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Preliminary Parameterisation of the Hybrid Model 3-PG for *Eucalyptus fastigata* in New Zealand

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EXECUTIVE SUMMARY

Eucalyptus fastigata is a fast growing species that is disease resistant and can tolerate a wide range of New Zealand environments. It has high potential as a plantation species for pulp and paper, timber, and for carbon forestry. However, not enough permanent sample plots (PSPs) exist to develop a robust empirical growth and yield model for the entire country. Process-based modelling is an alternative physiological based approach that requires fewer data to model stand growth accurately. The process-based model 3-PG$_2$S (physiological processes for predicting growth spatially), was parameterised for *E. fastigata* for New Zealand conditions, and then validated. The model was used to simulate a series of management scenarios for decision makers to assess the suitability of this species throughout New Zealand.

This project is part of Objective Three; Implementing designed production systems, Task 3.01.2.11. The primary objective of this project is to provide FFR members with a model that integrates process-based information that is parameterised for *E. fastigata* in New Zealand. This is to provide industry with more precise information as to where *E. fastigata* can be successfully grown and managed.

Key Results

1. Climate data from NIWA and soils data from Landcare were modified and successfully integrated into the model.
2. 3PG$_2$S was successfully parameterised using data from 38 plots from seven sites throughout the country, with an average error of 14% across these sites.
3. The soil fertility growth modifier was kept at a constant value due to a lack of data. However, fertility varied between sites and this was probably the primary reason for differences in growth between simulated and actual growth data. Future research will define fertility effects and integrate them into the model.
4. The accuracy of the model below 500 m^2 cell size is limited due to a lack of precise information on soil characteristics and soil depth. Due to the lack of soils information for some areas of New Zealand, notably the East Coast, it is recommended that a larger cell size be used to average model output.
5. A series of carbon forestry and timber management scenarios was successfully generated with 3PG$_2$S. The output is in a raster format that is ArcGIS (Environmental Systems Research Institute Inc., Redlands California, USA) capable. Industry can interrogate the output to a 500 m^2 scale spatially and compare results with those of other geographic information systems (GIS) datasets. Decision makers can use this output to assess the productivity of *E. fastigata* throughout New Zealand and the potential of the tested management scenarios for carbon forestry and a timber regime.

This project has provided FFR members with a fully parameterised and integrated process-based model for *E. fastigata*. The model provides precise spatial information of *E. fastigata* productivity throughout New Zealand, and a range of management scenarios can be tested without the costly establishment of a large number of PSPs and silvicultural trials. The GIS-capable output allows members to integrate this information easily into existing GIS data management systems. 3PG$_2$S is flexible enough to incorporate any improvements in data easily, especially accurate soil characteristics and soil fertility data. The effects of climate change scenarios on *E. fastigata* productivity will be tested as part of a MAF contract in the next six months and will be available to FFR members. The two major components of this project were the establishment of sampling protocols for model parameterisation, and the modification and testing of climate and soils input data layers. With these components in place, any future work with 3PG$_2$S for modelling other species would be simpler and more streamlined.

INTRODUCTION

Mathematical models are used in forestry to predict stand growth and yield. These models are typically statistically-derived and known as empirical-based models [1,2]. Data for empirical-based models for a species are collected from permanent sample plots (PSPs) located over the range of sites and stand ages. Although empirical-based models are normally more than adequate, their accuracy is limited to the species and site conditions for which they were originally developed [3]. Such models cannot simulate the growth and yield in changing environmental or management conditions [4,5]. If a species was not previously considered as a commercial species, it can be time consuming and expensive to develop a PSP system.

Eucalyptus fastigata (Deane and Maiden; brown barrel) was successfully introduced to New Zealand and can tolerate a wide range of New Zealand environments and is resistant to pathogens that afflict other eucalypts. The species has been identified by Scion as fast growing, with multiple uses including pulp and paper, timber production, and carbon sequestration. A limited number of PSPs (22) was established for *E. fastigata*, concentrated in the Central North Island. These 22 existing PSP sites are simply not enough to develop a robust empirically-based model for the species.

An alternative approach is required to assess the suitability of *E. fastigata* for a particular site, and to assess management options.

Process-based modelling is an alternative approach to empirical-based modelling. This approach involves the simulation of growth by the underlying physiological processes or mechanisms that regulate tree growth on a stand basis, and the way the processes are affected by the site conditions. This allows process-based models to be applied to sites, ages and situations beyond the original data sets.

3-PG (physiological processes for predicting growth), is a process-based model developed by Landsberg and Waring [6]. It was designed to be more practical than other process-based models by using a combination of physiological principles and empirical data to simplify model parameterisation. Although 3-PG is most commonly used for eucalypts, it is neither species, site nor age specific [7]. The model has been widely used in Australia, but it has also been used to model various species in other countries including United Kingdom, Scandinavia, Portugal, South-eastern and North-western United States of America, Brazil, South Africa, and China [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. In addition to eucalyptus, the above studies parameterised 3-PG for other species, including *Pinus taeda*, *P. abies, P. radiata, P. ponderosa, P. patula, P. sylvestris, Picea sitchensis*, and *Pseudotsuga menziesii*.

The latest version of the model, 3-PG_2 spatial (3-PG_2S), includes a number of improvements on earlier versions. This includes the simulation of the forest's water balance; that is water entering, leaving and being stored in the system. Water movement in soil discriminates between water in the "root zone" and "non-root zone" of the soil profile [19]. The ability of the model to simulate stand growth spatially gives the user information of productivity of a species across the landscape. This removes the need for running thousands of individual "point" models, then combining individual outputs into a map. The output from 3-PG_2S is in a format that can be used directly in ArcGIS software (Version 9.2 and later, ESRI). This gives the user the ability to combine the model's output with other georeferenced data and maps. 3-PG_2S can be used to test for any location, the suitability of a species, productivity of different stockings and management regimes, carbon sequestration potential, and the effects of climate change.

This study has the following objectives:
1) calibrate *E. fastigata* for New Zealand conditions,
2) collect and develop appropriate site and data for inputs for the model,
3) validate the model, and

4) generate for FFR members geographic information systems (GIS), compatible productivity maps for a range of management scenarios.

METHODS

There were three phases in model development:

- Collection, verification, and modification of spatial input layers.
- Model parameterisation from field measurements and calibration.
- Development of model management scenarios.

Spatial Input Layers

3-PG$_2$S requires climate and soil data in a spatial format as input. This provides site data to simulate tree growth throughout the country without relying on data for each individual site. The monthly climate data required by the model is mean daily maximum and minimum temperature (^{o}C), rainfall (mm), number of rain days (days per month), solar radiation (megajoules per square metre per day), and number of frost days (days per month). These data were provided by National Institute of Water and Atmospheric Research (NIWA) on a 500 m raster grid. Soil type data was modified from Landcare Research's fundamental soil layer particle size classification map to a format appropriate for 3-PG$_2$ on a 500 m raster grid. Optional spatial input layers included latitude (to adjust for daylength) and soil fertility modifier. A 500 m latitude raster grid at 0.2 degree increments was developed as a spatial layer. All layers were masked with a mean annual temperature layer of less than 8^{o}C. This removed mountainous areas of New Zealand that would be too cold to grow most commercial tree species, and improved model processing time by removing areas that would not be considered for *E. fastigata* stands. Soil fertility spatial layer was not developed due to a lack of information (see results below). Soil fertility modifier was set to 0.6 for all soil types throughout the country. All raster layers were snapped to the soil spatial layer before geoprocessing. All raster grid files were converted into float files before being uploaded to the model.

Datasets

Thirty eight plots from seven PSP and non-PSP sites were selected from sites measured in an earlier *E. fastigata* study [(20)]. The selected sites had to provide the greatest range of sites and site productivity, as well as a high number of measurements at each site. Seven sites were used to calibrate the model (Table 1).

Table 1: Site descriptions of *E. fastigata* stands used for the calibration set

Site	Region	Plots	Initial Stocking (SPH)	Thinned?	Measurement Ages
Karaka	Northland	9	1100	Age 9, 700 SPH	9, 21, 22
RossD	East Coast	2	1100	Age 8, 345 SPH	10 - 13
Kapenga	Waikato	7	1270	No	8 - 9
Waerenga	BOP	3	625	No	9, 10, 11, 13
	BOP	3	833	No	9, 10, 11, 13
	BOP	3	1111	No	9, 10, 11, 13
	BOP	3	1667	No	9, 10, 11, 13
	BOP	3	2500	No	9, 10, 11, 13
Omataroa	BOP	2	1100	No	11, 13, 14, 17
Drummond	Nelson - Marlbourgh	2	1100	Multiple	13 - 25
Milligan	Southland	1	1100	Age 4, 750 SPH	10, 13

Model Parameterisation

Data for model parameterisation were collected from various PSP and non-PSP sites. Further adjustments were made to the model with the calibration dataset. A full list of 3-PG_2S parameters for *E. fastigata* is provided in Appendix A. Biomass allocation was provided from allometric harvests of above- and below-ground biomass at Kapenga and Kaingaroa [(21)]. Fully stocked plots from Waerenga, Karaka, Kapenga and Omataroa, and other sites were used to develop a self-thinning line and mortality parameters. It was assumed that the slope of the self thinning line was similar for younger (ages 9 -13) and older stands (ages 21-24). 3-PG_2S uses cumulative tree biomass and stocking to identify when self-thinning begins. The slope of biomass per tree vs. stocking was 2.39 (Appendix B), but due to the limitations of the mortality module, a steeper value (4) had to be used (see results section below). Waerenga was used to develop parameters for general tree mortality.

The age where stand leaf area peaks was identified from measurements from seven sites including Karaka, Kapenga, Waerenga, and Tolaga Bay. Stand leaf area was found to increase rapidly after establishment until reaching a peak of 5.5 m^2 per m^2 at age nine (Appendix C). Then leaf area steadily declined with increasing age. The rate of forest canopy turnover and litterfall rates were determined with two-monthly measurements at Kapenga. These measurements were used to parameterise litterfall and root turnover variables (Appendix A). Specific leaf area was determined from leaf collections from five locations including Kapenga, Waerenga, and Tolaga Bay. Specific leaf area was found to be 7.5 cm^2 per gram with little difference with stand age and stocking.

Temperature modifiers of growth were based on earlier studies with *E. fastigata* and other *Eucalyptus* species. Frost and fertility modifiers of growth were based on adjusting these variables to fit the calibration data set.

Model Management Scenarios

3-PG_2S was used to generate two management scenarios for the country;

1. Carbon forest regime. With initial stockings of 1111, 1667, 2000, and 2500 stems per hectare.
2. Carbon forest regime with one thinning at age 15. Initial stockings of 1667, 2000, and 2500 stems per hectare.
3. Timber regime with three thinnings. Initial stocking of 1111 stems per hectare. Thinning at age nine to 700 stems per hectare, age 15 to 500 stems per hectare, and age 25 to 350 stems per hectare.

ArcGIS-compatible stand volume and mean annual increment maps were generated for each management scenario at ages 10, 15, 20, 25, 30m and 40.

RESULTS

Mortality

The 3-PG_2S model poorly predicted tree mortality. The mortality module is a basic module that either assumes mortality at a constant percentage over the lifetime of the stand, or applies a self-thinning rule when the stand reaches the biomass threshold at 1000 stems per hectare. Although the parameters of the constant mortality function and self thinning rule can be quite ready defined, the rest of the thinning module is inflexible. Thus, 3-PG_2S does not completely capture the dynamics of intraspecific competition after canopy closure. But 3-PG_2S does well in simulating self-thinning when initial stocking is either above 1500 stems per hectare or below 800 stems per hectare. It underestimates self-thinning between these two stockings from canopy closure to approximately age 15. Data from the Waerenga site appears to indicate that 3-PG_2S adequately simulates stand volume for these stockings after this age. Thus, 3-PG_2S's mortality model performed adequately over the length of the rotation.

The self-thinning dynamics of *E. fastigata* have been analysed for this project (Appendix D) by Chikumbo and Nicholas [(22)], and earlier studies [(23,24)]. There are enough data to develop self-thinning equations suitable for this species, but that would require the development of a new mortality module. We will discuss the feasibility of such a redevelopment with CSIRO.

Fertility Growth Modifier

The fertility modifier for 3-PG_2S is a linear function from zero (completely infertile) to one (highly fertile). The more fertile the site, the faster the growth rate. Using the calibration dataset to adjust growth rate that could not be explained by climate or soil characteristics, the fertility modifier was set for 0.6 for the entire country. Although the fertility modifier value appeared to reflect average stand growth adequately across the calibration data set, it is likely that stand soil fertility varied between sites. Previous research [(20)] clearly showed that *E. fastigata* site productivity was influenced by extractable phosphorus and soil order. These characteristics are likely to influence site productivity throughout New Zealand, even for ex-pasture sites with low carbon to nitrogen (C:N) ratios. However, the number of sites used for that study was limited and did not cover the range of sites that would be suitable for *E. fastigata* forestry. Keeping the fertility modifier constant removes bias by arbitrarily adjusting this variable to fit the growth of individual sites.

More site soil fertility and site productivity data would be required to develop a national soil fertility map for 3-PG_2S. A bid has been submitted to MAF's sustainable land management and climate change fund to develop such a map. If successful, research would be begin in August 2011 and the results would be made available to FFR members and incorporated into 3-PG_2S.

Frost Days Growth Modifier

Frost can have a number of direct and indirect effects on tree growth. This can include physical damage to certain cells within the leaf limiting photosynthesis, the entire leaf is irreversibly damaged, or there is a reduction in water uptake due to low temperature at the root zone – which restricts photosynthesis. Frost damage can be immediate or cumulative and has a far greater effect on plant tissue if it occurs out of season. 3-PG distils the complex impacts of frost on tree growth into a simple growth modifier. The modifier is a linear function of the proportion of growth lost per day when a frost event occurs. The higher the number of frost days, the greater the cumulative number of growth days lost for the tree for each year. Thus, if two sites have similar temperature and precipitation, the site with more frost days would be less productive. For *E. fastigata*, the frost days growth modifier was set was set to 0.5 for the entire country. The frost modifier does not take into account the severity of frosts, or the impact of out-of-season frosts. Despite these limitations, the modifier did an appropriate growth penalty to *E. fastigata* for areas that are frost prone. Thus, 3-PG_2S can provide a strong indicator of areas where *E. fastigata's* growth is inhibited due to the high frequency of frosts.

Resolution

The resolution of the output of 3-PG_2S is restricted by the 500 m^2 grid size of the raster climate layers. Thus the resolution of the output is five hectares. Due to the complex interactions of the multiple input layers, the productivity of *E. fastigata* between adjacent grids can be large. Figure 1 illustrates this for the output at age 30 for a carbon forest regime with an initial planting of 1667 stems per hectare with no thinning. At the New Zealand-wide scale, the output looks coarse. However, when it the map is zoomed to a fine resolution, the differences in values become apparent even at the finest resolution (Figure 1). The model does not take into account the steepness of the terrain, aspect, or wind exposure. The individual grid outputs can be averaged to provide an assessment of the potential *E. fastigata* productivity from a compartment, a forest, or an entire region.

It is possible to have a finer resolution for simulated productivity, but that is dependent on the input data. Additional data required would include microsite effects that are more likely to influence productivity at a finer resolution. For example the slope of a hillside and the proximity of adjacent hillsides can affect solar radiation exposure, soil water storage, and soil fertility. Moreover, the accuracy of some of the data at a 500 m^2 grid is limited. The model's soil water module requires detailed information on the soil drainage characteristics and soil depth. This information is generally lacking for soils on land that is forested, or is suitable for forestry, because soil surveys in these areas are typically not intensive. Indeed, spatial soil layers for the Gisborne Region are not publicly available. The Landcare soils layer used in this model should be treated as an indication of soil water storage capacity of the dominant soil particle size of the area, not as an accurate model of soil water dynamics. For sites with poor soil characteristics and soil depth data (i.e., the Gisborne region), it is recommended that the 500 m^2 raster output is averaged to at least 1,000 m^2 grid size. That is, the model output for productivity should be averaged from four 500 m^2 raster grids.

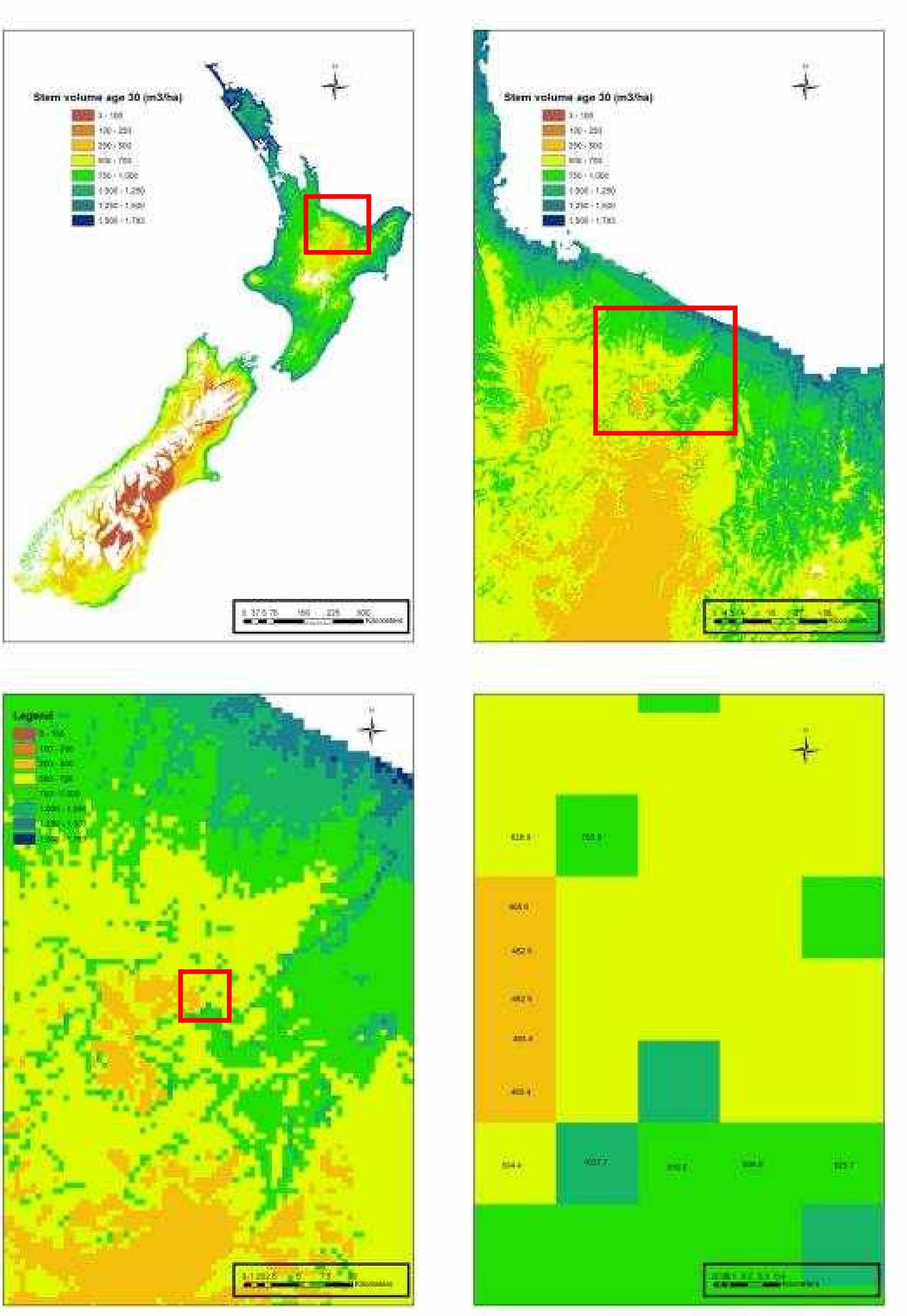

Figure 1: Example of $3PG_2S$ output for a carbon forest regime at initial stocking of 1667 stems per hectare from coarse to fine resolution. Cell stem volume is in cubic metres per hectare.

Calibration

Overall, $3PG_2S$ performed very well with the calibration data. The model was able to simulate growth for all but three calibration sites to 10% of actual volume (Table 2). The model struggled for three sites, Waerenga at 625 stems per hectare initial stocking, RossD, and Milligan. The model had probably over-estimated volume at the Waerenga site due to an underestimation of mortality for the lowly-stocked stand. The model performed well for all the other stockings for the same site. Thus, the climate and soil parameters performed well. For RossD, the overestimation of volume was probably due to the site's low soil fertility. All simulations used the same fertility modifier of 0.6. Thus, $3PG_2S$ would overestimate less fertile sites and underestimate growth in more fertile sites. When fertility was assumed to decline, the simulated volumes were similar to the actual volumes; 136 m^3/ha (+5%) at age 10 and 195 at age 13 (+4%). To avoid bias, further work is required to develop a fertility measurement independently for *Eucalyptus* plantings. Once developed, it would be simple to add this to the model. There was only one plot at Milligan, and other PSPs exist in Southland. Thus, it is difficult to determine if the low measured volume is due to microsite effects, a less fertile site, or if the site is colder than the temperature or frost layers indicate.

It is important to note that the climate data used in the model are from average weather conditions for each region. Thus $3PG_2S$ will not reflect the effects on site productivity if a region has suffered from drought, high rainfall, or unusual weather conditions that deviate from long term averages. If a region is known to have experienced unusual weather conditions, it is recommended that actual weather data are used for the site.

The effects of climate change were not assessed in this project. All output from this model is based on 10-year climate averages. The effects of climate change scenarios on *E. fastigata* productivity will be tested as part of a MAF contract in the next six months. These effects will be added to $3PG_2S$ to quantify the potential climate change effects on productivity using the same management scenarios. This output will be available to FFR members in the format described below.

Management Scenarios Datasets Available to FFR Members

$3PG_2S$ was run for the series of management scenarios for carbon forestry and timber management regimes. The model was run for 30 years and output was generated on a per hectare basis for the following:

- stem volume,
- mean diameter at breast height, and
- mean annual increment.

Output was generated for years 10, 15, 20, 25 and 30. Other stand data can be generated if required. The output available to FFR members are 500 m raster grid files that can be readily imported into ArcGIS version 9.2 and later. The raster files for each management scenario are contained in a separate folder with metadata. The spatial reference is NZGD 1949. The effects of climate change scenarios on *E. fastigata* productivity will be tested as part of a MAF contract in the next six months and will be available to FFR members.

Table 2: Calibration set actual volume verses simulated volume by site

		Volume (m^3 / ha)		
Site	Age	Actual	Modelled	Difference (%)
Karaka	21	884	832	-5
	22	780	859	+10
Kapenga	8	193	187	-3
Waerenga 625 sph	11	212	277	+31
	13	271	354	+31
Waerenga 833 sph	11	279	283	+1
	13	362	339	-6
Waerenga 1111 sph	11	325	282	-13
	13	332	340	+2
Waerenga 1667 sph	11	258	286	+11
	13	308	346	+12
Waerenga 2500 sph	11	296	275	-7
	13	313	336	+7
Omataroa	11	359	455	+27
	14	509	587	+15
	17	656	704	+7
RossD	10	129	243	+88
	13	187	385	+106
Drummond	13	204	251	+13
	16	402	288	+6
	21	403	363	-10
	25	455	400	-12
Milligan	10	45	191	+324
	13	109	263	+141

CONCLUSION

The $3PG_2S$ model provided a reasonably accurate representation of *E. fastigata* growth throughout New Zealand. Despite having only 38 plots across seven sites for the calibration set, the process-based model could predict stand growth across a number of environments. There are limitations to the model including:

- a limited mortality and self-thinning model,
- limited information available on soil characteristics, and
- depth for the water balance module, and no quantification on the effects of soil fertility on stand growth.

Despite these limitations, the model was able to predict the species response to a range of silvicultural scenarios. Indeed, some of the current limitations for the model stem more from the lack of adequate climate and soil data than from the model itself. Future improvements to input data, and understanding of the response of *E. fastigata* to silvicultural treatments, can be readily incorporated into the model. This project generated a series of georeferenced raster grid files that can be readily imported into ArcGIS. Decision makers can use this output to assess the productivity of *E. fastigata* throughout New Zealand and the potential of the tested management scenarios for carbon forestry and a timber regime.

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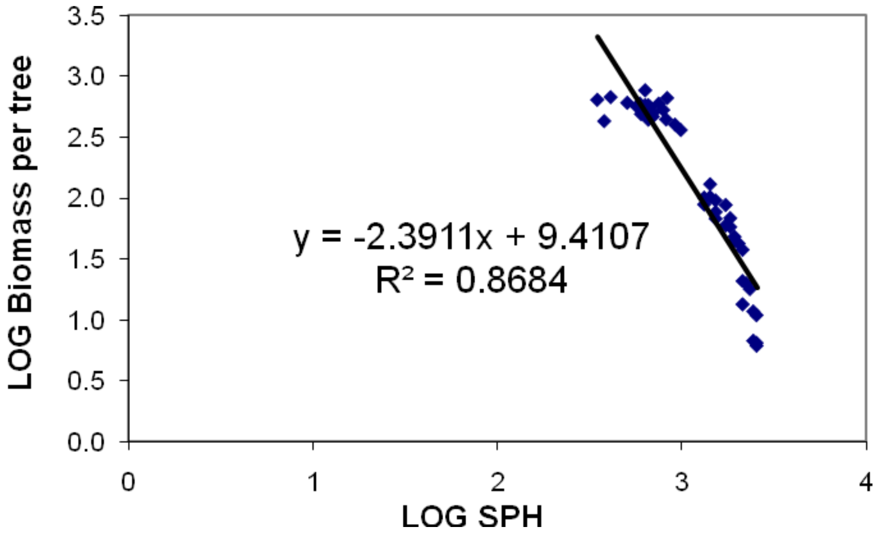
APPENDICES

Appendix A: *Eucalyptus fastigata* parameters for 3-PG$_2$S

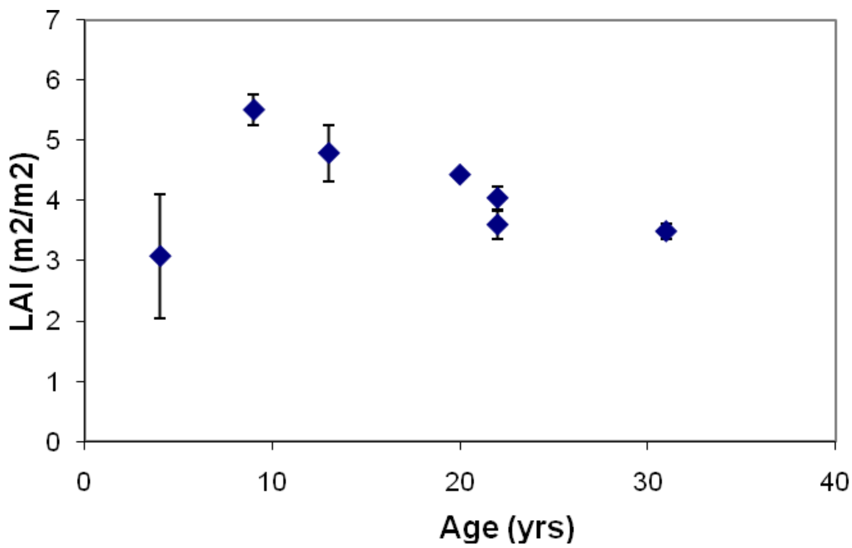
Parameter	Value
1. Allometric Relationships and Partitioning	
Foliage-stem ratio at DBH 2 cm	1
Foliage-stem ratio at DBH 20 cm	0.1
Constant in stem mass verses diameter relationship	0.158
Power in stem mass verses diameter relationship	2.1
Max. fraction of NPP to roots	0.85
Min. fraction of NPP to roots	0.3
Volume of soil accessed by 1 kg of root dry matter	3.8
2. Litterfall and Root Turnover	
Max. litterfall rate per month	0.023
Litterfall rate at time=0	0.0001
Age at which litterfall has a median value - months	72
Average monthly root turnover rate per month	0.015
3. Temperature Modifiers	
Minimum temperature for growth	6
Optimum temperature for growth	20
Maximum temperature for growth	35
4. Frost Modifiers	
Days of production lost per frost day	0.5
5. Fertility Effects	
Value of m when FR=0	0
Value of fNutr when FR=0	0.6
Power of (1-FR) in gmNutr	1
6. Salinity Modifiers	
Not used	
7. Age Modifiers	
Max stand age used in age modifier	60
Power of relative age in function for fAge	4
Relative age at fAge = 0.5	0.95
8. Stem Mortality and Self Thinning	
Mortality rate for large t	5.5
Seedling mortality rate	0
Age at which mortality rate has median value	8
Shape of mortality response	0.5
Max. stem mass per tree at 1000 trees per ha	333
Power in self thinning rule	4
Fraction mean single tree foliage biomass lost per dead tree	0
Fraction mean single tree root biomass lost per dead tree	0.2
Fraction mean single tree stem biomass lost per dead tree	0.2
9. Specific Leaf Area	
Specific leaf area at age 0	11
Specific leaf area for mature leaves	7
Age at which specific leaf area is half	2.5
10. Light Interception and VPD Attenuation	
Extinction coefficient for absorption of PAR by canopy	0.5
Age at canopy cover	3
LAI for 50% reduction of VPD in canopy	3
11. Rainfall Interception	

Max. thickness of water retained on leaves	0.25
Max. proportion of rainfall evaporated from canopy	0.5
LAI for max. rainfall interception	3
12. Production and Respiration	
Canopy quantum efficiency	0.06
Edge tree growth % enhancement	20
Ratio NPP/GPP	0.47
13. Conductance	
Max. stomatal conductance	0.008
Radiation at which conductance is half of max.	100
Min. canopy conductance	0
Max. canopy conductance	0.02
LAI for max. canopy conductance	3.33
Defines stomatal response to VPD	0.05
Canopy aerodynamic conductance	0.2
Soil aerodynamic conductance	0.02
14. Branch and bark fraction	
Branch and bark fraction at age 0	0
Branch and bark fraction for mature stands	0
Age at which branch and bark fraction is half	0
15. Basic density	
Min. basic density for young trees	0.4
Min. basic density for older trees	0.5
Age at which basic density is half	10
16. Stem height	
Constant in the stem height relationships	2.08
Power of DBH in stem height relationship	0.7
Power of stocking in stem height relationship	-0.0036
17. Stem volume	
Default	
18. Carbon Parameters	
Ratio canopy quantum efficiency CO_2 growth modifier at 700 – 350 ppm	1.4
Ratio canopy conductance efficiency CO_2 growth modifier at 700 – 350 ppm	0.7
19. Conversion Factors	
Intercept of net verses solar radiation relationship	-90
Slope of net verses radiation relationship	0.8
Molecular weight of dry matter	24
Conversion of solar radiation to PAR	2.3

Appendix B: Self-thinning relationship for fully stocked stands for parameterising 3PG$_2$S self-thinning function: stems per hectare (SPH) and tree biomass per tree on a logarithmic scale.



Appendix C: Stand leaf area index (LAI) by stand age.



Appendix D: Reineke stand density index for fully stocked plots: quadratic mean diameter (QMD) by stems per hectare (SPH)