, temperature and fertility modifiers on use of intercepted photosynthetically active radiation. This model can be categorised under the general class of “radiation use efficiency” models.

The net primary productivity component of the 3-PG model can be expressed as:

$$NPP = C_E \varepsilon \sum_{t=1}^T APAR_t \min\{f_\theta f_D\} f_k f_F f_S \quad (1)$$

where in (1)

NPP=net primary productivity, t = time interval (month), APAR=absorbed photosynthetically active radiation, C_E = carbon use efficiency (i.e. the NPP/GPP ratio, being conservative at about 0.47), ϵ =maximum quantum efficiency for a species, f_{θ} =soil water modifier (0-1), f_D =vapor pressure deficit modifier (0-1), f_k =temperature modifier (0-1), f_F =fertility modifier (0-1), f_S =senescence modifier (0-1).

The model runs a soil water balance using soil depth, soil type, rainfall, temperature, LAI and the Penman-Monteith equation for calculating evapotranspiration to estimate the soil water modifier. Most modifiers are calculated using models that represent underlying processes, such as the exponential decline of stomatal conductance with increasing vapour pressure deficit. Currently the fertility modifier is simply a number chosen by the user.

Once GPP has been estimated for a given month, the amount of photosynthate used for respiration is calculated using a constant supplied by the user (e.g. $1 - C_E = 0.53$), and the rest is allocated to foliage, stems or roots. Allocation coefficients are estimated from measurements of allometry, assuming that lower fertility results in increased allocation to roots. The actual proportions allocated to these pools depend on coefficients supplied by the user that make allocation vary with tree diameter at breast height.

The 3-PG approach has some attractive features, but it is too complicated to compare favourably with a well-constructed growth and yield model. Pinjuv et al. (2006) thoroughly compared the 3-PG model with mensurational growth and yield models using a large validation set of permanent sample plot (PSP) measurements in Canterbury, New Zealand, finding that the 3-PG model was less precise and more biased than the best growth and yield model. A simpler mixed eco-physiological and mensurational (hybrid) approach is required.

A simpler, but more statistically rigorous, synthesis of mensurational models and physiological approaches like 3-PG can be built by directly substituting 'potentially used radiation sum' for time in sigmoidal projection equations commonly used by mensurationists (Mason et al. 2011b). With such a synthesis no attempt is made to directly measure APAR, nor is carbon allocation explicitly represented, as these two processes would require intensive measurements, several assumptions and cumbersome calculations across a wide range of sites and stands. Yield equations used for juvenile trees and sigmoid equations used for older crops implicitly represent effects of APAR and allocation on relative growth rate. Using modifiers such as those in the 3-PG model to assess what proportion of incoming light could potentially be used by plants if it were intercepted makes these hybrid equations sensitive to changes in growth resource availability that may be influenced by competing vegetation, changing sites, silvicultural operations, or varying weather patterns from year to year.

When soil water is limited the stomata close, limiting light use, and this limitation has to be reflected in a light sum model. The model framework maintains a water balance model from month to month, which together with vapour pressure deficit in the atmosphere, control stomatal conductance. There are several parameters required for a robust water balance modelling; some can be attributed to the soil and some to the vegetation. Rooting depth, soil texture and soil structure in a given soil type are critical parameters for any modelling system that estimates eco-physiological effects in dry regions.

Our preliminary investigations suggest that the New Zealand fundamental data layer (a geographical information system data layer that is publicly available and widely used) often under-estimates rooting depth and maximum available soil water for tree crops.

Site nutritional fertility affects both radiation use and allocation of photosynthate, with more allocated below ground of less fertile sites. Despite its importance, fertility has been poorly represented in the 3-PG framework, and recent work at the School of Forestry has identified some good candidates for fertility modifiers on radiation use in modelling frameworks (Bown et al. 2007; Bown et al. 2009). We intend to assemble data that allows us to try these candidates across a wide range of sites in New Zealand. Fertility modifiers will be compared for their capacity to improve the fit of a radiation sum model to PSP data.

Previous findings

Nitrogen (N) and phosphorus (P) are the nutrients that most frequently limit primary productivity in all ecosystems in the biosphere (Aerts and Chapin, 2000; Hall *et al.*, 2005). This is not surprising, as N is a vital constituent of proteins playing an essential role in all enzymatic activities, P is involved in energy transfers in the cell, and both are important structural elements in nucleic acids (Marschner, 1995). Aerts and Chapin (2000) suggested that imbalances between these two elements may be more important than absolute amounts of either element in plants, and therefore these type of imbalances may lead to nitrogen or phosphorus deficiencies (Reich and Schoettle, 1988; Marschner, 1995; Aerts and Chapin, 2000). Knecht and Göransson (2004) argued that the optimum ratio of nitrogen to phosphorus in terrestrial plants is similar for a wide range of species and is approximately 10 on a mass basis (*i.e.*, 23 on a mole basis). Bown et al. (2007) partitioned photosynthetic responses to N and P limitations using a foliage N:P ratio of 10 g g⁻¹ (23 mol mol⁻¹), finding a good mechanistic explanation to N and P limitations to growth. Liebig's law of the minimum (*i.e.* the nutrient limiting the most would constrain physiological processes) would conform to this explanation.

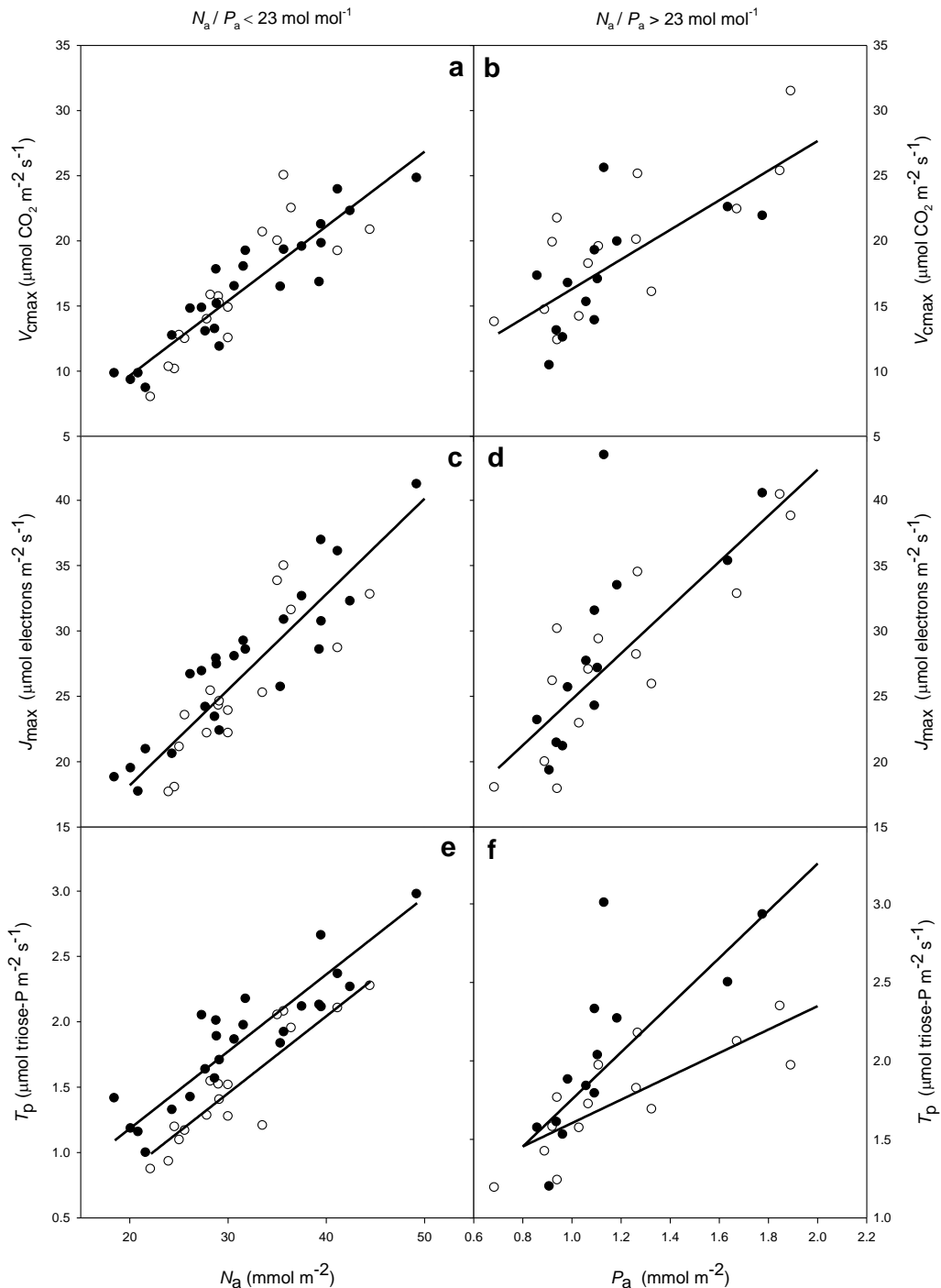


Figure 2. Relationship between (a, b) maximal rate of rubisco carboxylation, V_{cmax} , (c, d) maximal rate of electron transport driving regeneration of RuBP, J_{max} , and (e, f) rate of triose phosphate export, T_p , and foliage nitrogen and phosphorus concentration on an area basis (N_a , P_a) for Clones A (○) and B (●). On the left side, measurements are nitrogen limited ($N_a/P_a \leq 23$), and on the right side, measurements are phosphorus limited ($N_a/P_a > 23$). Different lines were fitted to clones where the relationship varied significantly. Source: Bown et al. 2007.

Therefore, stoichiometric ratios as presented in Figure 2, seem to be a plausible method to separate nutrient deficiencies. Bown et al. (2009, 2011) made a carbon allocation study in permanent sample plots in the South Island of New Zealand. Plots under study were mostly N-

limited as indicated by a ratio of biomass N:P content of less than 10:1 on a mass basis (Figure 3).

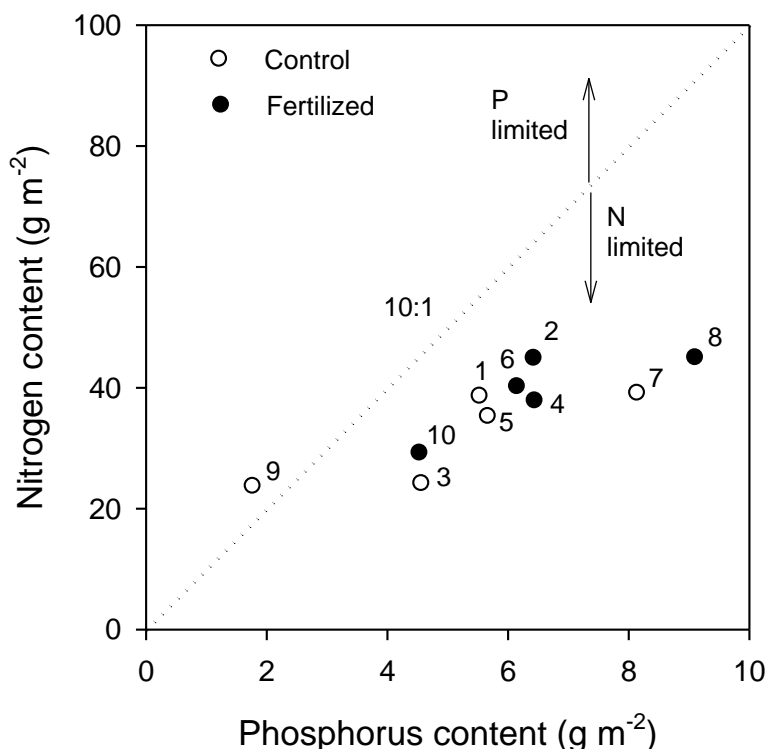


Figure 3. The relationship between above-ground biomass nitrogen and phosphorus content in control (open- symbols) and fertilized (closed-symbols) mini-plots of four-year old *Pinus radiata* in five sites on the South Island of New Zealand. The dotted line has a slope 10:1, separating nitrogen ($N : P < 10$) from phosphorus ($N : P > 10 \text{ g g}^{-1}$) deficiencies. Plot numbers are indicated besides symbols: 1-2 Rai Valley, 3-4 Golden Downs, 5-6 Tekapo, 7-8 Catlins, 9-10 Longwoods. Source: Bown et al. (2011).

They found, for this N-deficient set, that the fertility rating, f_N , was positively correlated to the soil N and inversely correlated to the soil C:N ratio in the upper 10 cm of soil (*i.e.*, $f_N = 1.32 + 0.99 \text{ N} (\%) - 0.04 \text{ C:N}$, $r^2 = 0.73$, $P = 0.009$). This result seems reasonable because primary productivity is strongly driven by N mineralization in the soil (Reich *et al.*, 1997; Newman *et al.*, 2006) and in the plant (Walcroft *et al.*, 1997), and there is a negative relationship between N mineralization and the soil C:N ratio (McLaren and Cameron, 1996; Bengtsson *et al.*, 2003). By transitivity it may be expected that fertility and the fertility modifier increase with soil N and decrease with the soil C:N ratio as seen in Figure 4. If confirmed, this relationship may prove useful for representing nutrition in hybrid growth and yield models. However, caution should be exercised for sites in which mineral nutrients other than nitrogen are limiting productivity.

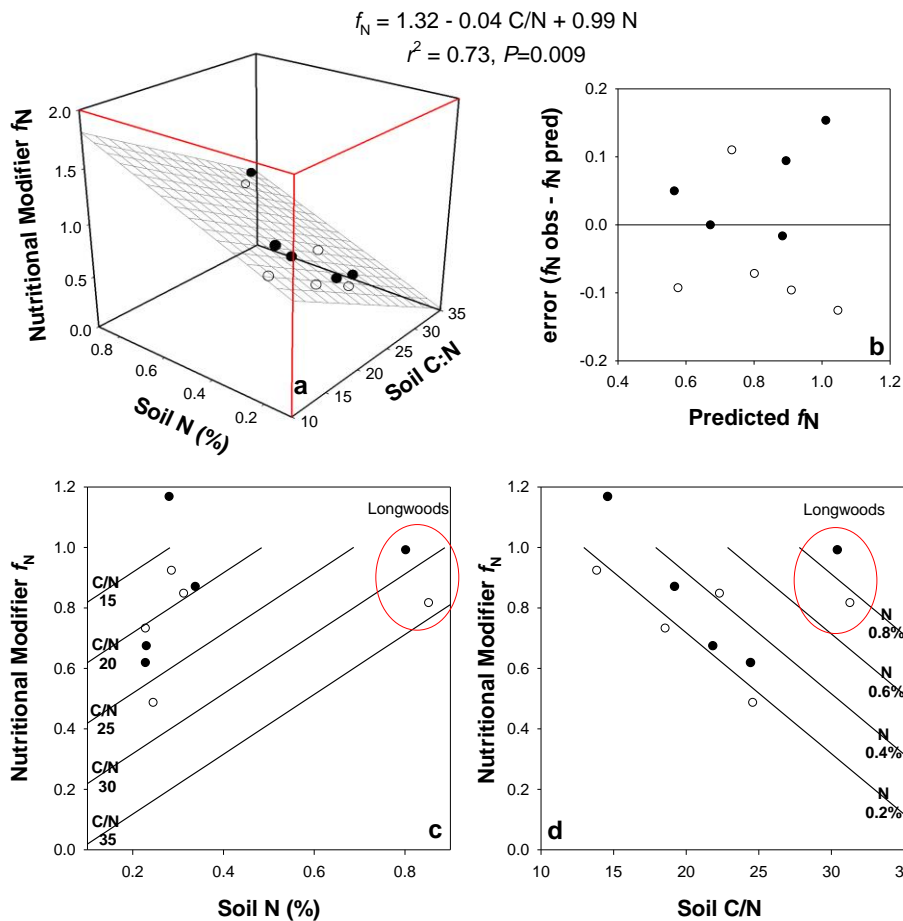


Figure 4. The relationship between the fertility ratio, soil N and the soil C:N ratio in control (open-symbols) and fertilized (closed-symbols) mini-plots of four-year old *Pinus radiata* in five sites on the South Island of New Zealand. The fertility ratio (f_N), a unitless parameter between 0 and 1, was fitted to actual values of GPP obtained in the field using a minimum set of parameters from 3-PG. Ellipsoids in (c) and (d) show the high leverage of the Longwoods site for soil N and soil C/N. Source: Bown *et al.* 2013.

Smith *et al.* (2010) assessed the response of *P. radiata* to residue management and fertilization at three contrasting sites (Woodhill, N deficient; Tarawera, N marginal and Kinleith, N satisfactory). They found that the forest floor C:N ratio correlated inversely to DBH at each site except for Kinleith, the site where N was satisfactory. Smith *et al.* (2010) argue that litter quality only had an effect on site productivity when total soil N content was small, as observed in Woodhill sandy soils. The weaker relationship between forest floor C:N and tree growth with increasing ecosystem N content, suggests that the mineral soil N supply has the capacity to "buffer" immobilisation by coarse woody debris and maintain adequate N availability. Using data from Smith *et al.* (2000) a potential nutritional modifier was developed that scales positively with soil N and negatively with the soil C:N ratio (Figure 5). This modifier follows the same pattern as that developed by Bown *et al.* (2013).

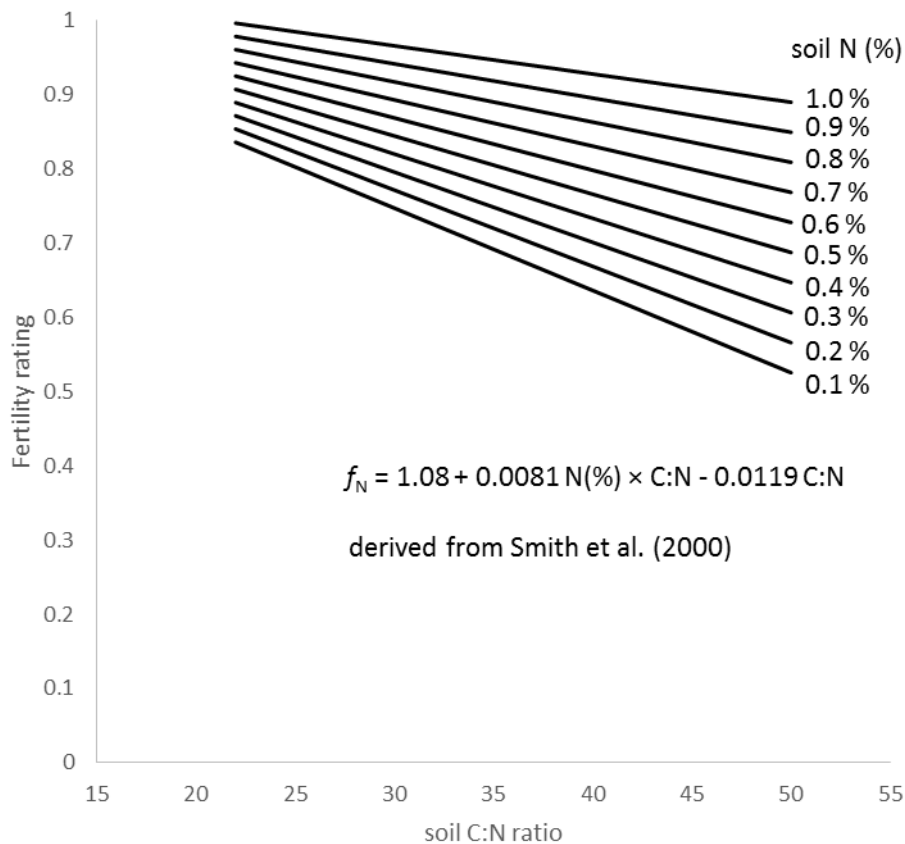


Figure 5. Potential fertility modifier developed using data from Smith et al. (2000).

These nutritional modifiers (both) are simple and based on stable soil attributes that are routinely measured in standard soil chemical analyses, *i.e.*, soil N and soil C:N. Kimmins and Scoullar (1984) suggested that the current state of knowledge of plant nutrition does not allow for the high resolution often used in today's tree growth models and that adopting a simpler approach to process descriptions avoiding time resolutions less than one year should be preferred. This broader approach has been followed here proposing a fertility modifier based on soil chemical attributes which do not change much over time.

Mason et al. (2010) developed a fertility modifier based on 33 fertilization trials with 4 year old *Pinus radiata* in which response to phosphate fertilisers was measured across New Zealand. When the first Bray P extraction was greater than Ballard's (1974) limit of 12 mg kg^{-1} , the fertilization ratio was generally high, but where the first extraction was below 12 mg kg^{-1} the fertilization ratio was highly variable (Figure 6). They showed that repeated Bray-P extraction (up to 10) could explain up to 64% of the variance in the fertility modifiers. Better responses were observed for plots in which cultivation and weed control was carried out (Figure 6).

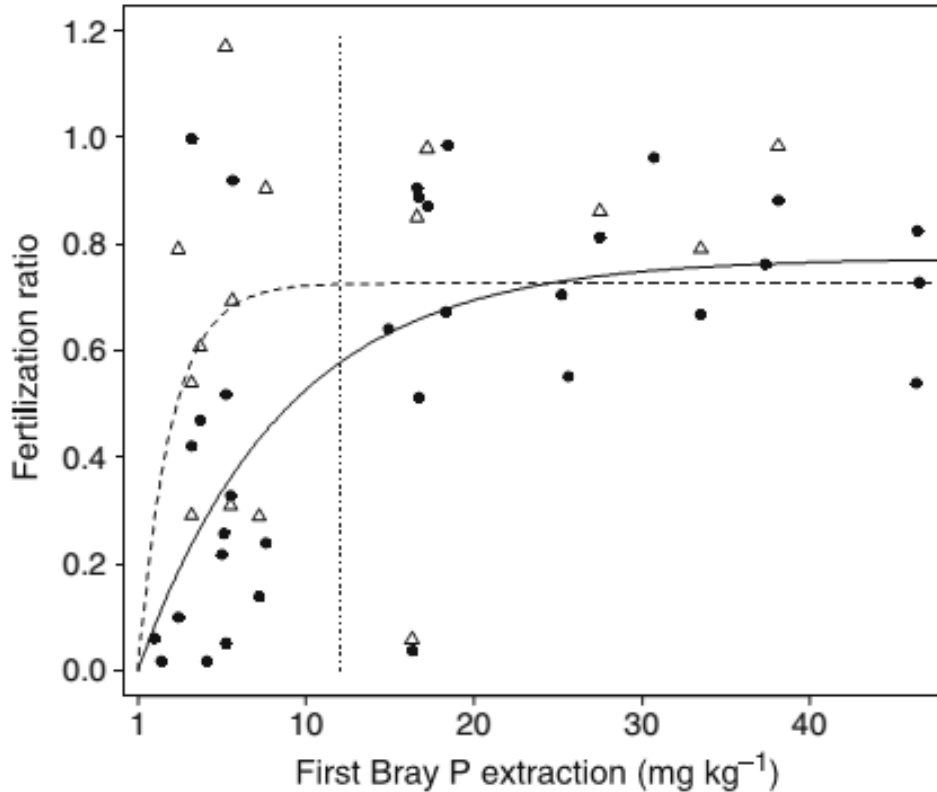


Figure 6. Fertilization ratio versus a single Bray P extraction. Filled circles and solid line denote plots with cultivation or weed control, while open triangles and dashed line denote those with neither cultivation nor weed control treatments. Lines show fits using the Mitscherlich equation. Fits had r^2 values of 0.495 ($n=33$) for the plots with cultivation or weed control and 0.025 ($n=15$) for those with neither cultivation nor weed control. Fitted lines are both forms of Eq. 2, $FR = \phi (1 - \exp(-(\gamma)BP1))$, where FR=fertilisation ratio and BP1=the first Bray P extraction from a sample. $\phi=0.7262$ and $\gamma=0.5028$ for sites with weed competition, and $\phi=0.7734$ and $\gamma=0.1142$ for sites without weed competition. The dotted line at BP1=12 is the limit set by Ballard (1974). Source: Mason *et al.* 2010.

For our modelling purposes, it seems reasonable to partition N from P limitations as the main nutrient limitations within New Zealand's forest plantations. This could be done through foliage or soil N:P ratios i.e. N:P <10 implies N limitations and N:P >10 implies P limitations. Additionally we could consider that plantations would be P limited if Bray P is less than 9 (Will 1985) to 12 ppm (Ballard 1974); and N limited otherwise.

MATERIAL

Global datasets

A set of global climate layers (climate grids) with a spatial resolution of about 1 square kilometre (30 arc seconds x 30 arc seconds) are available from WorldClim (Hijmans et al. 2005). Relevant layers within WorldClim include monthly precipitation and mean, minimum, and maximum monthly temperatures that are interpolated from data records predominantly from years 1950–2000. Another relevant global layer is the number of rain days per month ($0.5 \times 0.5^\circ$ grid, period

1971-2000) from the University of East Anglia (UEA) Climatic Research Unit (CRU) (<http://iridl.ldeo.columbia.edu/maproom/Global/Climatologies>). Monthly averages for solar radiation and relative humidity can be extracted from the NASA Surface meteorology and Solar Energy Global Data Sets (1×1° grid, period 1983-2005) (<http://eosweb.larc.nasa.gov/sse/>).

Soil properties can be extracted from the Harmonized World Soil Database (HWSD, version 1.2) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012) resulting from a joint project between FAO, the International Institute for Applied System Analysis (IIASA), ISRIC – World Soil Information, European Soil Bureau Network (ESBN) and the Institute of Soil Science, Chinese Academy of Sciences. More than 16000 different soil mapping units are recognised in the HWSD and linked to soil physical and chemical properties. The spatial resolution of the database is ca. 1 km² (30 arc seconds x 30 arc seconds) matching that of the WorldClim database. Some relevant variables are: soil fine fraction (fractions of silt and clay), water holding capacity and top-soil (0-30 cm) organic carbon.

New Zealand datasets

Access to the New Zealand's National Climate Database.(CliFlo) is through the National Institute for the Water and Atmosphere (NIWA) web page (<http://cliflo.niwa.co.nz/>). The CliFlo database holds data from about 600 weather stations throughout the country. CliFlo returns raw data at the ten minute, hourly and daily frequencies. Raster layers of weather data can be also obtained from NIWA.

The Land Resource Information System (LRIS, <https://lris.scinfo.org.nz/>) provides soil information covering all New Zealand. These layers are based on the New Zealand Land Resource Inventory (NZLRI) (Newsome et al. 2008). These layers are used as a planning and research tool, being accessible by most regional and district councils, universities, government agencies, research institutes and private organizations.

The soil fundamental data layers (FDLs) comprise 60.849 polygons for the North Island and 46.477 for the South Island, totalling 107.326. It contains spatial information for 16 key attributes, which are given numeric values that later are assigned to categories. These attributes were selected through a consultation with stakeholders, being related to soil fertility/toxicity, soil physical properties and topography. Variables are slope, potential rooting depth, topsoil gravel content, proportion of rock outcrop, pH, salinity, cation exchange capacity, total carbon, phosphorus retention, flood interval, soil temperature, total profile available water, profile readily available water, drainage, and macropores (Newsome et al. 2008). Some relevant soil physical and chemical variables are presented in Figure 7. Some codes are presented in Appendix A.

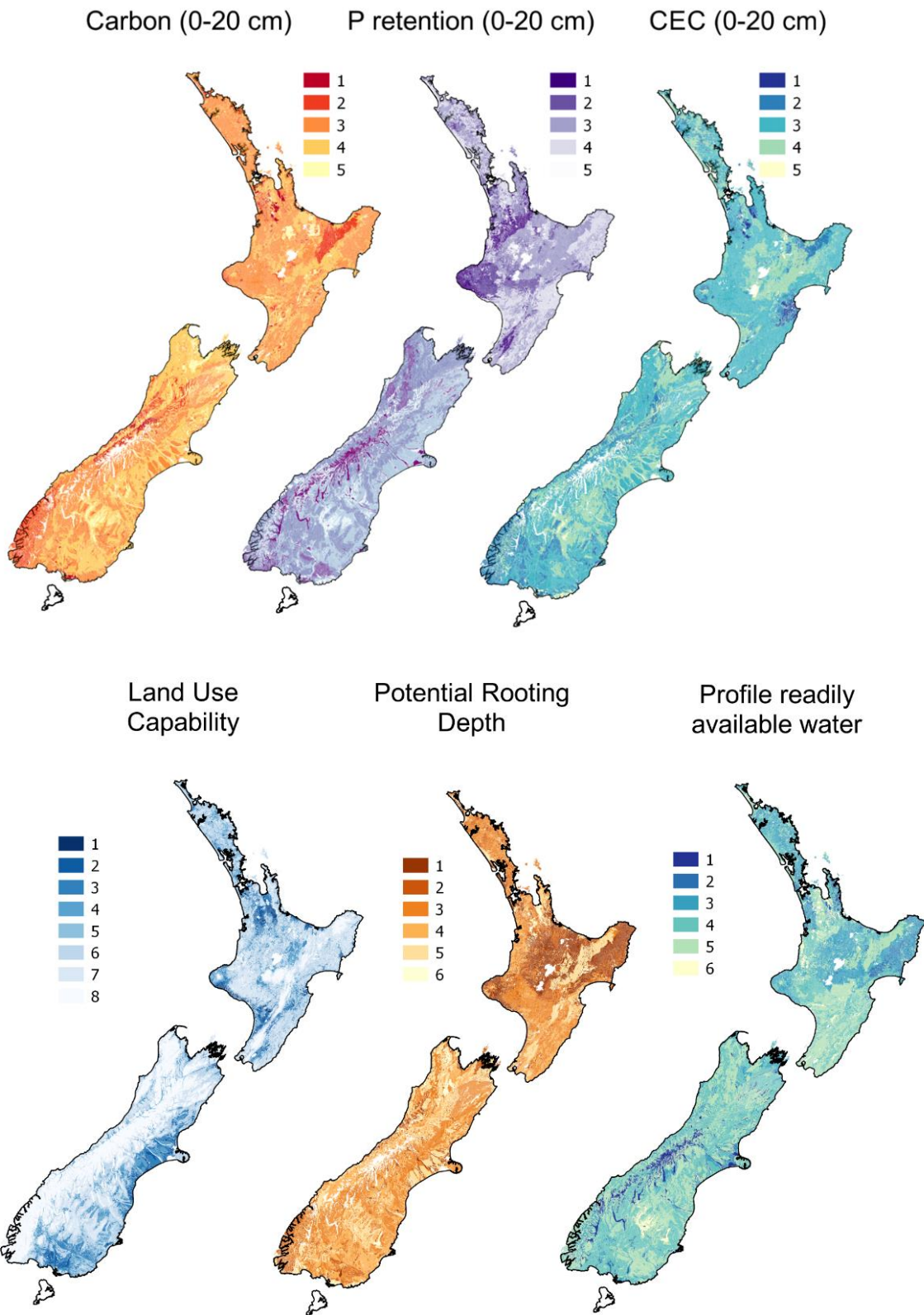


Figure 7. Some relevant soil physical and chemical properties from the Fundamental Soil Layers (LRIS, <https://lris.scinfo.org.nz/>).

The digital soil map for New Zealand (S-map, <http://smap.landcareresearch.co.nz/home>) is the new national soils database. When completed, it will provide unparalleled digital soil map coverage for New Zealand. S-map provides greater spatial detail than the fundamental soil layers. Each polygon is characterized by a single combination of attributes (NZSC classification, parent material, rock type, dominant texture and permeability class). Soil classes are further characterised as siblings according to their depth to rock class, stoniness, land type, drainage, texture, functional horizons and miscellaneous information. The fundamental soil properties are depth (diggability), depth to slowly permeable layer, rooting depth, rooting barrier, horizon thickness, stoniness, clay and sand content. They are developed from sample information and expert knowledge. Derived layers will include available water (mm), macroporosity, water retention, bulk density, total carbon, total nitrogen, phosphorus, calcium, cation exchange capacity, pH, and phosphorus retention. S-map provides (will provide) comprehensive, quantitative soil information to support sustainable development and scientific modelling.

Fertilization trials

There is a long tradition of fertilization trials that dates back to the 1950s in New Zealand (Mead 1974). Access to these trials is through Scion Research (<http://www.scionresearch.com/>). A sample of such trials is presented in Table 1.

Region	Name	Expt	Texture	C	N	C:N	Bray-P	K	Ca	Mg	pH	Pen.Res.	Fertility rating		
				(%)	(%)	(%)	(ppm)	(%)	(%)	(%)	(Pa?)	D2H	height	DBH	
Auckland	Waipoua	522	Clay	2.465	0.085	29	1.55	0.08	0.50	0.95	4.35	23.54	0.57	0.82	0.78
	Riverhead	580	Clay	4.900	0.245	20	5.20	0.40	2.40	1.55	5.45	16.54	0.21	0.61	0.58
	Tairua	581	Clay	5.760	0.360	16	2.15	0.32	1.95	0.95	5.65	15.22	0.73	0.88	0.91
	Whitecliffs	662	Clay	2.880	0.160	18	2.20	0.18	0.60	1.55	4.05	23.91	0.05	0.34	0.37
	Tairua	741	Clay	8.075	0.475	17	2.30	0.40	3.40	1.20	5.65	16.16	0.26	0.60	0.65
	Hunua	841	Clay	4.960	0.310	16	1.65	0.49	1.10	0.60	5.05	17.01	0.36	0.78	0.67
	Aupouri	578/3	Sand	2.250	0.075	30	1.80	0.06	0.30	0.40	4.60	22.58	0.54	0.76	0.84
	Aupouri	578/5	Sand	1.650	0.055	30	1.35	0.05	0.40	0.40	4.80	19.10	0.84	0.96	0.91
	Shenstones	739/1	Clay	2.860	0.110	26	1.55	0.09	0.65	0.80	5.10	15.56	0.44	0.70	0.69
	Takou Bay	739/2	Clay	1.600	0.100	16	2.25	0.11	0.35	0.70	4.85	19.66	0.32	0.71	0.67
	Te Kao	850/1	Sand	3.375	0.125	27	0.95	0.01	0.35	0.65	4.35	21.06	0.06	0.42	0.38
Maramaku	850/2	Clay	1.785	0.105	17	1.55	0.04	0.65	0.55	4.45	11.84	0.02	0.34	0.23	
Canterbury	Balmoral 63	394	Sand	1.500	0.100	15	51.70	0.52	1.55	0.65	5.35	26.66	0.54	0.80	0.82
	Eyrewell	396	Sand	2.480	0.155	16	20.85	0.39	1.55	0.80	5.10	22.32	0.96	1.00	0.98
	Balmoral 16	404	Sand	3.450	0.230	15	32.85	0.14	1.20	0.40	5.20	24.96	0.82	0.93	0.94
Nelson	Harakeke 151	422	Loam	0.600	0.030	20	2.75	0.08	0.10	0.35	4.60	17.16	0.22	0.62	0.59
	Dovedale 382	439	Loam	1.300	0.065	20	12.75	0.09	1.80	0.55	4.85	22.62	0.67	0.78	0.93
	Pupu 3	489	Sand	1.430	0.065	22	2.85	0.10	1.20	0.30	4.75	13.28	0.05	0.41	0.36
Rotorua	Kaingaroa 1031	1063	Sand	4.935	0.235	21	12.55	0.48	1.20	0.35	5.40	26.44	0.86	0.96	0.95
	Kaingaroa 1032		Sand	4.935	0.235	21	12.55	0.48	1.20	0.35	5.40	24.50	0.81	0.98	0.91
	Kaingaroa 887	1963	Sand	4.025	0.175	23	13.15	0.25	0.45	0.15	5.45	33.68	0.98	1.02	0.98
	Kaingaroa 888		Sand	4.025	0.175	23	13.15	0.25	0.45	0.15	5.45	30.50	0.87	0.95	0.96
	Kaingaroa 558	1964	Sand	5.180	0.185	28	18.05	0.18	0.50	0.15	5.65	47.68	0.79	0.92	0.93
	Kaingaroa 559		Sand	5.180	0.185	28	18.05	0.18	0.50	0.15	5.65	13.56	0.67	0.92	0.85
	Kaingaroa 567	1984	Sand	9.240	0.330	28	22.65	0.19	1.50	0.35	5.50	11.54	0.73	0.93	0.88
	Tauhara 32	1985	Sand	4.160	0.160	26	41.90	0.25	3.85	0.70	5.70	22.74	0.76	0.91	0.92
Southland	Rankleburn	416	Loam	4.000	0.200	20	7.55	0.22	0.80	0.90	4.80	15.06	0.51	0.86	0.77
	Otago Coast	472	Loam	4.100	0.205	20	10.95	0.30	3.15	2.50	5.05	26.10	0.99	0.94	1.03
	Beaumont	482	Loam	0.320	0.020	16	25.25	0.06	0.25	0.60	5.55	43.32	0.55	0.82	0.82
	Berwick 124	503	Loam	5.670	0.270	21	4.45	0.10	0.40	0.50	4.40	23.24	0.89	0.98	0.95
	Rankleburn	560	Loam	4.300	0.215	20	10.80	0.14	0.80	0.65	4.50	13.22	0.64	0.90	0.85
Wellington	Awahohonu 23	203	Loam	5.740	0.410	14	21.30	0.85	10.70	3.05	5.95	13.28	0.98	0.98	1.00
	Awahohonu 24		Loam	5.740	0.410	14	21.30	0.85	10.70	3.05	5.95	13.94	0.88	0.96	0.96
	Karioi 66	261/1	Loam	2.320	0.145	16	6.35	0.09	0.70	0.15	5.85	11.13	0.81	0.89	0.95
	Karioi 16	261/2	Loam	4.400	0.275	16	13.40	0.16	3.80	0.80	5.80	13.29	0.88	0.99	0.94
Westland	Aratika	180	Clay	6.400	0.320	-	17.15	0.06	2.45	0.75	4.25	16.92	0.70	0.79	0.95
	Paparoa 3	223	Clay	2.185	0.095	23	2.80	0.06	0.40	0.15	4.55	17.80	0.02	0.28	0.25

Table 1. Some soil chemical and physical variables across 33 sites. Fertility ratings were calculated as the ratio of diameter at breast height (D), tree height (H) or D^2H of the control to the fertilized treatment. Soil C:N was extracted from the Fundamental Soil Layers (FDLs) while soil C was calculated as $N \times C:N$.

METHODS

The aim of this report was to explore ways to represent fertility in high-precision hybrid growth modelling. We found that fertility modifiers can be approached through:

- (i) Soil chemical properties
- (ii) Crop evenness
- (iii) Satellite imagery

Soil chemical properties can be used to estimate the fertility modifier. Stape *et al.* (2004a, b, 2006) suggested using paired plots with and without fertilization to parameterize the fertility modifier required to calibrate hybrid models such as 3-PG (Landsberg and Gower 1997). They related the fertilization response of *Eucalyptus* plantations in Brazil with soil exchangeable K, total P and cation exchange capacity with medium accuracy ($r^2 = 0.56$, $P \leq 0.001$). This is one of the approaches that we would follow for this project, and therefore a description of the trials is required (Table 1). These are the same trials used by Mason *et al.* (2010). Also a dataset collected by Bown *et al.* (2013) will be used to cross validate some of the results from Mason *et al.* (2010). Additional databases from the literature and SCION will be considered.

Crop evenness may prove to be an alternative to estimate the fertility modifier. More variability is expected in poor fertility sites because plants may spend proportionally more energy foraging for resources and intra specific competition will be likely to be harder in poorer than in richer sites.

Darwin's law of survival of the fittest might operate more strongly in poor than in rich sites.

Therefore there might be a signal of fertility in our PSPs. A signal to noise can be found in the standard deviation of DBH or height divided by the mean of DBH or height i.e. their coefficients of variation. To test this idea we classified (2008) the forest estate of Forestal Mininco into croptypes which were made out of main growth zones (soils) and site index classes (Table 2). Only croptypes covering more than 5000 ha were considered, with available inventories from pre-pruning at age 4 (PPI4) to pre-harvest. We then assessed how the coefficient of variation changed with soil (growth zone), site index and age/management.

Site Class	Top Height (m)	Forest Estate by Growth Zone (ha $\times 10^3$)						Sub-total	
		TRUMAO 4	ARENA 5	COSTA 6		ARCILLA 7			
I	≥ 32.5	(1) 14	1	(7)	10	(10)	9	34	
II	< 32.5	(2) 16	4	(8)	13	(11)	26	59	
III	< 29.5	(3) 8	(4)	10	(9)	9	(12)	19	46
IV	< 26.5	2	(5)	10	3	(13)	5	19	
V	< 23.5	0	(6)	10	0	2		13	

Table 2. Classification of Forestal Mininco’s Forest Estate into croptypes according to growth zones (soils) and site indices (top height at age 20 years) for the main four growth zones. Croptypes selected are indicated by numbers between parentheses and shaded cells.

Satellite imagery can also provide information to estimate the fertility modifier. The idea is to extract bands from different satellites intersecting the location of permanent sample plots, and correlate such values against the residuals of site index from hybrid growth modelling considering only environmental variables. If such correlation exists, the signal should be relatively independent from when the image was taken, and this can be objectively tested. For the interim results we correlated residuals against the visible bands (blue, green, red) of Landsat 8.

RESULTS

Potential fertility ratings based on soils

We analysed the fertility rating response in growth to several soil chemical and physical variables in the upper 20 cm of the soil based on trials reported by Mason et al. (2010) (Table 1). Among all soil chemical and physical variables, only pH (Spearman- $r = 0.53$, $P < 0.001$), and Bray-P ($r = 0.4$, $P = 0.005$) significantly influenced the fertility rating, while soil carbon ($r = 0.28$, $P = 0.054$), nitrogen ($r = 0.26$, $P = 0.074$) and potassium ($r = 0.27$, $P = 0.071$) were marginally significant. All other soil variables; namely, K, Ca, Mg, and penetration resistance were insignificant ($P > 0.09$). Besides, the variable that most strongly correlated with the fertility rating, pH, was also strongly autocorrelated with N (Spearman- $r = 0.47$, $P < 0.001$), C ($r = 0.4$, $P = 0.005$), C:N ($r = -0.32$, $P = 0.03$), Bray-P ($r = 0.44$, $P = 0.002$), K ($r = 0.52$, $P < 0.001$) and Ca ($r = 0.51$, $P < 0.001$); but not with Mg ($r = 0.13$, $P = 0.37$). The simplest model is then:

$$f_N = -0.252 + 0.205 \text{ pH} , r^2 = 0.28, P < 0.001 \quad (1a)$$

When adding the second most important variable, Bray-P, it did not significantly improved the model ($P = 0.15$). The same happened when sequentially adding the other soil chemical variables. Thus, despite the low power of prediction we keep (1a) as the best candidate for a fertility rating for the Mason et al. (2010) data. It is worth noting than when fitting this model to the dataset of Bown et al. (2013) almost the exact model was found, although the data is for a soil depth 0-10 cm, and the model is insignificant:

$$f_N = -0.301 + 0.211 \text{ pH} , r^2 = 0.30, P = 0.10 \quad (1b)$$

So pH is likely to affect the fertility rating; the higher the pH the higher the fertility rating. There is some common sense in this trend; usually pasture to ex pasture lands would have a higher pH closer to neutral, and would be usually more fertile than where pH is more acidic.

We previously found (Bown et al. 2013) that the fertility rating, f_N , was positively correlated to the soil N and inversely correlated to the soil C:N ratio in the upper 10 cm of soil (*i.e.*, $f_N = 1.32 + 0.99 \text{ N} (\%) - 0.04 \text{ C:N}$, $r^2 = 0.73$, $P = 0.009$). Assuming that the soil C:N ratio is relatively

constant at about 20 (19.96 ± 4.13 from Bown et al. 2013; except Longwoods). Then f_N would simplify to,

$$f_N = 1.32 + 0.99 N (\%) - 0.04 C:N$$

$$f_N = 1.32 + 0.99 N (\%) - 0.04 \times 20$$

$$f_N = 0.52 + 0.99 N (\%) \text{ with } f_N = 1 \text{ if } N(\%) > 0.48\% \quad (2a)$$

From Mason et al. (2010), N (%) from the upper 10 cm (not upper 20 cm) significantly correlated with the fertility rating through a relationship very similar to (2a):

$$f_N = 0.39 + 0.83 N (\%) \text{ with } f_N = 1 \text{ if } N(\%) > 0.73\% \quad (2b)$$

($r^2=0.10$, $P=0.03$)

Additionally, $N = C/C:N$ (assuming $C:N=20$), and then (2a, from Bown et al. 2013) can be transformed into an equation able to resolve f_N from soil carbon (upper 10 cm),

$$f_N = 0.52 + 0.05 C (\%) \text{ with } f_N = 1 \text{ if } C(\%) > 9.6\% \quad (3a)$$

Interestingly, a similar form and similar coefficients were found for the Mason et al. (2010) data for the upper 10 cm of the soil:

$$f_N = 0.389 + 0.041 C (\%) \text{ with } f_N = 1 \text{ if } C(\%) > 14.9\% \quad (3b)$$

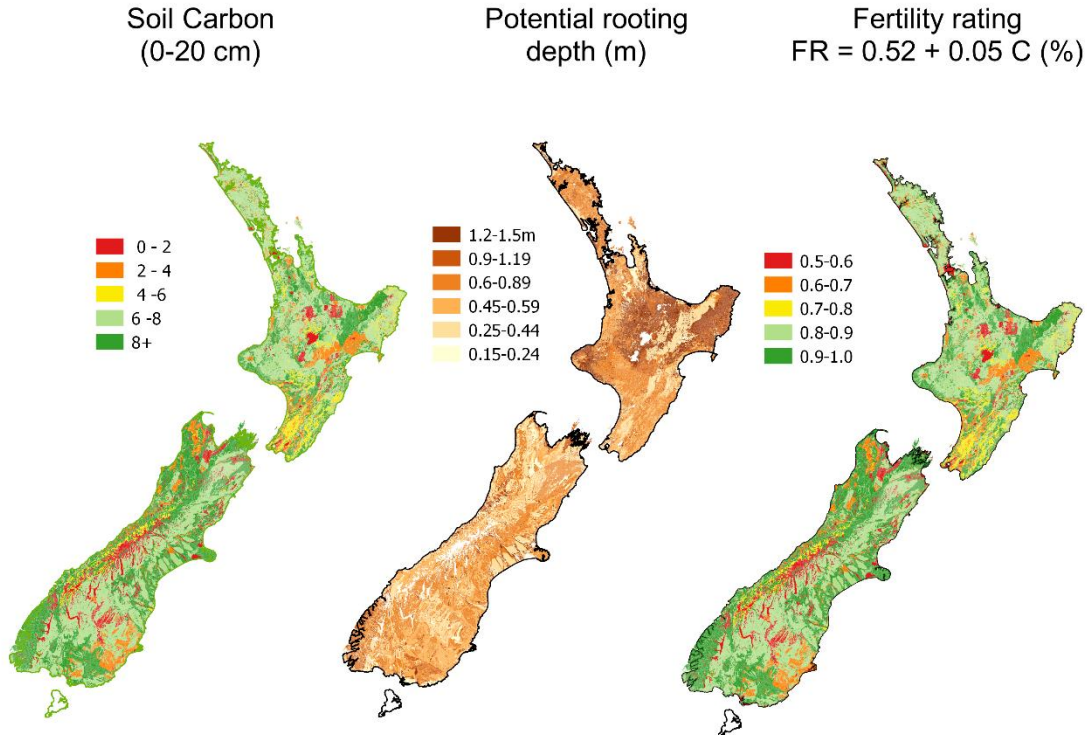


Figure 8. Fertility ratings based on soil carbon for New Zealand plantations. The fertility rating was calculated as: $f_N = 0.52 + 0.05 C$ (%) with $f_N = 1$ if $C(\%) > 9.6\%$, where C is soil carbon (%) in the upper 20 cm of the soil.

Therefore obvious candidates to estimate the fertility rating across the landscape are soil C, soil N and pH. Be aware that these relationships were derived from point measurements and were generally weak (r^2 generally below 0.3). Given that we want to predict the fertility ratings at the landscape scale based on data at the polygon scale, we should not expect great gains in precision but hopefully some significance. All these soil chemical variables i.e. (soil N, soil C and soil C:N), are, or can be derived at a cost, from the Fundamental Soil Layers (FSLs) and S-maps. Additionally for those conditions in which Bray-P is less than 12 ppm (Ballard 1974) we will use the fertility modifier proposed by Mason et al. (2010) based on Bray-P:

$$f_N = 0.7734 (1 - \exp(-0.1142 \text{BP1})) \quad (4)$$

where f_N =fertilisation ratio and BP1=the first Bray P extraction from a sample.

Can we use soil data at the polygon scale to the plot scale?

There were 1483 permanent sample plots available for Kaingaroa for fitting an hybrid growth and yield model. The problem is that when we extract the values of the FSLs, those 1483 plots account for about 10 different values of soil properties as they come from 10 polygons. Figure 8 shows the relationship between site index residuals (m) and soil pH in the soil upper 20 cm. The correlation is extremely low ($r^2 = 0.01$) but highly significant ($P < 0.001$) ($y = -5.88 + 1.02 x$). Soil carbon, soil C:N, CEC and P retention were insignificant. For Nelson Forests there were no significant relationship between residuals of site index and soil chemical properties from the FSLs.

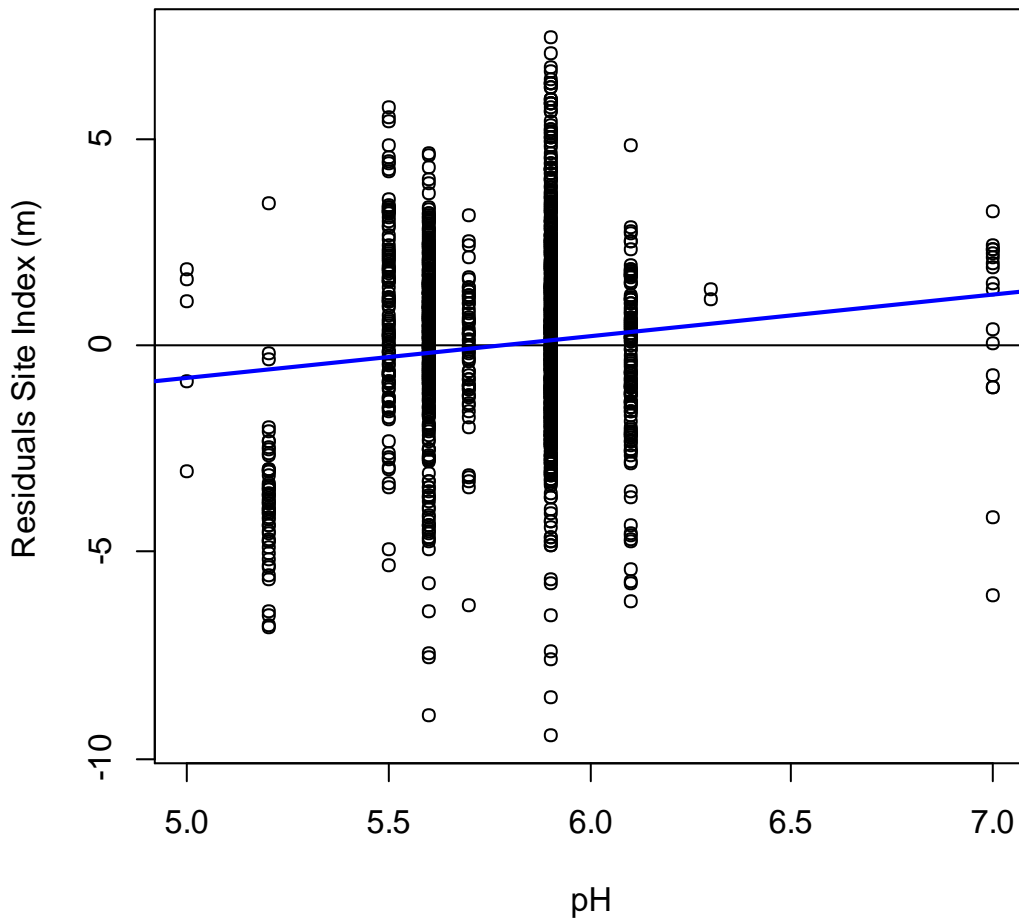


Figure 9. Plot of residuals of site index (m) against pH based on 1483 permanent sample plots from the Kaingaroa Forest.

Potential fertility ratings based on crop evenness

The coefficients of variation (c.v.) of the diameter at breast height (d.b.h.) and tree height at the time of the pre-pruning inventory (EPP4), varied significantly among croptypes ($P < 0.001$) and site classes ($P < 0.001$). The c.v. of the d.b.h. was generally greater than the c.v. of tree height by a factor of 1.3 to 2.1. Both coefficients of variation followed the same pattern being greater in poorer sites and smaller in better sites consistently across all growth zones studied (Figure 10). Lowest variability was generally observed in the growth zone Costa while the greatest in Arenas.

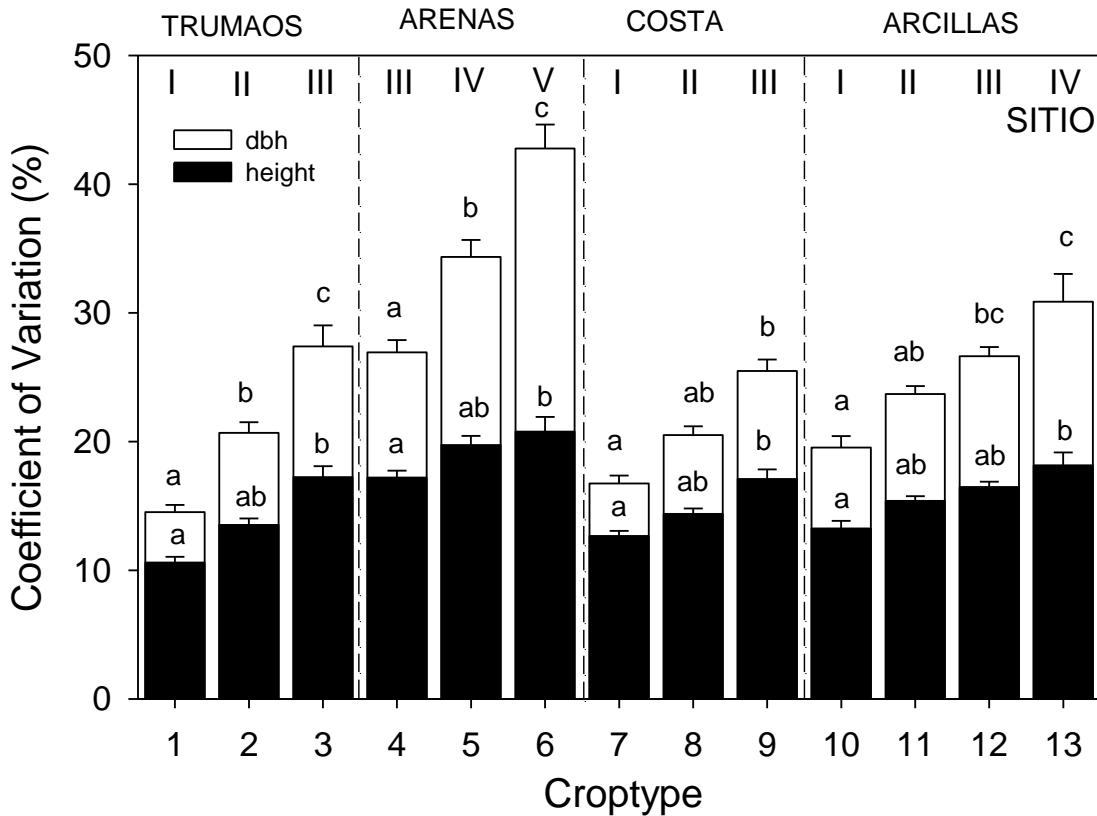


Figure 10. Coefficient of variation of diameter at breast height (d.b.h.) and tree height at the time of pre-pruning inventory (EPP4) for different growth zones and site classes. Values are presented as means (± 1 SE). Different letters within growth zones indicate significant differences at $P = 0.05$.

Analysis of covariance revealed that slopes ($P = 0.04$) and intercepts ($P = 0.01$) of the linear relationship between the c.v. of the d.b.h. (a square root transform) and site index varied significantly between growth zones (Figure 11). However the growth zone effect was far smaller than the effect of the site index on this relationship. Therefore there is strong statistical evidence to assert that (i) variability in d.b.h. and tree height decrease as the site improves, (ii) variability in tree height is far less than the variability in the d.b.h.

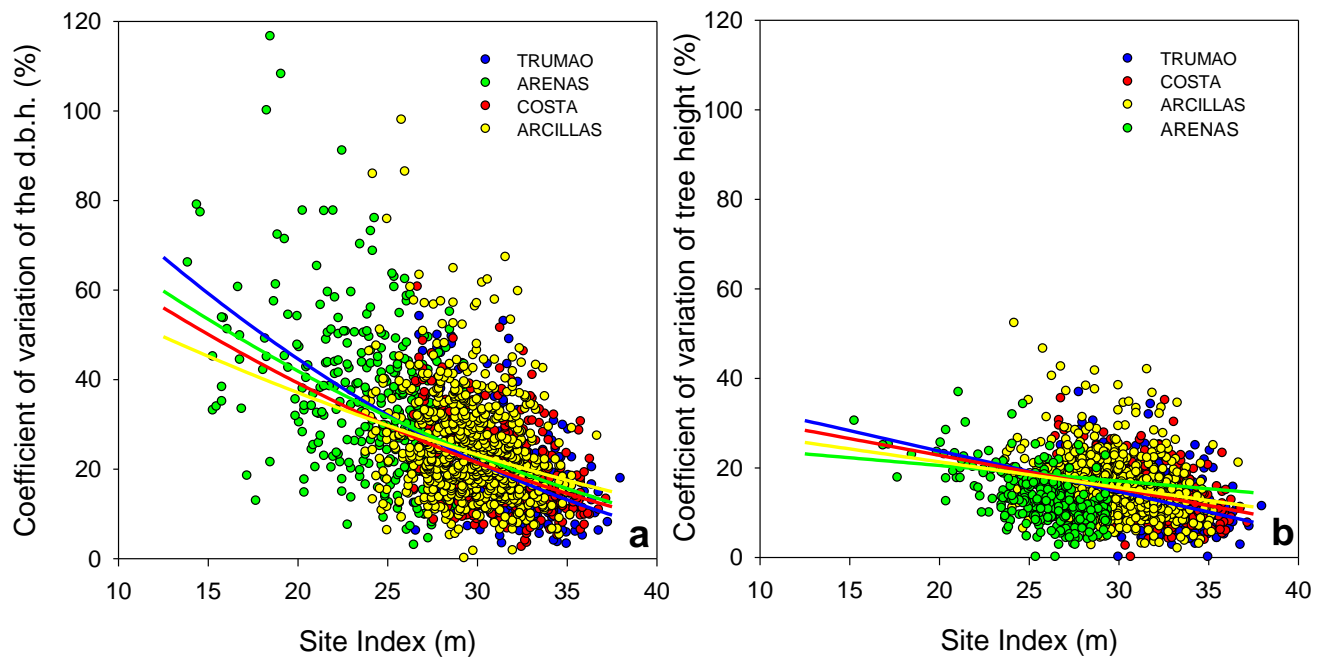


Figure 11. Relationship between the c.v. of tree d.b.h. (a) and c.v. of tree height (b) against site index. Slopes and intercepts were not influenced by growth zone in (a) but they were in (b). In (a): $y = (10.7489 - 0.2035 x)^2$, $r^2 = 0.20$, $P < 0.001$ (Trumaos); $y = (9.8306 - 0.1679 x)^2$, $r^2 = 0.17$, $P < 0.001$ (Arenas); $y = (9.5256 - 0.1632 x)^2$, $r^2 = 0.18$, $P < 0.001$ (Costa); $y = (8.6285 - 0.1270 x)^2$, $r^2 = 0.07$, $P < 0.001$ (Arcillas). In (b): $y = 41.9488 - 0.9089 x$, $r^2 = 0.14$, $P < 0.001$ (Trumaos); $y = 27.4596 - 0.3463 x$, $r^2 = 0.02$, $P < 0.01$ (Arenas); $y = 37.7657 - 0.7482 x$, $r^2 = 0.12$, $P < 0.001$ (Costa); $y = 32.8765 - 0.5759 x$, $r^2 = 0.05$, $P < 0.001$ (Arcillas).

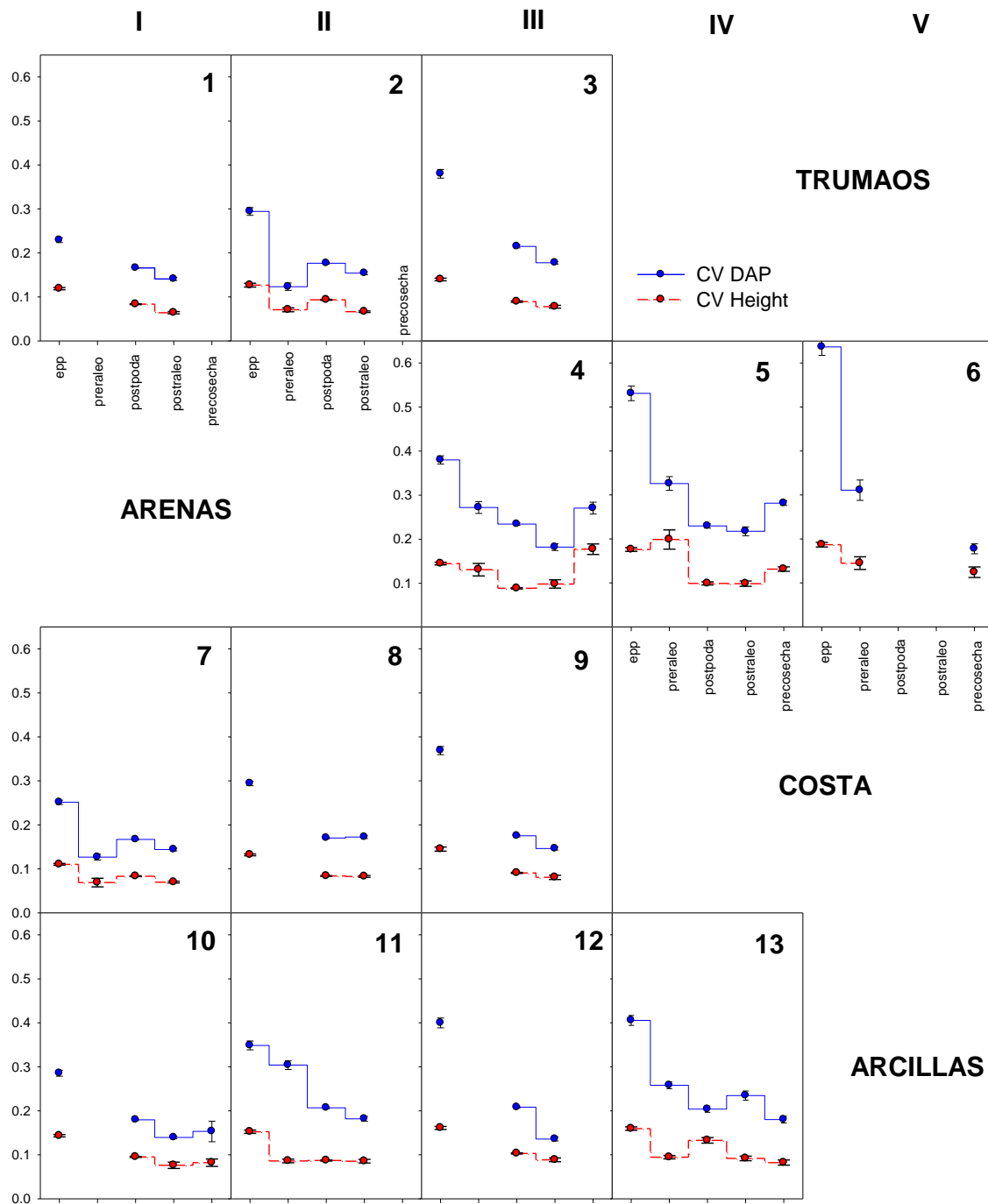


Figure 12. Evolution of the c.v. of tree height and dbh across croptypes and inventories. Arabic numbers indicate croptypes identification.

Changes in the cv of tree dbh and tree height across croptypes and forest inventories are shown in Figure 12. Croptypes are the result of crossing site classes (Columns) and growth zones (Rows). Within each graph (croptype), forest inventories are sequentially shown in the x axis while the cvs of both tree height and dbh are shown in the y axis. It can be seen that: (i) dbh and tree height coefficients of variation generally increased as site quality worsened across all inventories, (ii) the dbh coefficient of variation was always greater than the tree height coefficient

of variation, and (iii) the coefficients of variation of both dbh and tree height generally decreased over time (mixed effect of age and management).

For our modelling purposes this means that: (i) the coefficient of variation in DBH might be preferred to the c.v. in tree height as an indicator of fertility, (ii) the c.v. in DBH decreases with age and management and hence should be taken at early ages (e.g. 4 years old) before any management takes place, (iii) fertility modifier will be proportional to $1 - \text{c.v. plot} / \text{c.v. max}$.

Potential fertility ratings based on satellite imagery

We correlated residuals of site index for Kaingaroa and Nelson Forests with the blue, green and red bands of Landsat 8. For Kaingaroa, the three bands (blue B1, green B2, red B3) significantly correlated to the residuals of site index through the relationship: $\text{residuals} = -1.044 + 0.044 B1 + 0.022 B2 + 0.032 B3$, $r^2=0.05$, $P=0.001$. For Nelson Forests: $\text{residuals} = -1.5546 + 0.022105 x$, $r^2=0.06$, $P=0.001$. These relationships add in the order of 5-6% to the fitting, and therefore satellite imagery seems promising to get spatially explicit values of soil fertility. As a first step we would correlate residuals of best fit hybrid models against bands of Landsat 8. Landsat Bands in microns (μm) are:

1	0.45-0.52 μm	Blue-Green
2	0.52-0.60 μm	Green
3	0.63-0.69 μm	Red
4	0.76-0.90 μm	Near-infrared
5	1.55-1.75 μm	Mid-infrared
7	2.08-2.35 μm	Mid-infrared
6	10.40-12.50 μm	Far-infrared (thermal infrared)

CONCLUSIONS

Fertility modifiers for precision hybrid growth modelling can be approached through: soil chemical properties, crop evenness and satellite imagery. Relevant soil chemical variables for estimating a fertility modifier are soil carbon, soil nitrogen, soil pH, total soil phosphorus, and Bray-P. The fundamental soil layers (FSLs) and S-map for New Zealand do not provide the precision required for this project. Hence soil samples should be collected for all or a subset of the PSPs of each company. Crop evenness assessed through the coefficient of variation in d.b.h. seems to be an alternative approach to assess fertility provided that is collected at an early age before any management has taken place. Hence we would need for the companies to provide dbh for every permanent sample plot at the earliest age. The c.v. in dbh from temporal plots before any pruning or thinning ideally before year 5 would be also a valuable source to interpolate fertility across the landscape. Satellite imagery seems also to be valuable tool and should be further explored, as we found significant correlation in the order of 5-6% between residuals of site index and the visible bands of Landsat 8 for Kaingaroa and Nelson Forests.

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APPENDIX A

Some relevant soil physical and chemical properties from the Fundamental Soil Layers (LRIS, <https://iris.scinfo.org.nz/>).

Total Carbon: Total carbon (organic matter content) is estimated as weighted averages for the upper part of the soil profile from 0–0.2 m depth, and expressed as a percentage. The classes are described more fully in Webb and Wilson (1995) and Blakemore et al. (1987).

<i>CARBON_</i> <i>CLASS</i>	<i>CARBON_</i> <i>MIN (%)</i>	<i>CARBON_</i> <i>MAX (%)</i>	<i>CARBON_</i> <i>MOD (%)</i>	<i>Description</i>
1	20	60	Refer comment under 'Item values & Interpretation'	Very high
2	10	19.9		High
3	4	9.9		Medium
4	2	3.9		Low
5	0	1.9		Very low

Cation Exchange Capacity: CEC is estimated as weighted averages for the soil profile from 0–0.6 m depth and expressed in units of centimoles of charge per kg (cmoles (+)/kg). The CEC classes are described more fully in Webb and Wilson (1995) and Blakemore *et al.* (1987).

<i>CEC_</i> <i>CLASS</i>	<i>CEC_</i> <i>MIN</i> (cmoles(+)/k g)	<i>CEC_</i> <i>MAX</i> (cmoles(+)/k g)	<i>CEC_</i> <i>MOD</i> (cmoles(+)/k g)	<i>Description</i>
1	40	100	Refer comment under 'Item values & Interpretation'	Very high
2	25	39.9		High
3	12	24.9		Medium
4	6	11.9		Low
5	0	5.9		Very low

P retention: P retention (phosphate retention) is estimated as weighted averages for the upper part of the soil profile from 0–0.2 m depth, and expressed as a percentage. The classes are described more fully in Blakemore *et al.* (1987) and Webb and Wilson (1995).

<i>PRET_</i> <i>CLASS</i>	<i>PRET_</i> <i>MIN</i> (%)	<i>PRET_</i> <i>MAX</i> (%)	<i>PRET_</i> <i>MOD</i> (%)	<i>Description</i>
1	85	100	Refer comment under 'Item values & Interpretation'	Very high
2	60	84		High
3	30	59		Medium
4	10	29		Low
5	0	9		Very low

Land Use Capability: Polygon layer delineating land areas classified according to their capability to sustain continuous production. Land Use Capability (LUC) is a hierarchical classification identifying: the land's general versatility for productive use; the factor most limiting to production; and a general association of characteristics relevant to productive use (e.g., landform, soil, erosion potential, etc.).

<i>LUC Class code</i>	<i>Description</i>
1	Land with virtually no limitations for arable use and suitable for cultivated crops, pasture or forestry
2	Land with slight limitations for arable use and suitable for cultivated crops, pasture or forestry
3	Land with moderate limitations for arable use, but suitable for cultivated crops, pasture or forestry
4	Land with moderate limitations for arable use, but suitable for occasional cropping, pasture or forestry
5	High producing land unsuitable for arable use, but only slight limitations for pastoral or forestry use
6	Non-arable land with moderate limitations for use under perennial vegetation such as pasture or forest
7	Non-arable land with severe limitations to use under perennial vegetation such as pasture or forest
8	Land with very severe to extreme limitations or hazards that make it unsuitable for cropping, pasture or forestry

Potential rooting depth: Potential rooting depth describes the minimum and maximum depths (in metres) to a layer that may impede root extension. Such a layer may be defined by penetration resistance, poor aeration or very low available water capacity. These classes, described more fully in Webb and Wilson (1995), are as follows:

<i>PRD_</i> <i>CLASS</i>	<i>PRD_</i> <i>MIN (m)</i>	<i>PRD_</i> <i>MAX (m)</i>	<i>PRD_</i> <i>MOD (m)</i>	<i>Description</i>
1	1.2	1.5	Refer comment under 'Item values & Interpretation'	Very deep
2	0.9	1.19		Deep
3	0.6	0.89		Moderately deep
4	0.45	0.59		Slightly deep
5	0.25	0.44		Shallow
6	0.15	0.24		Very shallow

Profile readily available water: PRAW_CLASS is a classification of profile readily available water for the soil profile to a depth of 0.9 m, or to the potential rooting depth (whichever is the lesser). Values are weighted averages over the specified profile section (0–0.9 m) and are

expressed in units of mm of water. The classes originate from the work of Gradwell and Birrell (1979), Wilson and Giltrap (1982) and Griffiths (1985), and are described more fully in Webb and Wilson (1995). Profile readily available water classes and their corresponding values are as follows:

<i>PRAW_</i> <i>CLASS</i>	<i>PRAW_</i> <i>MIN (mm)</i>	<i>PRAW_</i> <i>MAX (mm)</i>	<i>PRAW_</i> <i>MOD (mm)</i>	<i>Description</i>
1	150	250	Refer comment under 'Item values & Interpretation'	Very high
2	100	149		High
3	75	99		Moderately high
4	50	74		Moderate
5	25	49		Low
6	0	24		Very Low

