Development of the Douglas-fir Productivity Spatial Surface using the Process-based model 3-PG

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Date: 31 August 2017

Publication No: SWP-T038

TABLE OF CONTENTS

FOREST GROWERS RESEARCH

EXECUTIVE SUMMARY

The problem

The objective of this report was to provide a New Zealand-wide productivity surface for Douglas-fir. This output addresses limitations of an earlier study of Douglas-fir spatial productivity that was based on very a limited number of sites.

This project

This report is produced for the Speciality Wood Products Research Partnership.

Key Results

The major results of the study were:

- Douglas-fir permanent sample plots (PSP) providing a comprehensive coverage of New Zealand's Douglas-fir growing areas were sourced and refined into a set of representative measurements for spatial growth modelling (calibration) and verification of the model (validation)
- Daily climate data matching PSP measurements were successfully modified and integrated into the model
- Allometric equations for stem and foliar mass by stem diameter at breast height (1.4m, DBH), and the wood density by age equation were successfully updated
- 3-PG was successfully parameterised using data from 32 sites from 23 locations throughout the country with an average mean DBH error of 10% across these sites.
- The Scion parameterised model was tested against a 25 site validation dataset from throughout the country and had an average mean DBH error of 38% across these sites. However, the majority of this error was due to the poor performance of the model for two sites.
- The Scion parameterised model was an improvement to the Waring et al. (2008) parameterised model.
- A Douglas-fir productivity surface was successfully developed using $3PG_2S$ showed higher productivity areas in the Nelson/Marlborough, Southern Canterbury, Taranaki and northern Gisborne regions.
- The Scion parameterised model provides a good foundation to understand and quantify site sensitivities for New Zealand grown Douglas-fir and to quantify any gap between actual and potential productivity.
- On site data collection and development of an independent site fertility index is required to improve the accuracy of the model.

Implications of Results for Client

This project has provided SWP members with a fully parameterised and integrated process-based model for Douglas-fir. The model provides precise spatial information of Douglas-fir productivity throughout New Zealand and a range of management scenarios can be tested without the costly establishment of a large number of PSP's and silvicultural trials. $3\text{-}PGS_2$ is flexible enough to easily incorporate any improvements in data, especially accurate soil characteristics and soil fertility data.

The GIS-capable output allows SWP members to easily integrate the Douglas-fir productivity surface into existing GIS data management systems and into Google Earth. This allows productivity data to be related to locations of interest.

INTRODUCTION

Background

Douglas-fir (*Pseudotsuga menziesii*) was successfully introduced to New Zealand from the Pacific North West of the United States of America, and is considered an option for sites marginal for radiata pine (Anon, 1994).

In the home range of Douglas-fir in the Pacific North West, studies of the relationship between productivity and site have found multiple local environmental conditions that impact growth, including soil nitrogen, soil carbon to nitrogen ratios, and soil moisture storage and availability (Devine et al., 2011, Coops et al. 2012, Littke et al. 2016). The productivity of New Zealand grown Douglas-fir is higher than in the Pacific North West (Waring et al. 2008), but the primary drivers for this increased productivity is unknown. Empirical modelling of the effects of site on Douglas-fir productivity in New Zealand has been unsuccessful due to several factors, including the limited number of sites where Douglas-fir is grown, the similarity of temperatures across these sites, and the confounding effects of Swiss Needle Cast. Process-based modelling was more successful; in 2008 Richard Waring and others modelled Douglas-fir productivity across New Zealand using the process-based model known as 3-PG (physiological processes for predicting growth).

Process-based modelling involves the simulation of tree growth based on: (i) the underlying physiological processes or mechanisms that regulate tree growth on a stand basis; and (ii) the way the processes are affected by the site conditions. The resultant process-based models can then be applied to sites, ages and situations beyond the original data sets. 3-PG, originally developed by Landsberg and Waring (1997), is a canopy leaf area driven model that uses physiological growth limitations for a particular species to simulate productivity for any one site. The sensitivity of a species to site conditions (e.g. temperature, frost days, and soil properties) differs from species to species.

3-PG has been applied to a number of different species and environments throughout the world. In New Zealand, the 3-PG model has been parameterised for *Eucalyptus fastigata* model (Meason et al. 2011). It has been used to generate productivity surfaces for MyLand and FFR stakeholders (Höck 2013), and to model the potential impact of climate change on the species (Watt et al. 2012, Meason and Mason 2014)

The 3-PG parameters developed for New Zealand Douglas-fir by Waring et al. (2008) were used to model Douglas-fir spatial productivity for the Ministry for Primary Industries. The spatial productivity layers produced by 3-PG2S, the spatial version of 3-PG, were developed in 2015 as input for the Forest Investment Framework (FIF) to understand the economics of Douglas-fir plantation forestry for Southland (Harrison and Meason, 2015), and in 2017 for all of the South Island (Harrison and Meason 2017).

The 3-PG productivity surface developed for Douglas-fir in 2008 produced an adequate "first attempt" at productivity for the South Island, however the parameters developed for the 3-PG modelling had major limitations. Firstly, the Waring et al paper heavily relied on parameters of Douglas-fir grown in Oregon which may or may not be applicable to New Zealand conditions. Secondly, the 2008 Waring and others paper used data from only two New Zealand Douglas-fir sites to parameterise their model.

In addition, 3-PG has been extended into a spatial version, the 3-PGS_2 growth model, to take advantage of environmental spatial and temporal data available through geographic information systems (GIS) (Almeida et al. 2010). 3-PGS_2 facilitates large spatial modelling as it removes the need for running tens of thousands of individual point simulations.

Objective

This study addresses the limitations of earlier studies of modelling Douglas-fir spatial productivity in New Zealand. A significant number of Douglas-fir growth data exists in the Permanent Sample Plot database (PSP). These data, while not being exhaustive across all the bioclimes of New Zealand, nevertheless represent the range of sites where the species is grown in this country. The PSP data have the potential to significantly improve the parameters of the 3-PG modelling.

The study uses the Douglas-fir data from the PSP database to re-parameterise the 3-PG model, and tests the robustness and accuracy of the results of the resulting modelled productivity surface.

This report outlines how the 3-PG parameters were created from PSP plot data and the respective biophysical data (climate and soil), how the parameters were fitted statistically, and how the new productivity surface was generated. The modelled results are then compared to values based on the Waring et al approach, and validated against plot data reserved for this purpose.

METHODS

Development of input data

3-PG requires growth, climate and soil data as part of the input data. This data needed to cover the different growing environments where Douglas-fir is found in New Zealand, to calibrate the model to fit all these different regions. Developing the best fit to as comprehensive a coverage of environments as possible ensures the soundest productivity modelling across the country.

Douglas-fir PSP data

The PSP database was analysed for Douglas-fir plots that have five or more measurements over a rotation. Priority was given for plots with more than one PSP measurement at any given location, and if a set of PSPs were part of a thinning trial. From this initial screening, 551 PSPs were identified. Permission was requested from the landowners and/or forest managers for the use of their data for this project. Permissions given resulted in 465 PSPs being available for this project.

Climate data

Actual climate data across the lifetime of the PSP plots replaced the previous modelling based on annual averages. NIWA's Virtual Climate Station (VCS) Network provides daily climate data on a regular (~5km) grid covering the whole of New Zealand (Cichota et al. 2008). The climate estimates are spatially interpolated from data observations made at climate stations located around the country, with the interpolation process incorporating local factors. As many forestry plots are in remote locations, this interpolation provides climate data that tends to be more accurate locally than distant weather station data.

The VCS nearest the Douglas-fir plots were selected. For each year relevant to the plot measurements, the daily data were converted to monthly values for: total rainfall for each month, maximum and minimum air temperature in a month, average monthly solar radiation, and number of frost days in the month.

Selection of 3-PG calibration sites

PSP plots were used to calibrate the 3-PG parameters. The plots needed to be representative of the range of known Douglas-fir growth responses in New Zealand, without over-emphasising areas where, for example, a field trial meant many measurements were available across a single environmental gradient. Hence a detailed methodology was followed.

The first step in the selection process grouped the Douglas-fir PSPs to their nearest VCS. Thirty-two groups (the 'VCS-groups') were found, with each group comprising one or more PSPs and multiple measurements per PSP. This step provided comprehensive coverage of different Douglas-fir climate conditions across New Zealand.

In order to select plots that were most representative of Douglas-fir growth across different silvicultural regimes, the stems per hectare (SPH) were plotted against basal area per hectare (BA) for each of VCS-groups. An example graph is given in Figure 1 showing different stockings and no thinnings. In the graph, the measurements over time at the same plot are linked; these sets of measurements are, for convenience, called a plot measurement set. The graphs indicated where similar, even identical, plot measurement sets occurred in a VCS-group. For example, replica plots in a trial may have the same SPH and very similar BA increments; these show as a 'black line' in the graph. For such duplications, a single set of plot measurements was considered sufficient to represent that SPH-BA relationship in the modelling of that location.

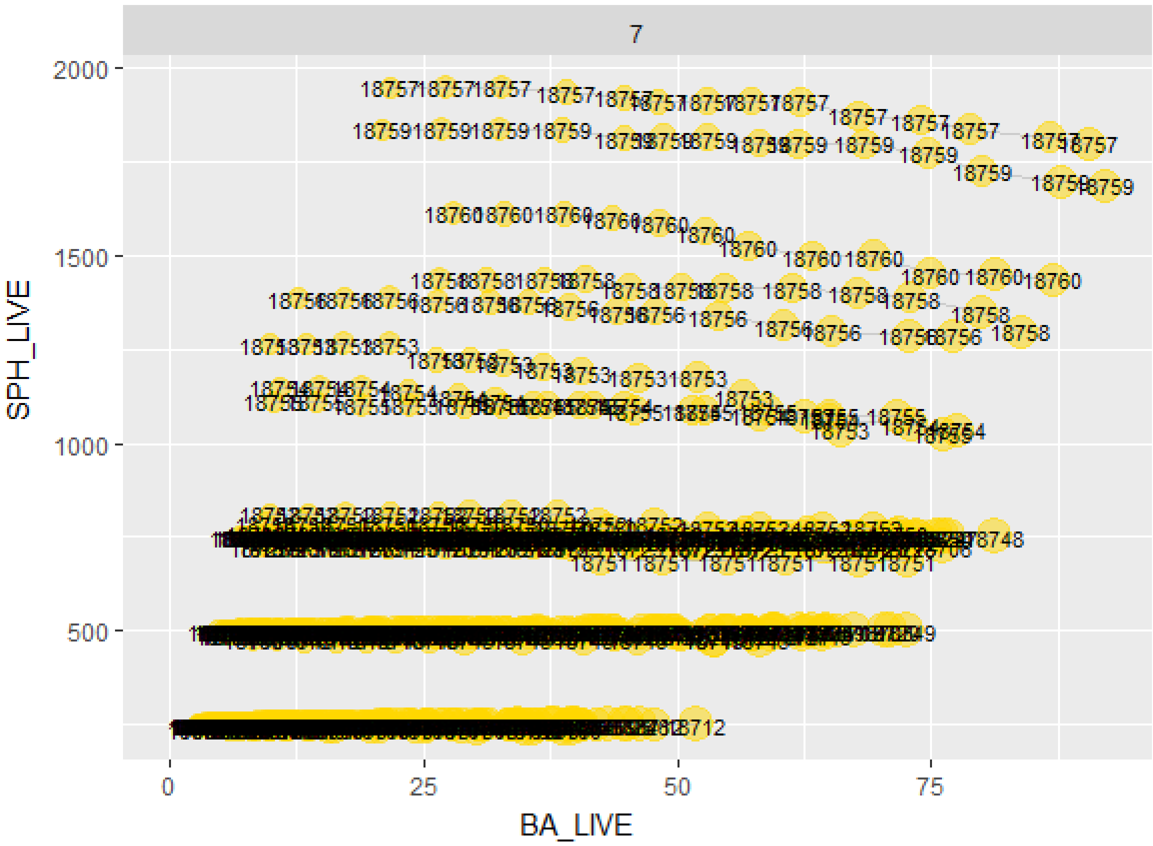

Figure 1. Example group (group 7) of plot measurements all in the vicinity of one NIWA virtual climate station (VCS), with a line linking the repeat measurements per individual plot for a stand of trees without thinning. The numbers are the plot identifier. There is a decline in stems per hectare (SPH_LIVE) for the higher stockings, likely through tree mortality. (BA_LIVE = basal area).

Plot measurement sets in a VCS-group with different SPH, or that showed the effects of thinnings (visible as larger changes in BA), provided Douglas-fir growth data for different silvicultural regimes at that the same location. The selection of plot measurement sets within each VCS-group aimed to get plot measurements that represented high, mid-range / median, and low stockings, particularly for regimes that also included thinnings. When there were insufficient plot measurement sets in a group, or the differences in measurements were insignificant, then less plots were selected. Where plots in one group were known to also be representative of other site factors, e.g. Douglas-fir planted over steep differences in elevation such as for Craigieburn Forest, then plot across this range were also selected.

The results of the selection process were checked for their geographical range. Where the approach had resulted in a selection that did not adequately cover the local environmental gradient, more plots were added. For example, additional plots were added to more fully capture the coast to mountain gradient in the Nelson area.

From the resulting options we selected 32 calibration sites across the groups (Figure 2). This selection of calibration sites ensured sites across the climate conditions (23 locations) while still retaining differences in regimes at some of the sites, where these were available (9 of the sites had different regimes). This left sites available for validation.

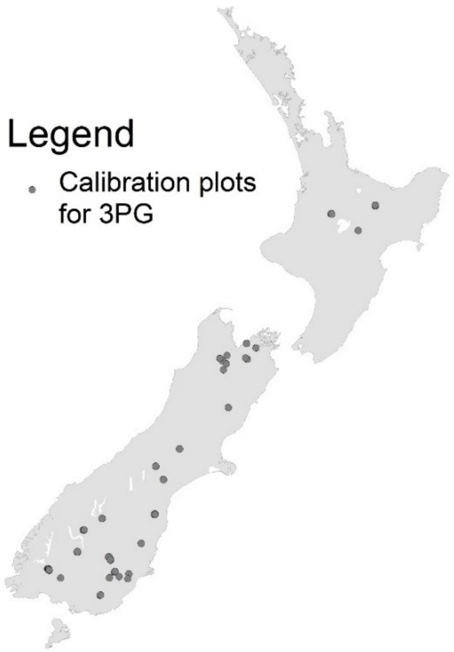

Figure 2. Calibration and validation site distribution for 3-PG Douglas-fir modelling, based on PSP plots selected to represent different regimes and climate conditions across New Zealand

Soil texture data

Soil data were taken from Landcare Research's New Zealand Fundamental Soil Layer (FSL) textural classification map with a 100 m resolution (Newsome et al. 2008). The classification is based on the interpretation of soil surveys from the 1:63,360/1:50,000 scale New Zealand Land Resource Inventory, either from reference to analytical results stored in the national soils database or as professional estimates by pedologists' acknowledged as authorities in the soils of the region in question (Newsome et al. 2008). Soil textural classes for each soil unit were based on earlier research (Webb and Wilson 1995).

Plant available soil water / Available soil water storage

Plant available soil water (PAW), known as available soil water storage (ASW) in Waring et al. (2008), was modelled based on climate data and the FSL (as developed in Palmer et al. 2009).

Preparation of spatial data

The raster layers were snapped to each other before geoprocessing. The resolution of the grid data for soil texture and PAW was 500m.

Allometric equations

Warring et al. (2008) derived coefficients for power functions to estimate stem mass, foliage mass, and tree height, from diameter at breast height (DBH). Equations were updated based on data collected by Beets and Oliver (2011) and were fitted to the new data on stem mass, foliage mass, height and DBH using Reduced Major Axis Regression (Seim and Saether, 1983).

Wood density

Data on wood density for Douglas-fir ages 2-40 was assembled from Kennedy (2011a, 2011b), Oliver et al. 2011, and Beets and Oliver (2011). The coefficients for the power functions for wood density based on tree age were developed by fitting the data using Ordinary Least Squares.

3-PGS$_2$ model input data

Three sets of spatial data were required to run 3-PGS$_2$ (Meason and Mason 2014); latitude for day length and sun angle, climatic data, and soil data for soil water balance and fertility subroutines. Latitude of each case study area was averaged to the nearest half-degree. The three grid datasets were at a 5,000-m resolution. The raster grid files were converted into float files before being uploaded to the model.

RESULTS

Model parameterisation

A total of 32 sites from 23 locations were used to calibrate the model for New Zealand grown Douglas-fir. The calibration dataset had a total of 228 observations. Allometric equations developed for stem and foliage biomass, as well as the wood density age function were used as part of the 3-PG model parameterisation process. As far as we are aware, there is no stand level leaf area index (LAI), needle specific leaf area, or needle retention data for these sites, and collection of this data is beyond the scope of this project. Thus, we used the canopy and foliage parameters from Waring et al. (2008). Without independent foliage and LAI data from New Zealand grown Douglas-fir, it was not possible to objectively adjust the parameters further. The model's site fertility modifier was set as a constant of 0.6 for most sites, unless there was a large difference between modelled and actual growth that could be explained only by site fertility. Three of the 30 plots had the fertility modifier adjusted.

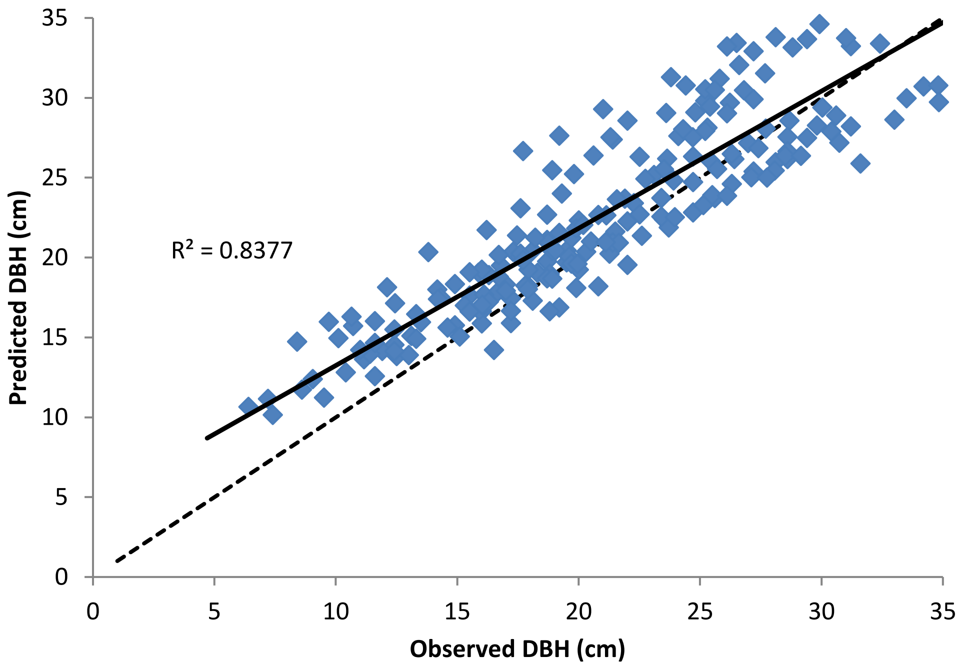

Figure 3. Observed Douglas-fir mean stand diameter at breast height (DBH) verses modelled DBH for the calibration dataset with the 1:1 line (dotted) and fitted linear regression line to the data (solid line) plotted

Overall, the parameterised 3-PG model over predicted mean stand diameter at breast height (DBH) growth by 10% (Figure 3). The model over predicted growth early in the rotation, typically less than 15 years-old, which is represented as the smaller DBH's in Figure 3. For older stands, the model's fitted improved with modelled DBH closer to the 1:1 line (Figure 3). For stands 20 years and older or with a DBH > 28 cm, the model over parameterised the calibration dataset by 4%. Thus, the parameterised 3-PG model was able to provide a more accurate model of stand growth in the latter half of the rotation. Hence the parameterised model provides a good indication of Douglas-fir productivity at the end of a 40 year rotation.

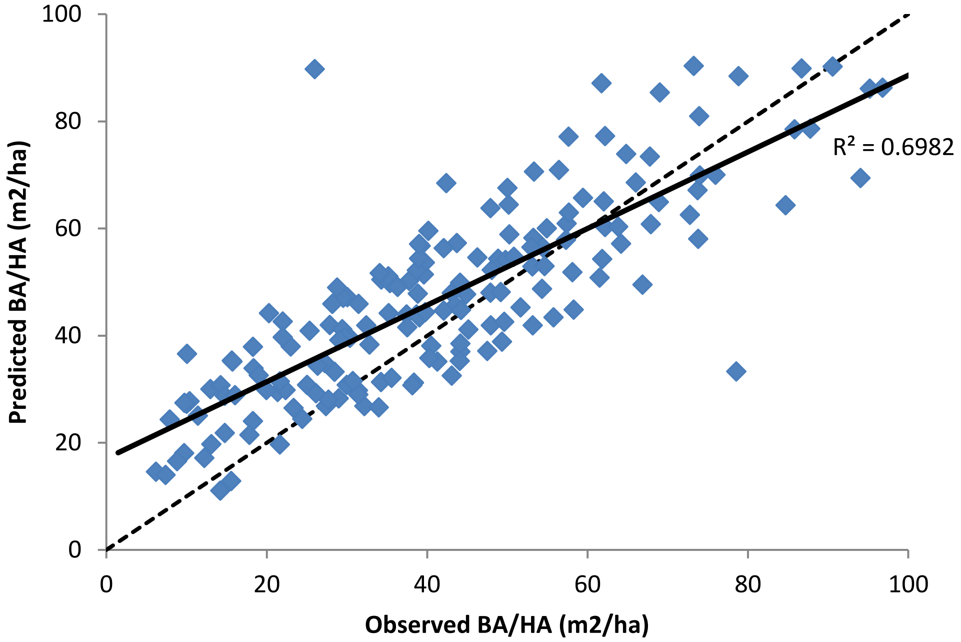

Figure 4. Observed Douglas-fir total stand basal area per hectare (BA/HA) verses modelled BA/HA for the calibration dataset with the 1:1 line (dotted) and fitted linear regression line to the data (solid line) plotted

The goodness of fit for the calibration dataset was the best for mean DBH with fitted linear regression of R^2 = 0.84 (Figure 3). The fitted model parameters explained less of the variability for basal area per hectare (BA/HA) with a R^2 = 0.70 (Figure 4). The model over predicted BA/HA for the calibrated dataset by 12.1%. The fitted linear regression for calibration dataset total stand volume had a better R^2 value than BA/HA with a value of 0.74 (Figure 5). Overall the model over predicted stand volume by 61.6%, however, this average was skewed by a handful of outliers (Figure 5). The model over predicted stand volume for values less than 600 m^3 ha^{-1} while it under predicted stand volume above this value (Figure 5).

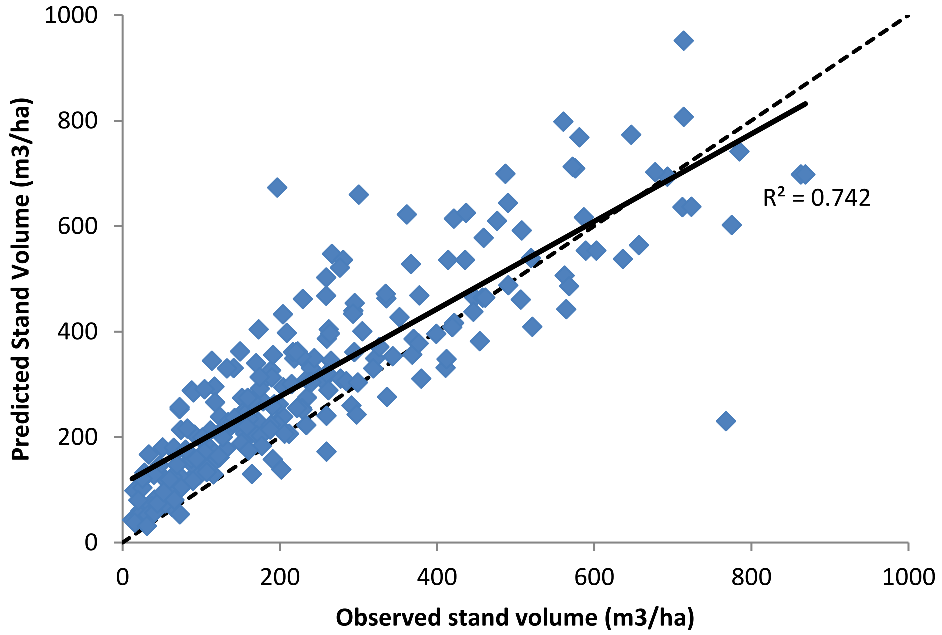

Figure 5. Observed Douglas-fir total stand stem volume per hectare verses modelled stand stem volume for the calibration dataset with the 1:1 line (dotted) and fitted linear regression line to the data (solid line) plotted

Comparison between parameterised models

The parameterised model was tested with an independent validation dataset consisting of 168 observations from 25 locations that were located across the country. The parameterised model's goodness of fit was compared to the parameterised 3-PG model used by Waring et al. (2008). Both models used a constant fertility modifier of 0.6. Scion's parameterised model over predicted mean stand DBH by 37.8% and for stands greater than 20 years old the model over predicted by 10.3% (Figure 6). Conversely, Waring et al. (2008) parameterised model over predicted mean stand DBH by 61.4% and for stands greater than 20 years old the model over predicted by 27.2% (Figure 6).

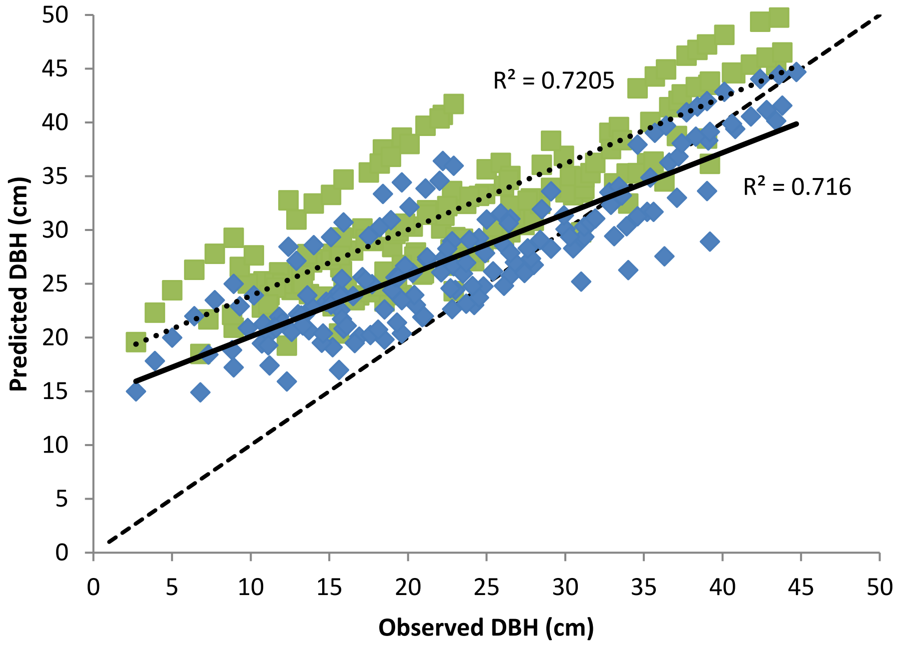

Figure 6. Observed Douglas-fir mean stand diameter at breast height (DBH) verses modelled DBH for the validation dataset using Scion's fitted parameters (blue diamonds) and fitted linear regression line (solid line) and Waring et al. (2008) fitted parameters (green squares) and fitted linear regression line (dotted line). The 1:1 line is represented by a dashed line.

Both models over-predicted the productivity of the validation dataset. However, Scion's parameters produced a more accurate model for larger trees that would be found in older stands. The slope of the fitted linear regressions for both models are similar (Figure 6). This suggests that Scion's parameterised model is a modest, yet significant improvement to the Waring and others model. Several reasons for this include limited information on actual site conditions, the use of constant fertility modifier across all sites, no information on stand LAI, limited or no information on stand history for most sites, and the potential impact on productivity of Swiss Needle Cast.

Both models performed poorly for two of the 25 validation sites, with the Scion model over predicting mean DBH by 174%. The large scatter of observed verses predicted total basal area per hectare (BA/HA) and low R^2 values for both models shows that is one or more unknown site characteristics impacting productivity that is not explained by the model (Figure 7). However, the Scion model performed a lot better for total stand volume with the individual points and fitted linear regression line a lot closer to the 1:1 line than the Waring and others model (Figure 8). The weak performance of the Scion model could be caused by a number of factors that need to be investigated further, however the large discrepancy could be from the impact of Swiss Needle Cast or some other pathogen. If the two poorly modelled sites were removed from the validation dataset, then the Scion model would be reduced. For mean DBH, the over prediction would reduce from 22.6%, and 3.9% for stands greater than 20 years old.

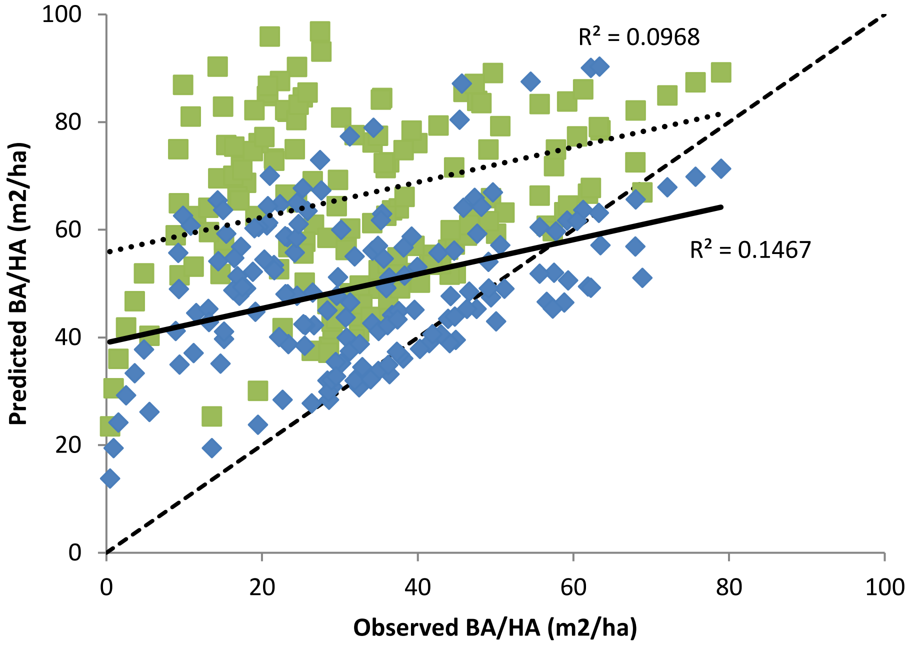

Figure 7. Observed Douglas-fir total stand basal area per hectare (BA/HA) verses modelled BA/HA for the validation dataset using Scion's fitted parameters (blue diamonds) and fitted linear regression line (solid line) and Waring et al. (2008) fitted parameters (green squares) and fitted linear regression line (dotted line). The 1:1 line is represented by a dashed line.

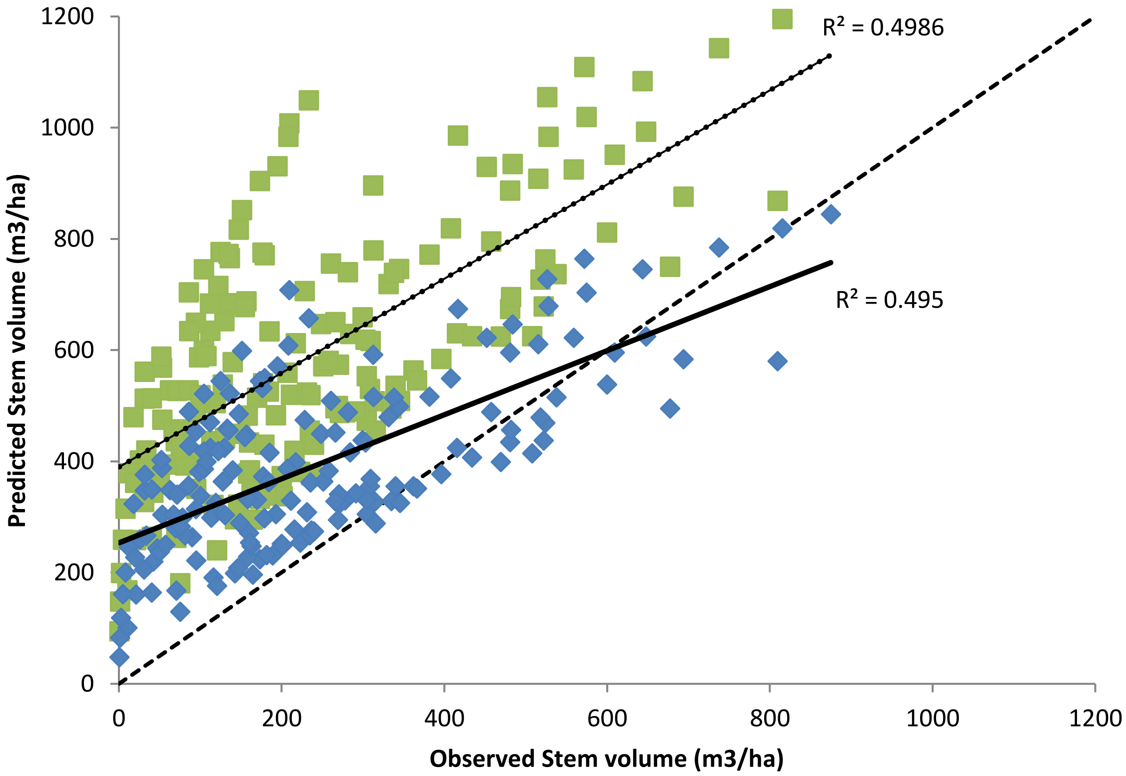

Figure 8. Observed Douglas-fir total stand volume per hectare verses modelled total stand volume per hectare for the validation dataset using Scion's fitted parameters (blue diamonds) and fitted linear regression line (solid line) and Waring et al. (2008) fitted parameters (green squares) and fitted linear regression line (dotted line). The 1:1 line is represented by a dashed line.

Despite the over prediction of most sites, Scion's parameterised model did simulate well the effects of climate and site on the rate of productivity over a range of different sites. Although a constant fertility modifier was used, it was clear from the calibration and validation datasets that some sites were more fertile than others and Douglas-fir's growth did respond to these conditions. This strongly indicates that like Douglas-fir grown in North America, New Zealand grown Douglas-fir is sensitive to site and climate conditions. This result also supports the finding that the newly parameterised model is a significant improvement in modelling productivity spatially, as previous research with empirical models have found no relationship between Douglas-fir productivity and site conditions More research is needed to quantify these sensitivities and to quantify the gap between potential site productivity and actual site productivity. An important component of any future research is the development of a spatial site fertility index for Douglas-fir that independently classifies soil fertility for the species throughout the country. This would remove a potential bias with the 3-PG model of adjusting the fertility modifier to get the model to fit the observed data.

Productivity Surface

Once the model was parameterised and validated, the 3-PGS$_2$ model was used to generate a spatial productivity surface for a sawlog regime (Figure 9) planted at 1667 stems per hectare, thinned to waste to 500 SPH at age 14, and harvested at age 45. A mean annual temperature mask of 9^{o}C was placed on the input dataset to remove high elevation areas from the analysis as these areas would likely be above the tree line. This is represented as white areas in the figures below. For each regime scenario, a total of 815,495 individual, site specific volume yields were generated at a 500m resolution. Over the entire country at age 45 the sawlog regime had an average yield of 33 m^3 ha^{-1} yr^{-1}, with a minimum yield of 25 m^3 ha^{-1} yr^{-1} and the maximum yield was 38 m^3 ha^{-1} yr^{-1} (Figure 9). It is likely that the model is over estimating the growth of the low productivity areas. Douglas-fir is the most productive in the South Island in the Nelson/Marlborough and Southern Canterbury regions and in the North Island in the Taranaki and northern Gisborne regions (Figure 9).

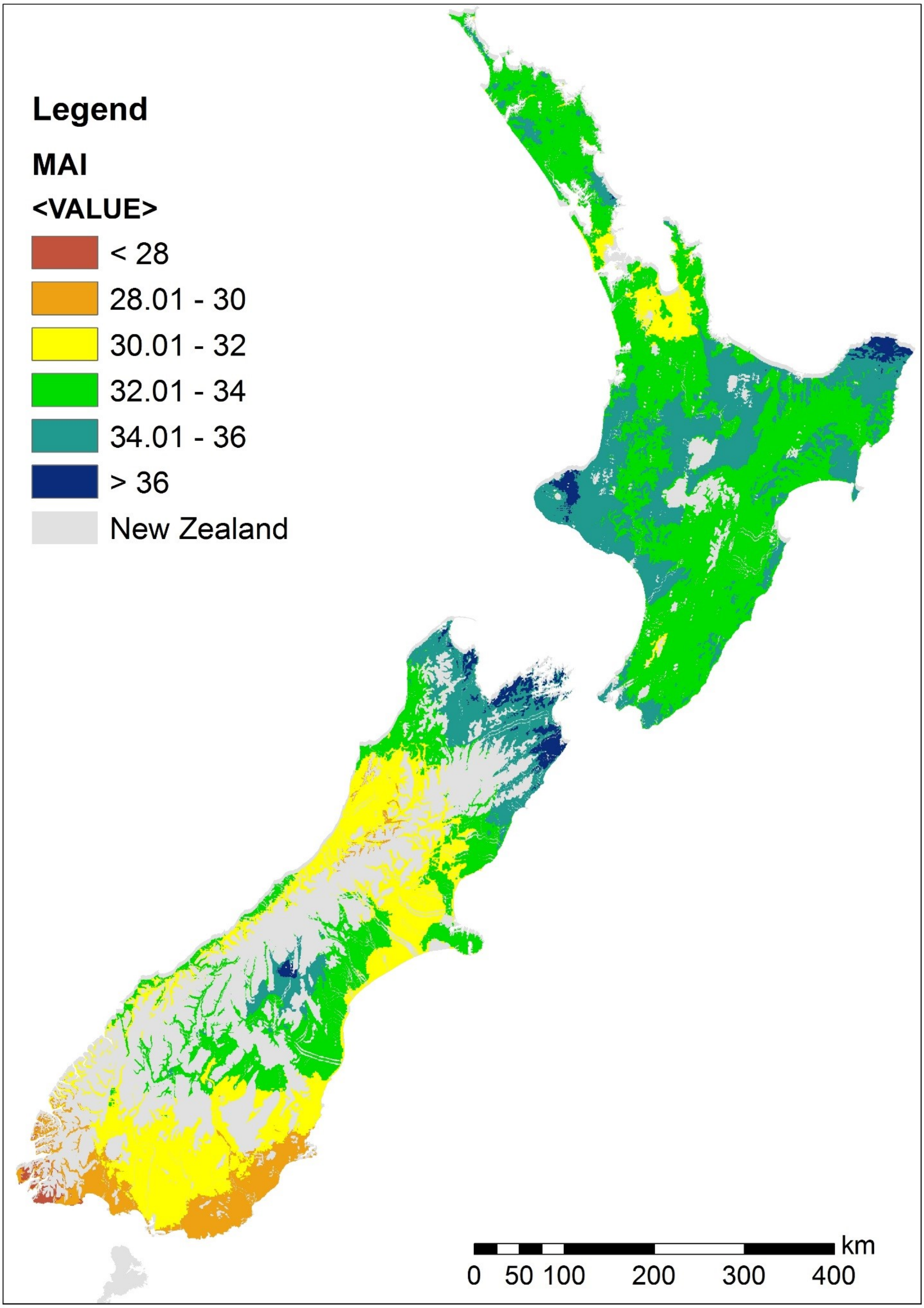

Figure 9: Spatial map of Douglas-fir mean annual increment (MAI) volume growth per hectare per year at age 45 modelled by $3PGS_2$ under a sawlog regime planted at 1667 stems per hectare (SPH) and thinned at age 14 to 500 SPH.

SUMMARY AND CONCLUSION

The 3-PG model was successfully parameterised for New Zealand grown Douglas-fir. The calibration and validation process demonstrated that Douglas-fir is sensitive to site and climatic conditions. Thus, this study is a big step forward in understanding the effects of site conditions on Douglas-fir productivity. The Scion parameterised 3PG model was a large improvement to the Waring et al. (2008) model, however the Scion model over predicted growth for the validation dataset. The spatial productivity surface provides for the first time a non-bias productivity map for Douglas-fir throughout New Zealand without the confounding effects of Swiss Needle Cast on productivity. More research is required to improve the parameterised model, including the measurement of canopy characteristics, identification of the severity of Swiss Needle Cast on existing sites, and developing an independent measure of site fertility for Douglas-fir.

This study has produced a spatial productivity map for SWP members in a GIS-capable format, a high resolution PDF map, and a file format that can be imported into Google Earth.

ACKNOWLEDGEMENTS

We would like to thank Carolyn Andersen and Christine Dodunski for providing the Douglas-fir PSP data and stand history information in the format required for the modelling in this report. We would like to acknowledge and thank the landowners who generously gave permission for us to use their PSP(s) data for this study.

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