Forest&Wood
Products Australia
Knowledge for a sustainable Australia

RESOURCES

PROJECT NUMBER: PNC288-1112

APRIL 2015

The extent and causes of decline in productivity from first to second rotation blue gum plantations

This report can also be viewed on the FWPA website
www.fwpa.com.au
FWPA Level 4, 10-16 Queen Street,
Melbourne VIC 3000, Australia
T +61 (0)3 9927 3200 F +61 (0)3 9927 3288
E info@fwpa.com.au W www.fwpa.com.au

The extent and causes of decline in productivity from first to second rotation blue gum plantations

Prepared for

Forest & Wood Products Australia

by

Michael Battaglia, Don White, Rob Musk, Tammi Short, Jody Bruce, Anthony O'Grady, John Wiedemann and Justine Edwards

Publication: The extent and causes of decline in productivity from first to second rotation blue gum plantations

Project No: PNC288-1112

This work is supported by funding provided to FWPA by the Department of Agriculture, Fisheries and Forestry (DAFF).

© 2015 Forest & Wood Products Australia Limited. All rights reserved.

Whilst all care has been taken to ensure the accuracy of the information contained in this publication, Forest and Wood Products Australia Limited and all persons associated with them (FWPA) as well as any other contributors make no representations or give any warranty regarding the use, suitability, validity, accuracy, completeness, currency or reliability of the information, including any opinion or advice, contained in this publication. To the maximum extent permitted by law, FWPA disclaims all warranties of any kind, whether express or implied, including but not limited to any warranty that the information is up-to-date, complete, true, legally compliant, accurate, non-misleading or suitable.

To the maximum extent permitted by law, FWPA excludes all liability in contract, tort (including negligence), or otherwise for any injury, loss or damage whatsoever (whether direct, indirect, special or consequential) arising out of or in connection with use or reliance on this publication (and any information, opinions or advice therein) and whether caused by any errors, defects, omissions or misrepresentations in this publication. Individual requirements may vary from those discussed in this publication and you are advised to check with State authorities to ensure building compliance as well as make your own professional assessment of the relevant applicable laws and Standards.

The work is copyright and protected under the terms of the Copyright Act 1968 (Cwth). All material may be reproduced in whole or in part, provided that it is not sold or used for commercial benefit and its source (Forest & Wood Products Australia Limited) is acknowledged and the above disclaimer is included. Reproduction or copying for other purposes, which is strictly reserved only for the owner or licensee of copyright under the Copyright Act, is prohibited without the prior written consent of FWPA.

ISBN: 978-1-925213-10-2

Researcher/s:

Michael Battaglia, Don White, Tammi Short, Jody Bruce, Anthony O’Grady
CSIRO Agriculture Flagship
Private Bag 12, Hobart, Tasmania 7001

Rob Musk
Forestry Tasmania
Melville Street Hobart, Tasmania

Justine Edwards
jedwards@usc.edu.au

John Wiedemann
john.wiedemann@wapres.com.au

Final report received by FWPA in April, 2015

Forest & Wood Products Australia Limited
Level 4, 10-16 Queen St, Melbourne, Victoria, 3000
T +61 3 9927 3200 F +61 3 9927 3288
E info@fwpa.com.au
W www.fwpa.com.au

Executive Summary

This is the final report for a project that aimed to quantify changes in productivity of blue gum plantations between the first and second rotation.

A short, initial review of observations and research into sustaining productivity through multiple rotations was carried out. The report finds that sustaining production through multiple rotations is a problem that silviculturalists have been challenged by, and resolved with good practice, over centuries. Well established principles about the impact of tree growth and management on the site resources can, and should, guide the practice of sustainable forestry.

For bluegums in Western Australia, the decline in available soil water from the first to the second rotation has been anticipated and subsequently measured. While the effect itself is not anticipated to be major, it is well known that a primary stress such as water stress can exacerbate secondary and ultimately more damaging impacts such as insect attack.

Appropriate soil and nutrition management have long been recognised as the cornerstone of sustained productivity, and again it has been anticipated, and well demonstrated, that practices such as residue burning will have a significant impact on long term production, especially on sandy soils.

The subsequent analysis in the report is in two parts.

The first part of the work developed predictive relationships that can fit rapidly and easily into existing company inventory systems. The results are based on historical data, and implicit in this approach is the assumption that the past will be indicative of the future. In Western Australia, where there has been a strong and long term decline in rainfall, this may not be a valid assumption. Similarly, there is now evidence of increasing pest problems, the effect of which will not be evident in historical data but may impact future productivity.

The main results from this part of the work are:

1. Empirical growth curves were constructed that allowed second rotation site index, basal area and volume to be calculated as a function of a standardised precipitation evaporation index and, where first rotation site index is known, to develop growth for the second rotation. Models displayed a reasonable level of skill, with model precision being 10% {%precision= $\sqrt{\frac{1}{N}\sum_{i=1}^{N} 100 \times \frac{(Y_i-\hat{Y}_i)^2}{Y_i}}$) where Y_i an individual observation, $\hat{Y}_i$ is the average stand value and N is the total number of observations}.
2. These curves can be applied to depict the relationship between first and second rotation productivity for management concurrent with the sample data. In dry environments and on deep soils the decline can be as great as 50%. The models

suggest that the effect becomes greater as stands age, that is little difference may be detected early in the rotation but effects will increase later.

The second part of the work sought to explain the causes, map the likely extent and explore some management changes to mitigate 2R decline. A process-based model, CABALA, was used to understand the likely processes driving the decline in production observed in the small sample set of plots provided by the project proponents. The model was then used to develop spatial maps of possible 1R and 2R production, and look at the contribution of soil water and changes in soil nutrients across the landscape under different starting soil conditions.

The main results of this work include:

3. When a sub-sample of 20 growth plots were analysed, some of the observed decline was due to variation in rainfall and plant available soil water between rotations. After accounting for the effect of water there was still a substantial residual, particularly on drier sites, and this was associated with a higher level of insect damage. Reduced soil nitrogen supply was observed on all plots but only affect 2R productivity on one of the sample plots. On sites where 1R site fertility was low, however, or in second and subsequent rotations, soil nutrition is highly likely to become a more seriously limiting effect.
4. If the same genetics are applied, and the same weather conditions prevailed, then without changed silvicultural practice 2R production can be expected to be lower on virtually all areas and all site types within the existing Western Australian bluegum estate. This reflects the change from the first to the second rotation in site resources. The first rotation benefited from high levels of fertility associated with prior land use and from substantial stored soil water resulting from land clearing. The effect will be most significant, in percentage terms, on low fertility sites with deep soil, where the change could on average exceed a 25% decrease, and possibly more if secondary insect attack occurs..
5. Burning or removal of forest residues will increase second rotation decline on sites currently nutrient limited, and will on all sites decrease the pool of available resources in subsequent rotations. Slash burning, or removal offsite of residues, is not likely to be a sustainable practice.
6. For the loss of each mm of soil water in the 2nd rotation, there is a corresponding loss in production of approximately 0.015m^3/ha. In the worst case this will result in a decrease of 12 m^3/ha (or around 8-10% decrease) in production, and possibly more if secondary insect attack occurs. While having a period of fallow will restore soil water, lengthening the rotation may not be economically viable, unless it is considered a necessary action to reduce the risk of stand mortality due to drought death or damage from pest attack.

Table of Contents

TABLES and FIGURES IN REPORT

Introduction

Prepared by CSIRO

The eucalypt hardwood industry was established in southern Australia in the early 1980's and expanded rapidly in the 1990's and early 2000's. Expectations of high growth rates in the first rotation were based on early trials that exhibited mean annual increments (MAI) of approximately 25 m^3 ha^{-1} yr^{-1} (Ferguson, 2014). These growth rates were not realised universally, and the observed growth rates have varied widely, with MAI in the Green Triangle region, for example, having an estimated mean of 17.2 m^3/ha (after Ferguson 2014) varying from 5 m^3 ha^{-1} yr^{-1} to more than 30 m^3 ha^{-1} yr^{-1}. This high variability, and lower than expected yield, comes despite nearly all of the 500 000 hectares of blue gum plantations in southern Australia being established on ex-agricultural land with accumulated stores of nitrogen, phosphorus and water. The lower than expected yields in the first rotation were followed by widespread concern of reduced productivity between the first and second rotation, as first rotation soil resources were depleted. Inventory indicates this effect at between 25-40% decline between 1R and 2R in some areas of the bluegum plantation estate (*pers. comm.* Ben Bradshaw *http://forestry.org.au/kcfinder/upload/files/7.%20Bradshaw%20Regime%20change%20E%20globulus.pdf*). Identifying and addressing declining productivity across rotations will be a major challenge for the hardwood industry. It can be difficult to attribute changes in potential site productivity against a moving baseline of changes in technology, genetics and climate: the run-down of site resources may be masked or offset by improved genetics or increased wood recovery at harvest, for example.

While it is generally true that plantation productivity has been sustained, and raised through successive rotations in many parts of the world (Morris, 2008; Evans, 1976;O'Hehir and Nambiar, 2010) declines in the productive potential of plantations between rotations have been noted in some situations.

Perhaps the earliest commentary of declining production comes from Evelyn (Evelyn, 1665) who noted "and in such places where anciently woods have grown but are now unkind to them, the fault is to be reformed by this cure: and chiefly by the sedulous expiration of the old remainders of roots, and latent stumps, which, by their mustiness and other pernicious qualities, sour the ground and poison the conception." More recently declines in third rotation Scot's Pine on sandy soils in Holland and declines in larch plantations in Japan have been noted (Evans, 1976), both possibly attributed to changes in nutrient capital, and declines in Norway spruce initially associated with changes in soil water availability , though later attributed to changes in soil nutrition as a result of acid rain (Katzensteiner et al., 1992).

The issue of second rotation decline in Australia was first noted during the expansion of the *Pinus radiata* industry. Concerns related to declining productivity were raised during the 1950's (O'Hehir and Nambiar, 2010). Keeves (1966) observed that basal area growth during the second rotation of *P. radiata* plantations was reduced by 25-30%, raising concerns that the establishment of *P. radiata* plantations may cause permanent deterioration of site conditions and reduced productivity in subsequent rotations (Squire et al., 1985). While more recent studies showed little evidence to support a permanent degradation of site conditions and indeed showed improved soil indicators of productivity with sound management, (O'Hehir and Nambiar, 2010) there has been much work to indicate inappropriate silvicultural management can negatively impact on subsequent rotations. Early studies indicated that the management of organic matter and nutrients played a significant role in maintaining productivity over multiple rotations (see Flinn, 1978 and Squire et al., 1979 cited in Squire, 1983), especially on sites characterised by podosolic soils. Squire and Flinn (1981, cited in Squire, 1983) calculated that the practice of burning logging residues on infertile sands typical of the plantation estate in South Australia could potentially remove 745 kg ha^{-1} N. Squire (1983) recognised that retaining litter and logging residue not only reduced nutrient losses but could also act as a mulch to conserve soil moisture and suppress weed growth. An analysis of long term growth plots from State Forests in NSW confirmed that in the absence of extra nutrients, second rotation productivity was on average 5-8% lower. In contrast, where second rotation growth was supplemented with the addition of phosphorous, productivity was up to 30% higher (Turner and Lambert, 2014), highlighting the importance of managing site and soil conditions over subsequent rotations.

Simultaneous to this work in Australia, observations of second rotation decline were also being reported in New Zealand. Whyte (1973) examined 2R productivity decline at a number of sites, finding a range of responses during the second rotation, from marked drops in productivity to little change from the first rotation. Declines in second rotation productivity were particularly prevalent on ridges and upper slopes where soils were shallow. In contrast, at sites with deeper soils or in valleys there were often no changes in productivity. Whyte (1973) noted that the magnitude of the decline, when apparent, was equivalent to extending rotation length by approximately 2 years and that much of the decline appeared to be associated with stagnated growth at the beginning of the second rotation. While recognising the issue, Whyte (1973) offered few insights into the mechanistic basis for these declines. Turner and Lambert (2014) have recently examined long-term growth data from trials established in NSW during the 1960s and found that changes in soil chemical properties between first and second rotation plantations explained a large amount of the variation in second rotation changes in productivity with respect to increased and decreased production.

Declines in productivity, observed during the 1970's in *Pinus radiata* plantations in the Green Triangle, were ultimately addressed by managing site organic matter to sustain nutrient supply combined with improved silviculture and planting material. Similarly, adding nutrients during the second rotation in NSW had significant impacts on second rotation productivity of *P. radiata*, that lasted well into the third rotation (Turner and Lambert, 2014). Together these studies highlight the importance of the management of nutrients, organic matter and soil moisture during and between rotations to ensure the long term sustainability of pine plantations.

More recently the issue of declining productivity in eucalypt plantations across subsequent rotations has received attention, both within Australia and internationally (Nambiar, 1999; Jones and Madieira, 1999; Mendham et al., 2011; Mendham et al., 2014). Eucalypts are a fast growing species and rotation lengths tend to be significantly shorter than for *Pinus radiata* plantations. With rapid growth, and short timeframes between disturbances associated with harvest, short rotation crops can present sustainability challenges (Harwood and Nambiar, 2014; Mendham et al, 2014).

The role of harvest residue management in productivity maintenance across multiple rotations in eucalypt plantations is well recognised (Jones and Madiera, 1999). Saint-Andre and Laclau (2008) compiled a comprehensive review of growth data and slash and litter management from a number of countries growing eucalypts including: Australia, Brazil, China, Congo, India and South Africa. Results across the various trials were mixed, ranging from no response, to significant growth impacts. While mechanisms driving the responses were not identified, a strong relationship between harvest residue management and an index representing the input of N in the residues as a function of N availability in the top soil was obtained. While N is the primary growth-limiting nutrient in many cases, N was also correlated with other limiting nutrients, meaning that N itself may be only a partial contributor to limitations imposed by multiple factors. Overall this study found that even in soils with relatively high nutrient availability, second rotation eucalypt growth was sensitive to the management and retention of residues on site. Concurrently, Mendham et al. (2008) examined harvest residue management and its impacts on soil nutrients and productivity in two *Eucalyptus globulus* plantations in south west Western Australia over a full ten year rotation. While harvest residue management had no significant effect on total soil carbon or nitrogen it did have any significant effects on exchangeable cations in surface soils, and where residue was retained nitrogen mineralisation rates were higher. It is worth noting that many of these plantations had been established on ex-agricultural land and that nitrogen supply rates are likely to naturally decline when the land is planted to successive crops of eucalypts (O'Connell et al., 2003). O'Connell et al (2003) advised that eucalypt plantation managers will need to take account of this, and implement management strategies to maintain adequate N nutrition to sustain tree growth in future rotations. This was supported by a modelling study that found the rate of decline in stemwood productivity to be sensitive to rates of nitrogen removal in harvested stems and to residue management (Corbeels et al., 2005). Simulations suggested that retention of harvest residues would be helpful to maintain stand productivity, and that application of fertiliser N will be necessary to maintain current levels of productivity in the long term.

There are complex interactions between site, soils, nutrition and productivity. Nambiar and Brown (1997) summarised some key principals for sustaining plantation production in the long term. The research above suggests that these principals are highly relevant to Western Australian eucalypt plantation management. The first of these is that plantation management should ensure that the soil base is protected and that disruptions to ecological processes in particular the carbon, water and nutrient cycles are minimised. The second advocates avoiding extreme soil disturbance and conserving site organic matter pools. Management during the inter rotation period represents a phase of heightened risk which can have significant impacts on subsequent rotations. In a review of plantation-productivity in south-east Asia, Harwood and Nambiar (2014) found that in countries where significant efforts were made to conserve site resources, productivity during subsequent rotations was maintained or even increased. However, they also describe practices that included the bulldozing of sites between rotations that lead to the loss of soil and soil organic matter, repeated deep ploughing between rows of growing trees as a means of weed control and the burning of slash and other vegetation that led to significant site degradation and loss of productivity. These practices may also be a cause of productivity decline in Australian eucalypt plantations; Nambiar (2010) in a critique of harvesting practices in bluegum plantations in Australia cited substantial site degradation during harvesting from dragging of whole trees and windrowing and burning of slash.

While the management of soils and soil nutrition is clearly critical to maintaining productivity during the second rotation, across much of southern Australia water availability represents a key constraint on plantation productivity (White et al., 2009). In south-west Western Australia, the *E. globulus* estate was established on ex-agricultural land where soil moisture availability was relatively high (compared to native forests and woodlands) because agricultural practices had removed much of the deep rooted perennial vegetation resulting in increased recharge of rainfall (Crosbie, 2010). Mendham et al. (2011) hypothesised that this may be a causal factor driving productivity of plantations across the region. They found that plantation growth during the first rotation resulted in significant declines in soil water availability throughout the soil profile and that there was often incomplete recharge of the soil profile between rotations, especially at drier sites. Thus, in many situations, second rotation plantations were being established on sites that already had less water available than the previous rotation. They extrapolated these results using the process based model CABALA and found that at sites where soils depths were deeper than 4 m, it was unlikely that there would be sufficient rainfall during one year of fallow to completely recharge soil profiles and that this was likely to become a significant constraint on the productivity of second rotation plantations.

Simultaneously, south-west Western Australia has experienced significant long-term declines in rainfall (Petrone, 2010) and across much of southern Australia there has also been a significant decline in autumn rainfall (CSIRO, 2014). Regardless of site management practices this trend alone may result in significant declines in site productivity in second rotation plantations. While this risk can be managed to some extent through silvicultural management (White et al., 2009), declining rainfall and rising temperatures and an expected increased frequency of heat waves suggests that many plantations, and particularly those in the drier regions of the current plantation estate will experience an increased risk of drought related mortality (Battaglia et al., 2009).

Plantations in Australia are classed as being moderately vulnerable to climate change (Hennessy et al., 2007) but have a high adaptive capacity largely through good physiological understanding of the results of silviculture interventions and the presence of alternative plantation species (Pinkard et al., 2014). There are likely to be both positive and negative impacts of climate change on plantation productivity, and these impacts will play out differently across the plantation growing areas of southern Australia. While CO_2 may stimulate biomass production, water and nutrient limitations may constrain the capacity of plantations to respond to rising atmospheric CO2 concentration (Battaglia et al., 2009). Furthermore, there are concerns that changing climates may alter the epidemiology of pests and diseases, and that predictions of plantation productivity that do not account for these changes are likely to be overestimates (Pinkard et al., 2011). Finally there is growing evidence to suggest that fire frequency and intensity may increase potentially causing increased plantation loss (Pinkard et al., 2014).

Sustaining and even increasing production into the future represents a significant challenge for plantation managers. Sustained productivity remains a foundation of all forestry enterprises (Nambiar, 2003) and as competition for productive land increases and climates across Australia change, maintaining and even increasing productivity across multiple rotations represents a significant challenge to the long term viability of the forest industry in Australia. As this review has shown, site quality is not fixed, and depends on management and the inherent productivity of a site itself will be modulated by underpinning changes in climate, germplasm and technology deployed for forest production (Nambiar, 1999). To date, current research on the drivers of second rotation decline have not translated to site-specific management recommendations. Any management response must be based on a quantitative understanding of the severity of any decline, a site-specific understanding of the causes and options for remediation. This, and other commentary (e.g. Nambiar 2010), suggest that there are two factors driving the loss of 2nd rotation productivity, Firstly there exists a complex interaction of variables related to, changing site resources through time. Secondly, this is exacerbated in some cases, by failure to implement best forestry practice (such as slash removal or burning) that accelerates the rundown of site resources.

The work in this report does not look at forestry practice, though we do later in the report look at the consequence on long term site nitrogen balance of removal of slash and inter-rotation soil water management.

This project aimed to provide the impetus and the basis for industry practice change by collating available industry data on multi rotation productivity and using this data to:

1. Develop empirical growth curves for second rotation hardwood plantations.
2. Quantify the extent and severity of second rotation decline in hardwood plantations and map spatially where and under what conditions of soil depth and inherent fertility might marked productivity change be observed.
3. Make an initial assessment of the primary causes of second rotation decline through changes in site resources, but not considering site degradation through harvesting techniques.

Part 1 – Empirical growth curves for *E. globulus*

Prepared by Forestry Tasmania

This section focusses on the derivation and implications of growth curves for mean top height, basal area and volume that, where necessary, use climate information to improve the precision of the predictions. Models to predict 2nd rotation site index and basal area at age 8 using 1st rotation observations are also presented and discussed. These models can be used to initiate mean top height, basal area growth models to estimate 2nd rotation growth from 1st rotation observations.

1.1 Data and methods

Observations were available from a number of permanent plots and silvicultural trials where stand metrics have been measured across two rotations. At these sites estimates of long term average precipitation-evaporation index (SPEI) values were also available and were derived using long term interpolated climate data.

Inventory data were supplied by WAPRES and CSIRO. The WAPRES data comprise 166 first rotation observations and 153 second rotation observations from 36 plots. The CSIRO data comprise 88 first rotation observations and 36 second rotation observations from 12 plots (**Error! Reference source not found.**).

Table 1. Data summaries

Owner	Rotation	Statistic	SPEI	Obs. per plot	A	M	G	V
CSIRO	1	min	-849.9	4	2.25	4.40	1.90	5.83
CSIRO	1	mean	-539.4	7.52	5.97	14.80	13.94	84.57
CSIRO	1	max	-280.6	8	9.55	24.60	29.25	251.14
CSIRO	2	min	-849.9	2	2.41	6.11	1.28	4.74
CSIRO	2	mean	-539.4	3.33	4.29	11.07	6.78	33.16
CSIRO	2	max	-280.6	4	5.87	18.97	18.21	120.57
WAPRES	1	min	-767.2	3	2.61	8.58	4.45	15.82
WAPRES	1	mean	-464.7	4.48	6.57	18.73	20.29	144.64
WAPRES	1	max	-30.7	6	11.48	34.28	36.51	421.38
WAPRES	2	min	-767.2	2	1.83	6.83	2.43	7.53
WAPRES	2	mean	-464.7	3.98	6.45	16.09	13.51	83.67
WAPRES	2	max	-30.7	5	11.66	32.55	29.26	306.12

Symbols used in the equations and in table 1 above are:

G stand basal area (m^2/hectare)

M mean top height (average height of the 100 tallest trees per hectare) (m)

S site index (stand mean dominant height at stand age 8 years)

A decimal stand age (years)

V total stand volume (m^3/hectare)

Mixed-modelling methods were used to accommodate the hierarchical nature of the observations. Residual maximum likelihood (REML) estimates are reported throughout. Penalised quasi-likelihood (PQL) is used to identify parameters in gamma-distributed generalised linear models. Laplace approximation (LA) was used to identify parameters in other models. All modelling used the R software environment (R Development Core Team

2013). PQL modelling used the MASS library (Venables and Ripley 2002). LA used the lme4 library (Bates and Maechler 2012).

Model performance was evaluated using bias and precision statistics.

Raw bias is given by:

$$\text{bias} = \frac{1}{N}\sum_{i=1}^{N}\left(Y_i - \widehat{Y_i}\right)$$

Percentage bias is given by:

$$\%\text{bias} = \frac{1}{N}\sum_{i=1}^{N} 100 \times \frac{\left(Y_i - \widehat{Y_i}\right)}{Y_i}$$

Where:

Y is the actual observation;

$\widehat{Y_i}$ is the predicted value of the observation;

N is the number of observations.

Raw precision is given by:

$$\text{precision} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Y_i - \widehat{Y_i}\right)^2}$$

Percentage precision is given by:

$$\%\text{precision} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} 100 \times \frac{\left(Y_i - \widehat{Y_i}\right)^2}{Y_i}}$$

Bias and precision statistics were calculated across age classes and SPEI classes.

1.2 Results

1.2.1 Mean top height increment

Mean top height was modelled using a state-space form of the three-parameter Richards model (Candy 1997),

$$M = \beta_1\left[1 - \left\{1 - \left(\frac{M_1}{\beta_1}\right)^{\frac{1}{\beta_2}}\right\}^{\frac{A}{A_1}}\right]^{\beta_2} \qquad (1)$$

where M was the mean top height at age A, M_1 the mean top height at age A_1, and $\beta_{1\text{ and }2}$ model parameters estimated from the data. The data were arranged into measurement pairs in each site and rotation combination comprising the 1st measurement (M_1, A_1) and subsequent measurements (M, A). A total of 358 measurement pairs were available for model fitting, mainly from the South West Region.

In order to accomadate the nested structure of the data, mixed-effects formulations of the model were constructed. In the 1st stage, single-level random effects were associated with each site and rotation combination (96 combinations). Chi-square tests were used to identify the following model:

$$M_{ij} = (\beta_1 + b_{1i})\left[1 - \left\{1 - \left(\frac{M_{1ij}}{(\beta_1+b_{1i})}\right)^{\frac{1}{(\beta_2+b_{2i})}}\right\}^{\frac{A_{ij}}{A_{1ij}}}\right]^{(\beta_2+b_{2i})} + \varepsilon_{ij} \tag{2}$$

where the $i = 1, \ldots, n$ subscript represented the i^{th} plot in a total of n plots and the $j = 1, \ldots, m$ subscript represents the j^{th} observation in a total of m observations on the i^{th} site and rotation combination, $b_{1i \text{ and } 2i}$ were random effects parameters with n elements, ε_{ij} were the residual observation-level errors. The random effects parameters were assumed to be the i^{th} independent realisation from a normal distribution with means equal to zero and variances $\sigma_{b_1}^2$ and $\sigma_{b_2}^2$. The residual errors ε_{ij} were independent of the random effects and identically, normally-distributed random variables with mean equal to zero, and variance σ_ε^2.

An inspection of scatterplots of random effects from model 2 and SPEI indicated weak relationships existed in the second rotation only. Second stage models were constructed with random effects at the site level only (48 sites) incorporating this information using a range of SPEI transforms and then assessed using Chi-square tests, together with bias and precision statistics (see appendix) that describe model performance in particular subsets of the data.

The identified second-stage model took the form:

$$M_{ij} = (\beta_1 + \alpha_1 \times R_i + b_{1i})\left[1 - \left\{1 - \left(\frac{M_{1ij}}{(\beta_1+\alpha_1 \times R_i+b_{1i})}\right)^{\frac{1}{(\beta_2+\alpha \times R_i \times C_i+b_{2i})}}\right\}^{\frac{A_{ij}}{A_{1ij}}}\right]^{(\beta_2+\beta_1+\alpha_1 \times R_i+b_{1i}b_{2i})} + \varepsilon_{ij} \tag{3}$$

Where R_i is an indicator variable taking values of 0 for the 1st rotation and values of 1 for the 2nd rotation and $C_i = \left(\frac{-SPEI_i}{1000}\right)^2$.

Fixed and random effects parameter estimates for model 3 appear in **Error! Reference source not found.**.

Table 2. Fixed and random effects parameter estimates for model 3

Parameter	β_1	β_2	α_1	α_2	$\sigma_{b_1}^2$	$\sigma_{b_2}^2$	σ_ε^2
Estimate	28.24202	1.13149	5.37822	-0.8781	25.26094	0.016589	0.68458
Standard error	0.9696	0.04516	1.24459	0.1005			

Error! Reference source not found. shows the residuals versus the fitted values from model 3 conditioned on the random effects for rotation 1 (a) and rotation 2 (b). The residuals appear homogeneous in both cases.

A comparison of fit and performance for models 2 and 3 was instructive. Despite reducing the random effects from site and rotation combinations to site level alone, incorporating the climate index and the rotation indicator variable significantly improveed model fit (

).

Table 3. Analysis of variance for a comparison of model 2 and model 3

	degrees of freedom	AIC	BIC	Log likelihood	Chi-square	Pr(>Chi-square)
model 2	5	449.50	468.90	-219.75		

model 3	7	417.61	444.78	-201.81	35.88	< 0.001

Incorporating climate and rotation information slightly increased model bias in 7 out of 8 cases but these increases were offset by improved model precision across all age classes (

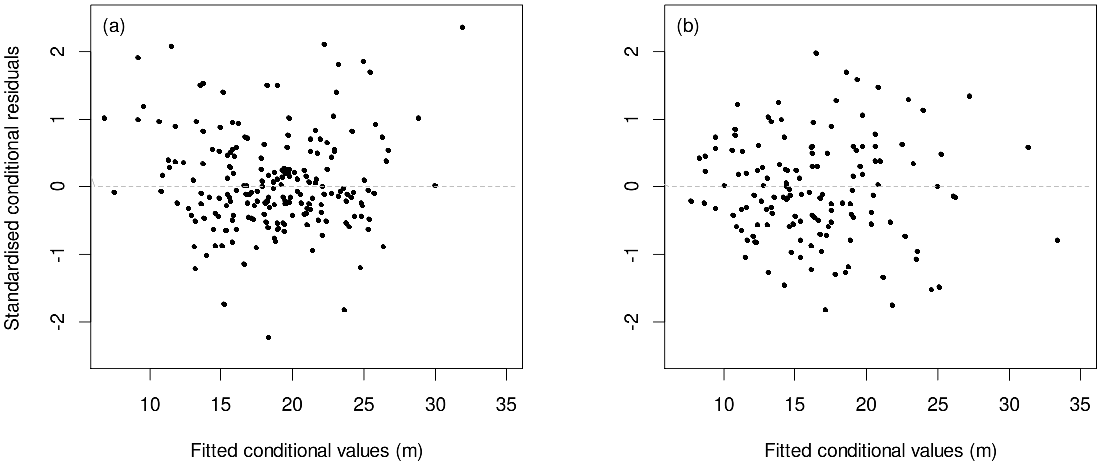


Figure 1. Residuals for model 3 as a function of fitted values

).

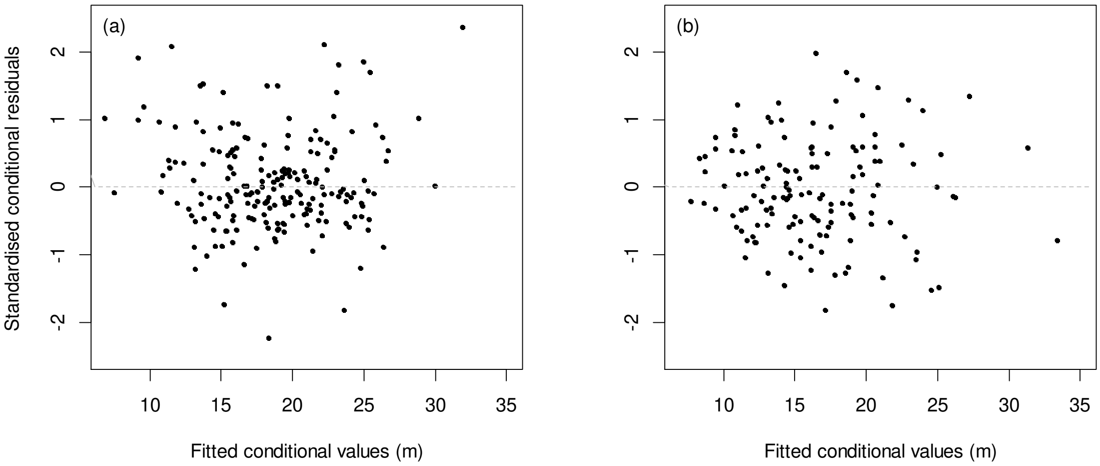


Figure 1. Residuals for model 3 as a function of fitted values

Table 4. Bias and precision statistics for models 2 and 3 by age class

		bias		%bias		precision		%precision	
age class	N	model 2	model 3	model 2	model 3	model 2	model 3	model 2	0model 3
< 4	71	0.085	-0.087	0.329	-0.880	0.795	0.772	6.384	6.164
< 6	130	-0.043	-0.146	-1.108	-1.474	1.084	1.062	6.881	6.753
< 8	116	-0.030	-0.078	-1.516	-1.650	1.651	1.517	8.730	7.946

>= 8	73	-0.355	-0.374	-3.207	-3.189	2.047	1.878	9.848	9.029

Incorporating climate and rotation information in the model increased model bias in 6 out of 8 cases but again these were offset by improved model precision in 6 out of 8 SPEI classes (**Error! Reference source not found.**).

Table 5. Bias and precision statistics for models 2 and 3 by SPEI class.

		bias		%bias		precision		%precision	
SPEI class	N	model 2	model 3	model 2	model 3	model 2	model 3	model 2	model 3
< -800	94	0.059	0.159	-0.053	0.804	1.492	1.232	9.940	8.167
< -600	74	-0.194	-0.001	-1.858	-0.391	1.035	0.915	6.147	5.264
< -400	99	-0.172	-0.271	-1.305	-1.913	1.158	1.131	5.853	5.771
< 0	113	-0.003	-0.383	-2.024	-4.271	1.723	1.743	9.428	9.800

1.2.2 Site Index

By rearrangement model 3 can be used to predict site index. Given the restricted range of ages in the dataset site index was defined as the predicted mean top height at decimal age 8.0. The model is given by:

$$S = \beta_1 \left[1 - \left\{ 1 - \left(\frac{M_1}{\beta_1} \right)^{\frac{1}{\beta_2}} \right\}^{\frac{8}{A_1}} \right]^{\beta_2} \tag{4}$$

Where S is site index. For each site and rotation combination site index was predicted using the observation pair M_1 and A_1 closest to age 8.0.

1.2.3 Stand basal area

Stand basal area was modelled using a state-space polymorphic model given by:

$$G = G_1^{\left(\frac{A_1}{A}\right)^{\beta_3}} \times \exp\left[\left(\frac{\beta_1}{\beta_3} + \frac{\beta_2}{\beta_3} \times S \right) \left(1 - \left(\frac{A_1}{A} \right)^{\beta_3} \right) \right] \tag{5}$$

Where G is stand basal area at age A, G_1 is stand basal area at age A_1 and $\beta_{1,2,3}$ are parameters estimated from the data. The same methodolgy as that employed in the 1st stage modelling of mean top height was employed to identify an appropriate mixed-effects formulation of model 5. This given by:

$$G_{ij} = G_{1ij}^{\left(\frac{A_{1i}}{A_{ij}}\right)^{(\beta_3+b_{3i})}} \times \exp\left[\left(\frac{(\beta_1+b_{1i})}{(\beta_3+b_{3i})} + \frac{\beta_2}{(\beta_3+b_{3i})} \times S_i \right) \left(1 - \left(\frac{A_{1i}}{A_{ij}} \right)^{(\beta_3+b_{3i})} \right) \right] + \varepsilon_{ij} \tag{6}$$

Where $b_{1i \text{ and } 3i}$ are random effects parameters with n elements and other symbols are as defined above. An inspection of scatterplots of random effects from model 6, rotation and SPEI indicated no relationship, and attempts to incorporate these variables in 2nd stage models did not lead to improvements in model performance (bias and precision statistics). Hence, model 6 was refitted with random effects at the site-level only for subsequent use in volume projection (**Error! Reference source not found.**).

Table 6. Fixed and random effects parameter estimates for model 6 appear in Table 6.

Parameter	β_1	β_2	β_3	$\sigma_{b_1}^2$	$\sigma_{b_3}^2$	σ_{ε}^2
Estimate	2.268575	0.070111	1.030451	0.0933736	0.0096878	1.2378304
Standard error	0.122863	0.006404	0.041269			

Error! Reference source not found. shows the residuals versus the fitted values from model 6 conditioned on the random effects for rotation 1 (a) and rotation 2 (b). The residuals appear homogeneous in both cases.

Table 7 Bias and precision statistics for model 6 by age class.

age class	N	bias	%bias	precision	%precision
< 4	71	0.184	-0.384	1.123	10.718
< 6	130	0.155	-0.820	1.521	10.764
< 8	116	0.022	-2.256	2.223	12.195
>= 8	73	0.267	-1.257	2.035	9.661

Table 8. Bias and precision statistics for models 6 by SPEI class.

SPEI class	N	bias	%bias	precision	%precision
< -800	94	-0.215	-3.335	1.396	10.257
< -600	74	1.190	5.952	1.869	10.221
< -400	99	0.535	2.269	1.577	8.244
< 0	113	-0.635	-7.581	2.089	14.411

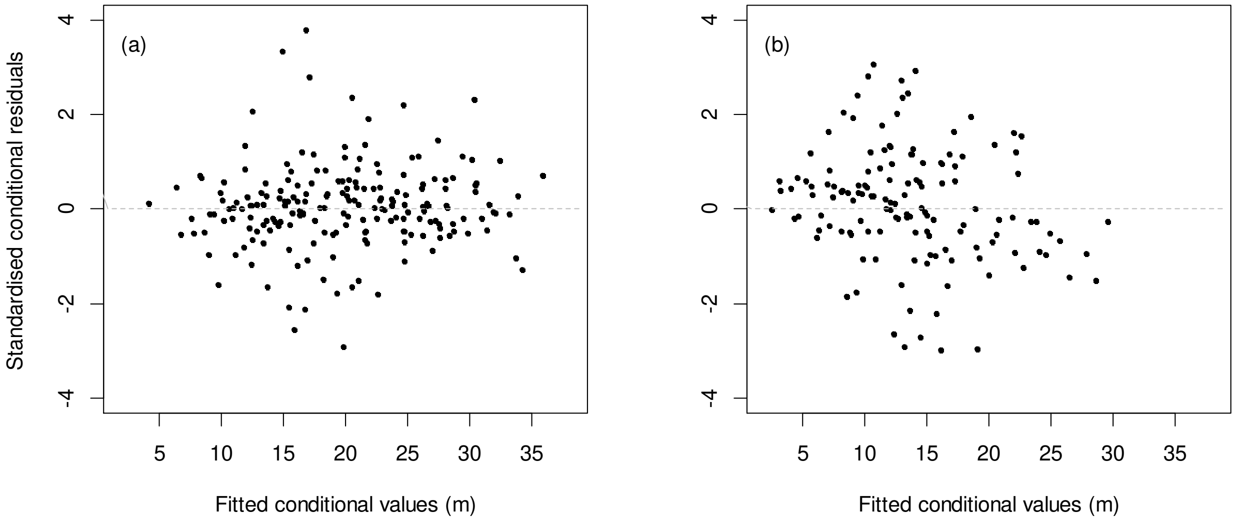


Figure 2 the residuals versus the fitted values from model 6 conditioned on the random effects for rotation 1 (a) and rotation 2 (b).

1.2.4 Stand volume

Stand volume was modelled using a generalised linear mixed-model with a gamma errors, an identity link function and normally distributed random effects. Climate effects, age and the suitability of the random effects structure were each assessed. Climate was not a significant variable in any tested model. The identified model takes the form:

$$V_{ij} = (\beta_1 + b_{i1}) + \beta_2 \times G_{ij} + \beta_3 \times M_{ij} + \beta_4 \times G_{ij} \times M_{ij} + \beta_5 \times A_{ij} \times M_{ij} + \varepsilon_{ij} \qquad (7)$$

Fixed and random effects parameter estimates for model 7 appear in **Error! Reference source not found.**.

Table 9. Fixed and random effects parameter estimates for model 7

Parameter	β_1	β_2	β_3	β_4	β_5	b_{1i}	ε_{ij}
Estimate	1.9481127	0.8404257	-0.292804	0.3233436	-0.017743	1.291087	0.000874347
Standard error	0.4163677	0.0534707	0.0584312	0.0029750	0.0054199		

Error! Reference source not found. shows the standardised Pearson residuals versus the fitted values from model 7 conditioned on the random effects for rotation 1 (a) and rotation 2 (b). The residuals appear homogeneous in both cases.

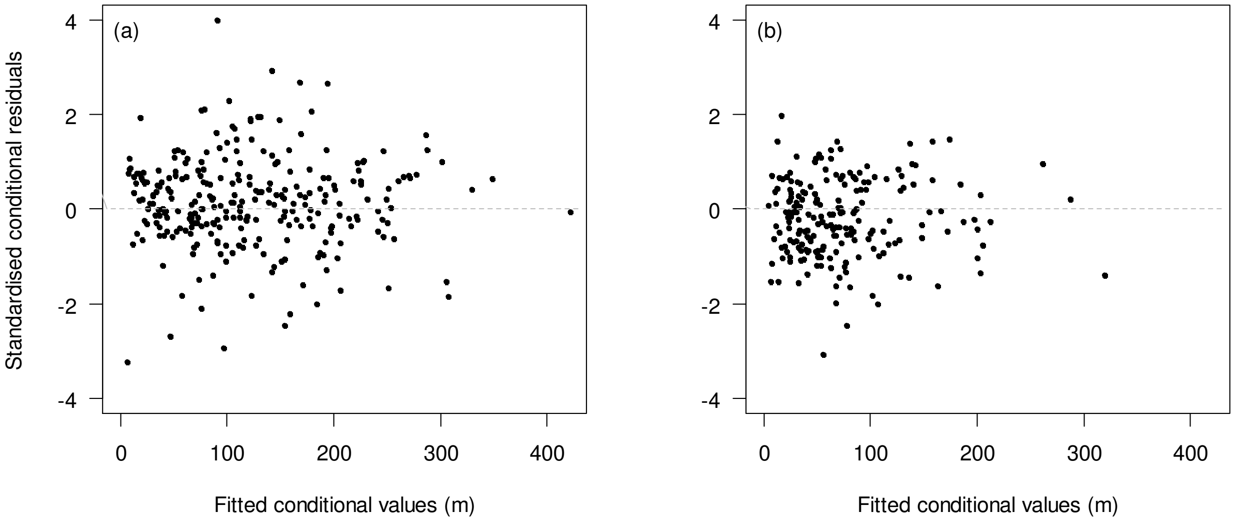


Figure 3. Standardised Pearson residuals versus the fitted values from model 7 conditioned on the random effects for rotation 1 (a) and rotation 2 (b).

In application stand volume was estimated from projected basal area and mean top height. **Error! Reference source not found.** presents bias and precision statistics for model 7 by age class using *observed* basal area and mean top height and *projected* basal area and mean top height. Declines in precision using projected basal area and mean top height were evident. Biases also increased in some cases. In particular, age class >= 8 and spei class < 0 show substantial biases when projected basal area and mean top height were employed.

Table 10. Bias and precision statistics for model 7 by age class employing *observed* basal area and mean top height and *projected* basal area and mean top height.

		bias		%bias		precision		%precision	
age class	N	observed	projected	observed	projected	observed	projected	observed	projected

< 4	71	0.719	1.625	1.611	0.297	1.800	7.458	3.610	14.196
< 6	130	0.383	1.113	0.594	-2.171	2.491	12.805	2.897	15.554
< 8	116	0.467	1.991	0.052	-4.608	3.515	24.127	2.670	18.960
>= 8	73	-0.251	1.513	-0.367	-5.113	4.902	25.484	2.874	16.276

Table 11. Bias and precision statistics for model 7 by SPEI class employing *observed* basal area and mean top height and *projected* basal area and mean top height.

		bias		%bias		precision		%precision	
SPEI class	N	observed	projected	observed	projected	observed	projected	observed	projected
< -800	71	-0.160	0.310	0.733	-2.149	2.727	12.838	3.541	16.233
< -600	130	-0.924	7.249	-1.359	4.360	2.847	15.964	2.648	13.150
< -400	116	0.377	2.465	-0.052	0.655	3.605	16.519	2.528	11.606
< 0	73	1.126	-2.09	1.470	-11.632	2.947	22.941	2.905	23.090

1.2.5 Predicting 2nd rotation growth using 1st rotation observations

An inspection of scatterplots of SPEI, site index and projected basal area at age 8 revealed strong covariances. Models were constructed to estimate 2nd rotation site index and basal area at age 8. Outputs from these models may be used to initatite growth projection in the 2nd rotation in the absence of 2nd rotation observations.

Generalised linear models with a gamma errors were identified after inspection of residual plots and Chi-square test results.

The identified 2nd rotation site index model takes the form:

$$S_2 = {}^{1}\!/_{\beta_1} + \beta_2 \times C + \beta_3 \times S_1 \tag{8}$$

Where S_2 was site index in the 2nd rotation and S_1 is site index in the first rotation.

Table 12 Parameter estimates for model 8.

Parameter	β_1	β_2	β_3	AIC
Estimate	0.0869894	0.0330008	-0.0018435	197.5
Standard error	0.0083548	0.0040836	0.0003672	

The identified 2nd rotation basal area at age 8 model takes the form:

$$G_{r2} = \beta_1 + \beta_2 \times C + \beta_3 \times G_{r1} \tag{9}$$

Where G_{r2} is basal area at age 8 in the 2nd rotation and G_{r1} is basal area at age 8 in the first rotation.

Table 13 Parameter estimates for model.

Parameter	β_1	β_2	β_3	AIC
Estimate	8.60135	-10.93741	0.44569	246.4
Standard error	1.91501	1.66771	0.07172	

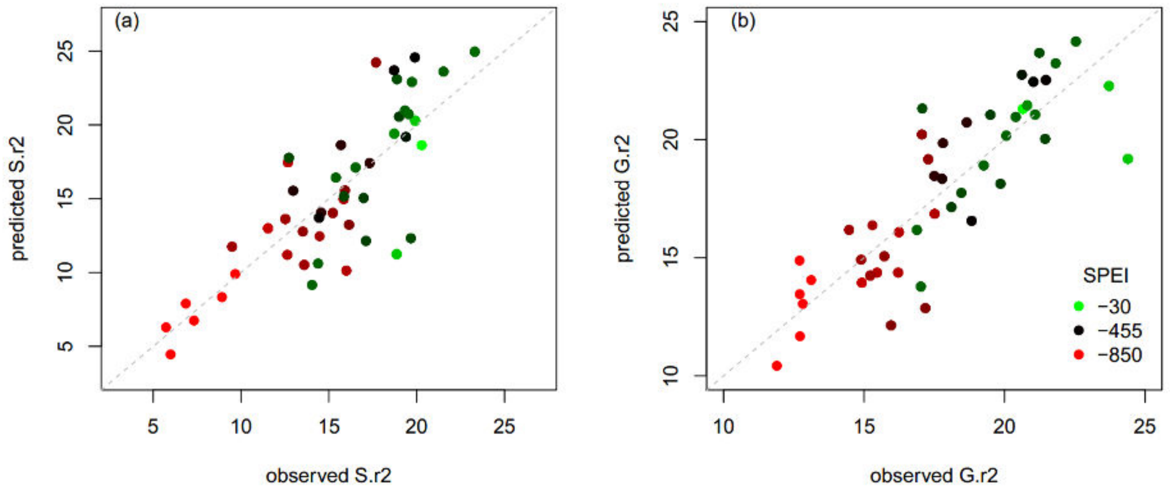


Figure 4. a) shows site index in the 2nd rotation predicted using model 9 versus observed site index in the 2nd rotation. (b) shows then same for basal area at age 8 in the 2nd rotation. Symbol size corresponds to SPEI values (larger are more negative).

To assess the utility of the 2nd rotation prediction models (models 8 and 9) their predictions were used to initiate the growth models described above (Approach 2) and the results compared with outputs from models initated with 2nd rotation observations (Approach 1).

For mean top height prediction in the 2nd rotation the approaches exhibit similar biases, however approach 2 exhibits lower precision (**Error! Reference source not found.**).

Table 14. Bias and precision statistics for mean top height prediction in the 2nd rotation using approaches 1 and 2.

				bias		%bias		precision		%precision	
		N	Approach	1	2	1	2	1	2	1	2
age class	< 4	33		-0.258	0.238	-2.437	0.624	0.576	1.199	4.967	10.660
	< 6	61		-0.128	-0.247	-1.245	-2.911	0.803	1.387	5.480	9.808
	< 8	41		0.335	0.059	1.112	-0.683	0.924	1.538	4.751	8.375
	< 12	21		0.171	-0.228	-0.534	-2.073	1.304	1.631	5.939	8.069
SPEI class	-200	47		-0.067	-0.262	-0.426	-1.544	0.568	1.436	4.414	9.430
	-600	38		0.041	0.144	-0.076	-1.572	0.649	1.540	4.279	11.29
	-400	39		0.268	0.191	0.964	0.028	0.828	1.562	4.346	8.770
	-800	32		-0.189	-0.437	-3.044	-3.587	1.237	0.978	7.326	7.580

For basal area prediction in the 2nd rotation bias in approach 2 is slightly higher in most classes than approach 1. Approach 2 exhibits lower precision. (**Error! Reference source not found.**).

Table 15. Bias and precision statistics for basal area prediction in the 2nd rotation using approaches 1 and 2.

				bias		%bias		precision		%precision	
		N	Approach	1	2	1	2	1	2	1	2
age class	< 4	33		0.268	0.398	1.768	-3.010	0.846	2.37	9.508	26.907
	< 6	61		0.087	0.283	-0.037	-3.882	1.142	2.285	9.483	20.188

	< 8	41	0.035	0.241	-0.808	-2.799	1.375	2.653	8.951	17.616
	< 12	21	-0.615	0.044	-3.264	-1.139	1.045	1.825	5.393	11.136
SPEI class	-200	47	-0.723	-0.006	-6.579	-5.277	1.522	2.230	12.170	21.990
	-600	38	0.446	0.384	3.652	-2.296	0.987	1.979	7.860	15.650
	-400	39	0.486	0.500	3.061	-1.361	1.270	2.882	8.590	20.700
	-800	32	0.024	0.160	0.172	-3.128	0.541	2.132	5.210	20.460

For stand volume prediction in the 2nd rotation approach 2 exhibits slightly higher bias in most classes than approach 1. Precision is ~2 to ~3 times lower throughout than approach 1.

Table 16. Bias and precision statistics for stand volume prediction in the 2nd rotation using approaches 1 and 2.

				bias		%bias		precision		%precision	
		N	Approach	1	2	1	2	1	2	1	2
age class	< 4	33		1.041	3.812	0.716	-3.440	5.291	13.733	12.799	33.983
	< 6	61		-0.564	1.657	-1.500	-8.201	8.168	17.070	13.464	28.475
	< 8	41		1.785	2.754	-1.577	-6.533	11.124	25.028	12.377	26.001
	< 12	21		-4.792	-2.100	-6.071	-6.364	12.245	20.190	9.427	16.710
SPEI class	-200	47		-4.596	-1.903	-9.327	-9.045	11.805	18.560	17.630	30.760
	-600	38		1.083	3.275	1.332	-7.376	7.625	15.483	10.780	23.670
	-400	39		4.596	6.142	3.673	-3.692	10.129	25.589	10.300	28.810
	-800	32		-0.997	-0.737	-0.485	-5.487	4.578	12.963	9.650	25.090

1.2.6 Applying the model to quantify decline

Error! Reference source not found. shows observed mean top height and observed basal area at the time of age 3. A strong correlation is apparent. Three pairs of mean top height and basal area were chosen to initiate growth projection across the range of observed SPEI. **Error! Reference source not found.** to **Error! Reference source not found.** show the resulting projections for mean top height, basal area and volume respectively. Declines in SPEI values lead to declines in productivity that increase in magnitude with age.

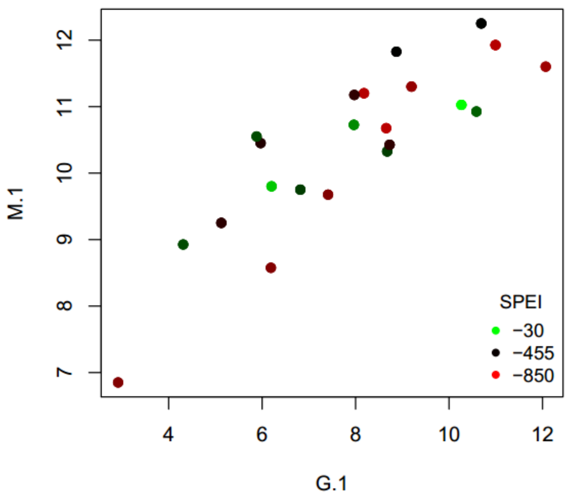


Figure 5. Observed mean top height and observed basal area at the time of age 3

For mean top height the magnitude of the decline increases with decreases in site productivity.

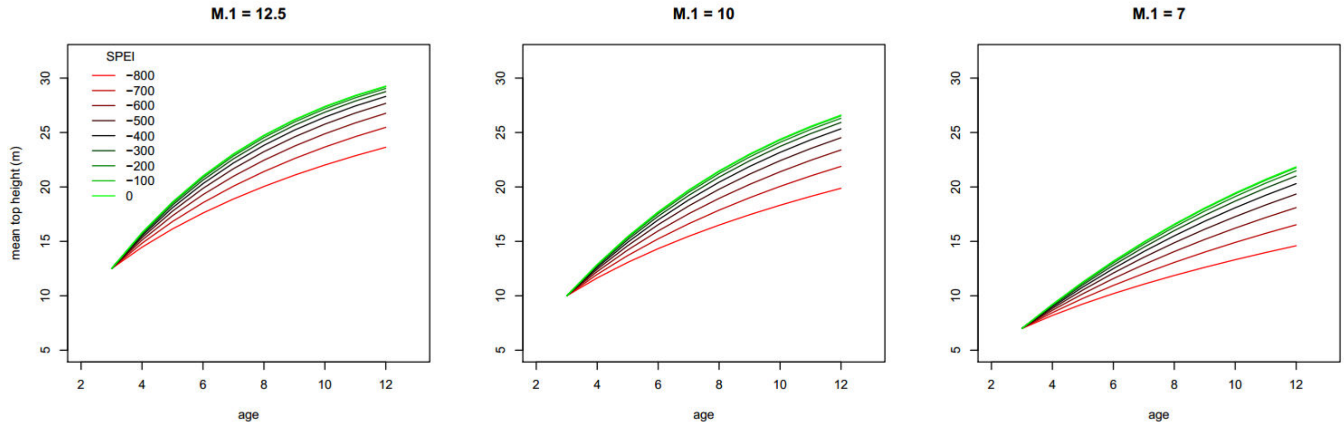


Figure 6. Mean top height as a function of stand age for three first rotation (1R) site indices and a range of climate indices (SPEI). Note for mean top height the magnitude of the decline between the first and second rotation increases with decreases in site productivity.

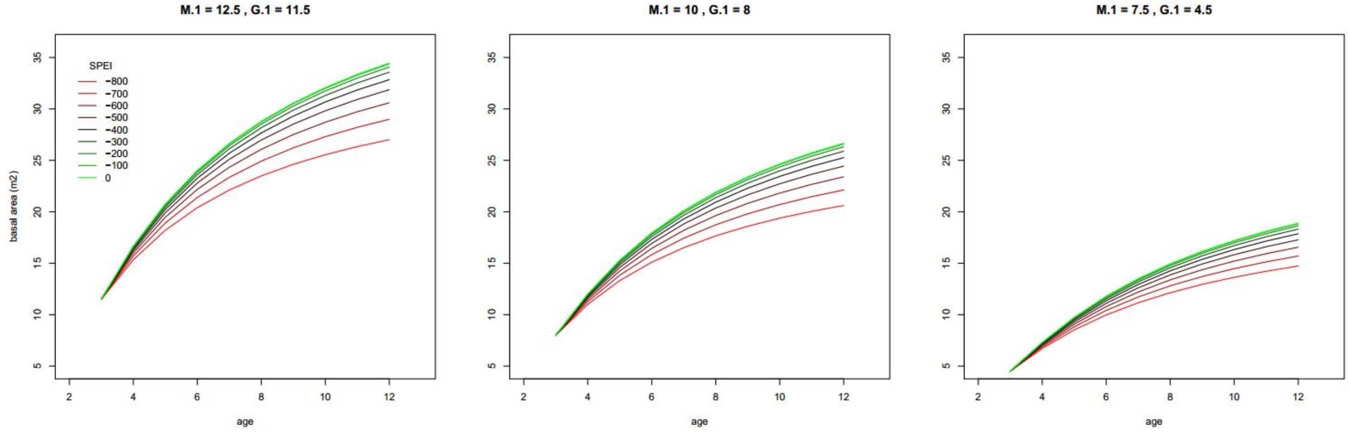


Figure 7. Basal area as a function of stand age for three first rotation (1R) site indices and a range of climate indices (SPEI). TThe magnitude of the decline decreases with decreases in site productivity.

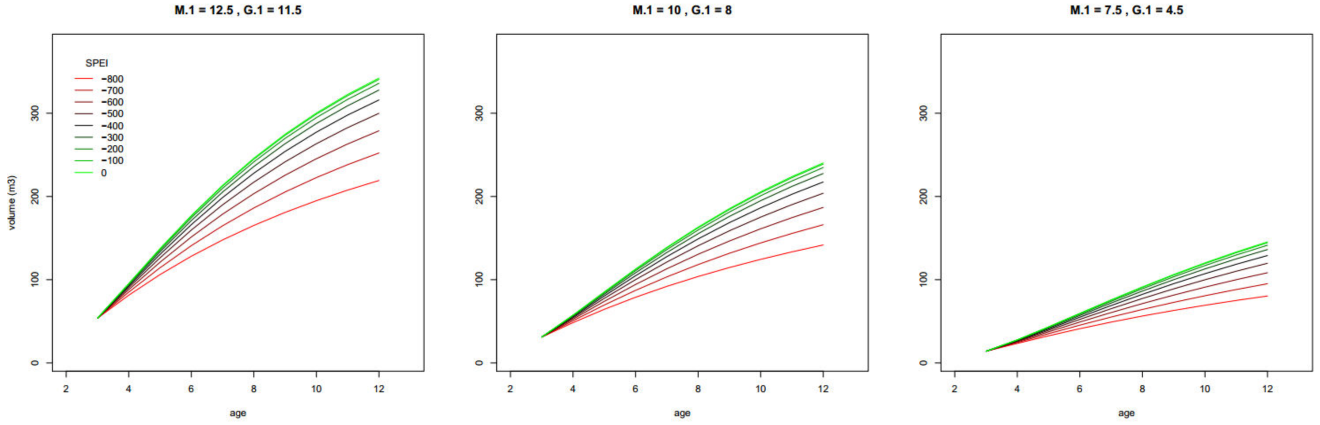


Figure 8. Volume as a function of stand age for three first rotation site indices and a range of climate indices (SPEI). For volume, the trend follows that of basal area. The magnitude of the decline decreases with decreases in site productivity.

Part 2 – Process-based modelling analysis of the extent and causes of second rotation decline among bluegum plantations in Western Australia

Prepared by CSIRO

Process-based models provide one means of assigning growth limits to various sources in multi-factor situations (Battaglia and Sands 1998). This makes them a useful tool for uncovering the factors contributing to 2R decline in Western Australia, where spatial heterogeneity (site conditions, regional differences in weather, plantation to plantation variation in silvicultural), and temporal variation in the growing conditions (the weather in particular rotations, the temporal dynamics of soil nutrient and carbon pools) have determined individual coupe and plantation (compartment) responses. Because inventory data of sufficient quality, with detailed site conditions for spatial mapping of vulnerability of plantations to 2R decline are sparse, these models provide a means to extrapolate spatially from the limited set of observations. Importantly, the models also provide the means to undertake 'what-if analyses' to look at the effectiveness of alternative management strategies to sustain productivity (McCown *et al.* 2002).

In this section we proceed with the following steps:

1. In section 2.1 we establish the effectiveness of a process-based model CABALA in predicting 1R and 2R growth using a small set of data where 1R, 2R growth, detailed site and weather conditions are available.
2. Using these plots, we breakdown the differences between 1R and 2R growth into contributing factors using model outputs: we explore the relative contributions of weather during the first and second rotation, the contribution of changes in nitrogen supply, the effect of changes in soil water storage at the start of the first and second rotation, and finally we investigate the residual variation and explore the extent to which this can be correlated with observation of intensity of insect attack.
3. In section 2.2., using a 0.1 degree map grid, we provide a spatial prediction of where in WA we might expect to observe a difference between 1R and 2R rotation, and we attribute these differences to changes in soil water and changes in soil nutrition from the first and second rotation. We also explore the role of slash management in amplifying inter-rotation soil nutrition changes.
4. Finally in section 2.3 we examine the relationship between extent of decline, site rainfall and the extent to which this can be mitigated by delaying reafforestation with fallow periods. We present some simple tools for industry to evaluate the trade-off between production decline and the opportunity cost of having fallow years.

In this study we use the forest growth process-based model CABALA. CABALA is a dynamic, process based stand growth model that links carbon, water and nitrogen flows through the atmosphere, soil and tree biomass (for full details of the model see (Battaglia *et al.*, 2004). The model runs on a daily time step, optimizing growth according to the resources available (light, nitrogen, carbon and water) to the stand at any one time, with the most limiting resource setting the bounds on production. Net daily production is calculated as the sum of gross primary production minus respiration costs (construction and maintenance). New biomass is allocated to minimise the imbalance between carbon acquisition of foliage, and water and nutrient uptake by roots while ensuring sufficient structural and transport organs exist. The model has been extensively tested and validated (Miehle *et al.*, 2009; Miehle *et al.*, 2010; White *et al.*, 2010a; Mendham *et al.*, 2011)

CABALA utilises a pseudo tipping water balance model – the first 3 layers of the soil profile (0-10cm, 10-20cm, 20-50cm) are required to fill before water can move into the remainder of the profile. The lower profile is then treated as a single pool. There are a number of overlapping compartments that are defined for the calculation of soil water effects. The pool of soil water available to the tree is determined by the dimensions of the root system. As tree roots expand laterally and vertically to fill the soil profile this pool also expands. The calculation of soil evaporation utilises the first three layers of the soil profile while runoff/deep drainage is calculated from the entire soil profile.

The version of model used here differs slightly from that originally described by (Battaglia *et al.*, 2004), and is modified to make it more generally applicable in line with recommended best practice. Medlyn *et al.*, (2011) provided a guide for the selection of appropriate models to use when evaluating the effects of elevated [CO_2] on forest productivity and CABALA was identified as suitable for the questions asked in this study. There have been some improvements to CABALA since that assessment. A biochemical model of C_3 photosynthesis (Farquhar *et al.*, 1980) has been incorporated into CABALA to capture the increase in optimum temperature for photosynthesis under elevated [CO_2]. This reduces the likelihood of over-estimating the effects of rising temperature on photosynthetic rate, particularly in cold sites. The inclusion of the biochemical photosynthesis model (in conjunction with the Ball-Berry optimisation already in CABALA) captures the increase in the ratio of photosynthesis to transpiration (both canopy and leaf scale) under elevated [CO_2]. This leads to improved water use efficiency in water limited environments. It has been observed that when plants are exposed to prolonged periods of elevated CO_2, leaf morphology and biochemistry can change and the maximum rates of photosynthesis are reduced (Franks *et al.*, 2013). In addition to the inclusion of the C_3 photosynthesis model, key parameters of the model ($Vc_{\max}$ and $J_{\max}$) are adjusted for ambient CO_2 levels (after Lewis *et al.*, 2013 and Logan *et al.*, 2010). The photosynthesis model is now linked to the SPA framework, a model of soil-plant hydraulics (Williams *et al.*, 2001) to calculate the hydraulic gradients in trees on an hourly timestep, allowing for better prediction of diurnal tree water stress. This has been described and validated in White *et al.* (2011).

Despite these improvements, there are some limitations with the CABALA model assumptions – nutrients other than nitrogen and carbon are assumed to be in adequate supply and there is uncertainty around the extent to which down regulation will moderate the initial stimulation of photosynthesis to elevated [CO_2]. The water balance components of the model have been previously validated (Mendham *et al.*, 2011). Validation of observed versus predicted values of actual evapotranspiration are presented in Figure S1 for a range sites and shows that under current atmospheric CO_2 conditions the model closely predicts observed *Et* for a range of environmental conditions, including access to groundwater.

A list of the *E. globulus* parameters used in this study is described in Appendix 1.

2.1 Individual plot analysis

2.1.1 Methods

Twelve bluegum plantation sites in south-western Western Australia were selected for this analysis. At these sites first and second rotation growth data and soil profile were available (Error! Reference source not found.**). With one exception sites were fertile and it is unlikely (supported by modelling) that nutrition was limiting in the first or second rotation if slash was retained on site (**

). At all sites, except Caile301, we model in excess of 80 kg N/ha/yr to be available for tree uptake. The sites covered a wide range of soil physical properties ranging from shallow sandy soils to very deep soils, and cover the range of mean annual rainfall range of the bulk of the Western Australian bluegum plantation estate. A qualitative categorisation of insect-damage to plantations into high and low damage, estimated from observed foliage and stem damage, was made by WAPRES staff after visual assessment of stands.

Table 17. Sites and summary of conditions used in analysis. Site names are the first rotation name and inventory number.

Site	OC (%) 0-10cm	CN 0-10cm	Soil Depth (cm)	Max ASW Profile (mm)	Av Annual Rainfall (mm)	Av Annual Evap (mm)	Insect damage in 2R
Caile301	2.58	15	480	520	654	1331	High
Carpe253	3.18	15	600	797	1097	1198	Low
Dunne256	1.15	30	780	511	973	1284	Low
Dunne340	4.02	12	900	820	959	1293	Low
Gardiner304	4.68	12	900	979	952	1457	Low
Linds260	2.97	35	200	291	933	1249	Low
Lovel203	3.98	30	560	557	691	1344	High
Lovel206	4.13	22	600	466	658	1366	High
Seato326	5.23	12	900	1658	616	1311	High
Tippe335	4.21	12	601	503	595	1327	High
Warde245	4.96	12	450	455	653	1326	High
WrenP217	3.36	16	435	553	954	1213	Low

Table 18. Predicted first and second rotation annual nitrogen available to plantations (total mineralised nitrogen less immobilised nitrogen)

Site	First rotation (kg ha^{-1})	Second rotation (kg ha^{-1})
Caile301	66	55
Lovel206	130	96
Lovel203	92	81
Seato326	118	103
Tippe335	103	91
Warde245	110	105
Carpe253	93	81
Dunne256	26	20
Dunne340	120	97
Linds260	89	83
WrenP217	96	85
Gardiner304	109	89

The following modelling protocol was carried out. Firstly, the model was used to simulate first rotation growth assuming the full soil profile as at field capacity. Stands were initialised at 1250 stems per hectare assuming seedling 15 cm height, 1:1 root to shoot ratio and with 150 cm^2 leaf area per seedling. The planting date used for the simulations was as recorded in inventory data supplied by the company. The second rotation was simulated as contiguous with the first, with planting date and fallow between the first and second rotation establishment as indicated in company inventory data (including changed stocking), and soil water and nutrient pools carried simulated continuously through the inter-rotation period. The second rotation was established in simulations as seedlings identical to those in the first rotation the first except for planting date (*i.e.* not change in genetics or seedling quality was assumed). Debris (leaf, bark, branches, stumps and small-ends) were assumed to remain on the site except in the case of Gardiner304, WrenP17 and Warde245 where all above ground slash were cleared as per field treatment.

In subsequent analyses to identify the limiting factors the second rotation was simulated as above except that:
1) In the first instance soil water storage was restored to full at the time of planting the second rotation;
2) In the second, the second rotation received an identical weather sequence to the first rotation;
3) In the third, the second rotation was simulated with the same nutrient supply as the first rotation;
4) And in the fourth, all of the conditions defined in 1), 2) and 3) were applied.

2.1.2 Results

First rotation volume production was predicted with reasonable accuracy ($p<0.001$, $r^2=0.89$, RMSE 27 m^3 ha^{-1}) and in an unbiased manner with the intercept of the regression not significantly different than zero and the slope not significantly different to unity (**Error! Reference source not found.**).

Second rotation production was not predicted as well as the first rotation production (**Error! Reference source not found.**, $r^2=0.60$, $p=0.003$, RMSE=125m^3 ha^{-1}). The model markedly over-predicted second rotation. Removing those plots with high insect damage substantially improved the correspondence between predicted and observed productivity ($r^2=0.86$, $p=0.002$, RMSE=70 m^3 ha^{-1}). The residuals of the second rotation predictions residual (or prediction error calculated as observed 2R volume minus predicted 2R volume) are strongly correlated with the observed, qualitative, level of insect attack in the second rotation (**Error! Reference source not found.**). The result of this is that productivity in plantations with high levels of observed insect damage in the second rotations was substantially over-predicted (mean residual -64± 5 m^3 ha^{-1}) while the predictions for those plots with low insect attack were accurate with a mean residual error not significantly different from zero (mean residual -6± 23 m^3 ha^{-1}).

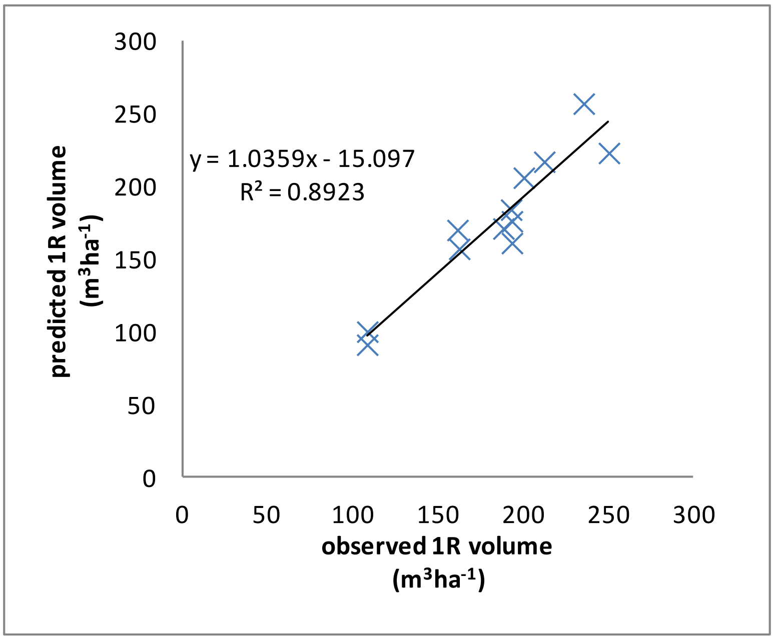


Figure 9. Observed and predicted first rotation volume at the time of last inventory for the case study sites.

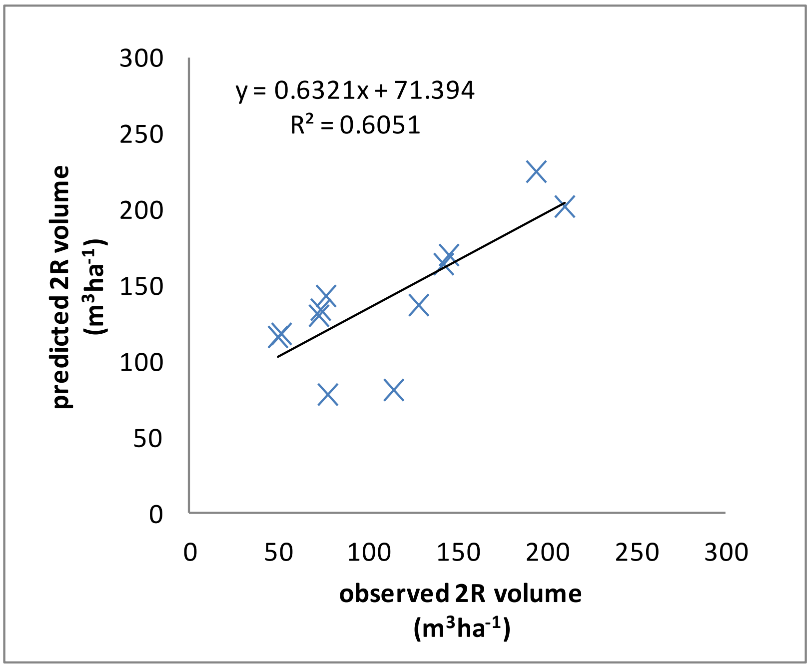


Figure 10. Observed and predicted second rotation volume at the time of last inventory for the case study sites.

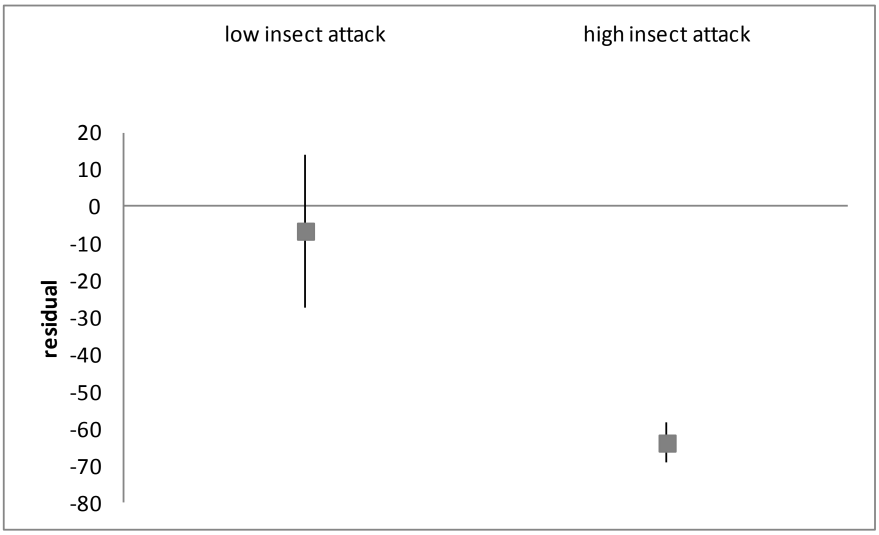


Figure 11 Residual classified against observed level of insect attack at the 2R sites where the residual is the difference between predicted and observed 2R volume at time of last inventory and the 95% confidence interval of the mean is shown for each class of attack.

Predicted water stress was more severe for second rotation compared to first rotation plantations (**Error! Reference source not found.**) and this effect was more pronounced in plantations in which a high level of insect damage was observed (**Error! Reference source not found.**). For those plantations that showed high water stress (this excludes Gardiner304, Wren217 and Carpe253), plots with low insect attack showed no significant increase in water stress between the first and second rotation whereas those with high insect attack showed an increase in water stress (average of 0.22±0.17 MPa).

Table 19 Predicted first and second rotation average leaf water potential (a measure of water stress – lower numbers equate to greater stress).

Site	1R average water stress to same age 2R (MPa)	2Rstress average water stress (MPa)
Caile301	-1.38	-1.40
Lovel206	-1.21	-1.28
Lovel203	-1.17	-1.43
Seato326	-1.17	-1.61
Tippe335	-1.39	-1.56
Warde245	-1.26	-1.41
Carpe253	-0.85	-1.00
Dunne256	-1.35	-1.38
Dunne340	-1.41	-1.55
Linds260	-1.33	-1.36
WrenP217	-0.97	-1.08
Gardiner304	-0.69	-0.71

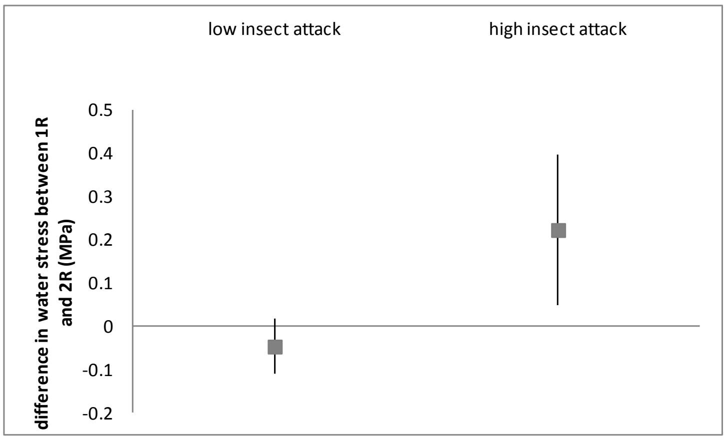


Figure 12 Predicted difference between 1R and 2R average rotation water stress for plantations observed with high and low insect damage, the 95% confidence interval of the mean is shown for each class of attack. Only plots for which significant water stress was observed are included in the analysis, Carpenters253 and Wrens217 where average rotation water stress in the 1R and 2R was less than -1MPa are excluded although both showed an increase of 2R water stress of approximately 0.15 MPa (Table 2).

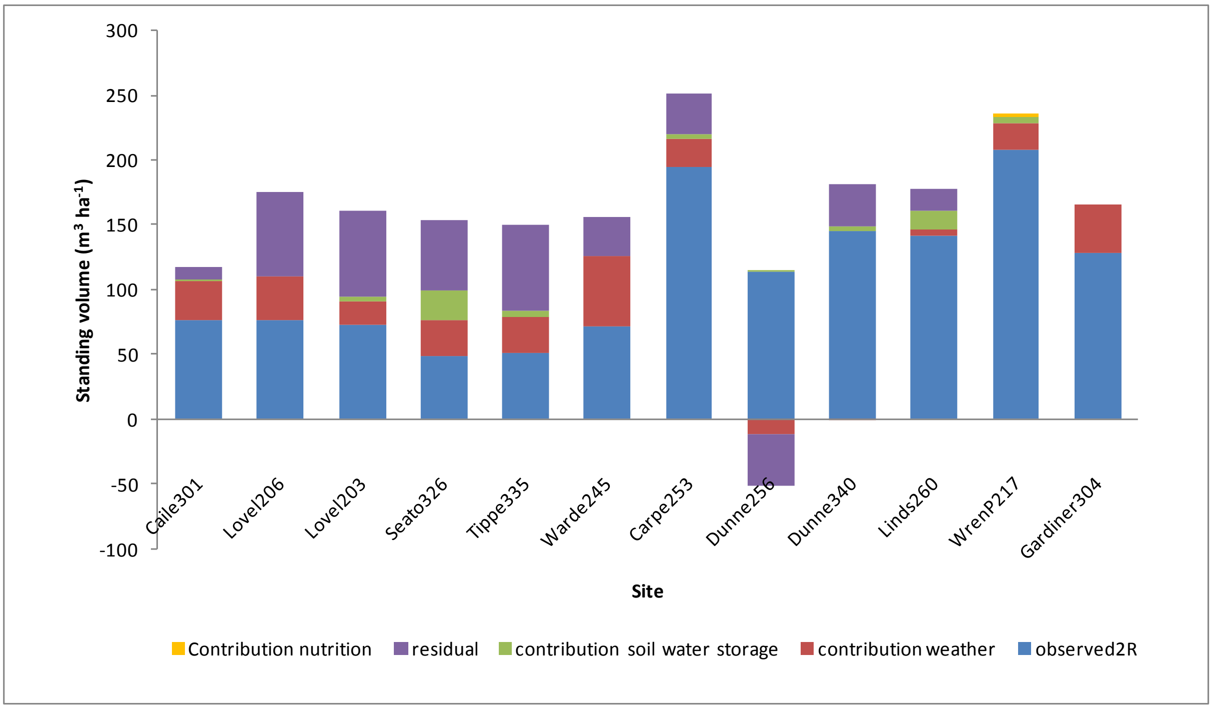


Figure 13. Contribution of soil water, nutrition and weather to the difference between first and second rotation growth. The total height of the each bar is the predicted 1R growth (noting 1R predictions were accurate) at the same age as the last inventory of the 2R, the blue component of each bar is the observed 2R growth. Where the bar drops into the negative it is because 2R growth exceeded predicted 1R growth. The green component was the predicted additional growth if the second rotation had the same soil water stores at time of establishment as the first rotation. The red component was the additional growth predicted if the second rotation had the same weather as the first rotation. The yellow component is that fraction due to nutrient supply change. The residual component is the unexplained shortfall between predicted and observed 2R growth and is the same residual as plotted in the insect damage growth.

Using a modeling approach we can look at the extent to which second rotation decline can be explained by changes in soil water storage and weather differences between the first and second rotation (Figure 13). In this figure, the total bar height above the x-axis (inclusive of all colours/factors) is the observed first rotation volume at the same age as the final second rotation inventory (often the second rotation was measured at an age lesser that the harvest age of the first rotation), while the blue bar is predicted second rotation productivity at the same age. In the case of Dunne256 the second rotation was higher than the first and this is shown by the additional component below the bar.

The analysis then seeks to look at how we can attribute the difference between production in the first rotation (the total bar height) and that observed in the second rotation, the blue bar height.

The green component describes the proportion of the difference that modelling suggests is due to soil water change between rotations. The first rotation typically started with, and was modelled with, the soil profile at field capacity; by the start of the second rotation this was often substantially diminished. On average, the modelled effect of decreased soil water at the start of the second rotation on production was $5 m^3ha^{-1}$ (or 3% of average 1R production), with a maximum contribution of $20\ m^3ha^{-1}$ at Seaton326 (close to a 50% decrease, or 13% of 1R volume). At Dunne 256 and Dunne 340 no portion of production change is due to changed soil water.

The red component is the fraction of change that the modelling suggests is due to weather differences between the first and second rotation. To uncover this the second rotation was simulated using the exact same weather sequence of the first rotation as well as that which actually occurred in the second rotation. In most instances the weather was drier in the second rotation, resulting in a decline in productivity of $22\ m^3ha^{-1}$ or (13% of 1R production), with the biggest decrease being $54\ m^3ha^{-1}$or 36% of first rotation production at Warde245.

The yellow component evident at Wren217 shows that production lost due to reduced nitrogen supply in the second rotation that has occurred following removal of debris in slash burning at harvest time. This practice has made a small (1.5%) difference in second rotation productivity.

An average, unexplained difference (residual) of $27\ m^3ha^{-1}$ remained between predicted and observed second rotation production (16% of first rotation production, or 50% of the total average difference between first and second rotation production). The over-prediction per plot was shown to be correlated with the severity of insect attack (Fig. 12) and was perhaps associated with high tree water stress in the second rotation (Table 19).

In summary, soil water change on average contributed a 3% reduction, weather a 13% reduction, and an unknown component, but one that is possibly due to insect attack contributed 15% of the change between first and second rotation. Simulation did not suggest changes in nutrient supply was yet contributing substantially to changes in productivity, but modelling did suggest that on all sites second rotation nitrogen supply was less than in the first and was likely to become a limiting factor in the future.

2.2 Spatial analysis

2.2.1 Approach: bounding the estimates

Across the Western Australian plantation estate factors controlling production vary markedly (White et al. 2009, 2010). In some areas, the estate is severely limited by water due to limited soil water storage capacity and/or low rainfall and high potential evapotranspiration, and in other parts, limited by soil factors such as nutrition. While the absence of spatially-explicit soils information limits our ability to make point accurate predictions of production the effect of climate can be assessed spatially for particular site classes. If we select 2 indicative levels of site nitrogen fertility, defining medium fertility as combinations of soil carbon and soil carbon to nitrogen ratio resulting in around 80 kg/ha/year of nitrogen mineralisation, and low fertility as combinations providing around 40 kg/ha/yr, and if we define a shallow soil as 4m of depth with around 450mm of plant available soil water storage and a deep soil as 10m depth with around 1200mm of plant available water storage, we can create a set of maps for the WA plantation estate for which the predictions encompass the majority of combinations of soil fertility and soil water storage. Given concerns about inter-rotation slash management, we can further examine the effects of residue removal (either by burning or whole tree harvesting) on productivity changes between the first and second rotation (Figure 14). For all 2R simulations coppice regeneration is assumed (arbitrarily and this should be reviewed in the future) with 10% of stools failing to reshoot with a coppice thinning of 40% of coppice shoots at age 2 years.

2.2.2 Results

Across the entire plantation estate in south west Western Australia, it is predicted that if the same weather conditions prevail in the first to the second rotation, then productivity in the second rotation will range between 0 and 25% lower than in the first where soils are deep (10m deep with around 1200mm of plant available soil water storage at the start of the first rotation). Removal of debris at the time of first harvest markedly increases predicted second rotation decline. In percentage terms the effect is greater on low fertility sites, though significantly lower first rotation production on low fertility sites means that in some cases the absolute reduction is nevertheless less than on medium fertility sites. The changes in both percentage and absolute terms are highest in high rainfall areas than they are in low rainfall areas.

Predicted soil water storage at the start of the second rotation is always lower than at the start of the second due to soil water depletion by the first rotation crop. In higher rainfall areas and on shallower soils this effect is slight, being less than 10% (Figure 15) as recharge is relatively quick due to high inputs (rainfall) or a small storage pool (shallow soils). In low rainfall areas up to a 70% difference can be observed, being equivalent to 700mm or more of stored water.

Another change evident into the second rotation is a decline in available soil nitrogen (Figure 16 and 17). Organic matter quality changes as the lower C:N and higher lignin plantation material replaces the initially high C:N humus material from past agricultural practices at the start of simulated first rotation. This results in a decrease in the predicted nitrogen mineralised (Figure 16), and a predicted increase in nitrogen immobilisation as soil lignin increases

(Figure 17). Over the full 10 years of the second rotation, the effect is in the order of 100 kg N ha^{-1} decrease on medium fertility sites with residue retention and up to 200 kg N ha^{-1} where residues are removed at the end of the first rotation. The effect in absolute supply terms is less on low fertility sites, though the effect has a more marked impact on production given the already limiting levels of available nitrogen. While mineralisation differences are predicted to be more severe on the drier environments, immobilisation is predicted to be higher on the wetter, more productive areas due to the higher lignin input through the higher litter input rate. Replacing 100 kgN ha^{-1} with Urea represents a cost of around \$100 ha, and given that other macro-nutrients will also be lost with residue burning (particular P) then replacing nutrients with a combination (say urea plus DAP) then the figure may be closer to \$300 ha^{-1} (assumed costs from http://archive.agric.wa.gov.au/PC_92453.html).

In summary, the change in productivity between the first and second rotation, predicted to occur across much of the area planted to bluegums in Western Australia, has components of both soil water depletion and of change nitrogen supply. In percentage terms, production decreases are expected to be highest in low rainfall areas, for in these areas the percentage change in soil water storage between the first and second rotation is predicted to be greater than in wet areas, and there is also predicted to be a greater difference between rotations in nitrogen mineralisation. Slash management in the inter-rotation period can markedly affect predicted production decline: removing debris is simulated to markedly decrease nitrogen mineralisation in the second rotation. Additional fertilisation in the second rotation compared with the first, in the order of 100-200 kg ha^{-1} yr^{-1}, may mitigate the changing nitrogen status. However, there may be other effects of residue removal that are not modelled in this analysis such as the loss of soil carbon and its effects on cation exchange capacity, and soil water retention. Addressing the effect of soil water reduction by the first rotation is more difficult. This is investigated in the next section.

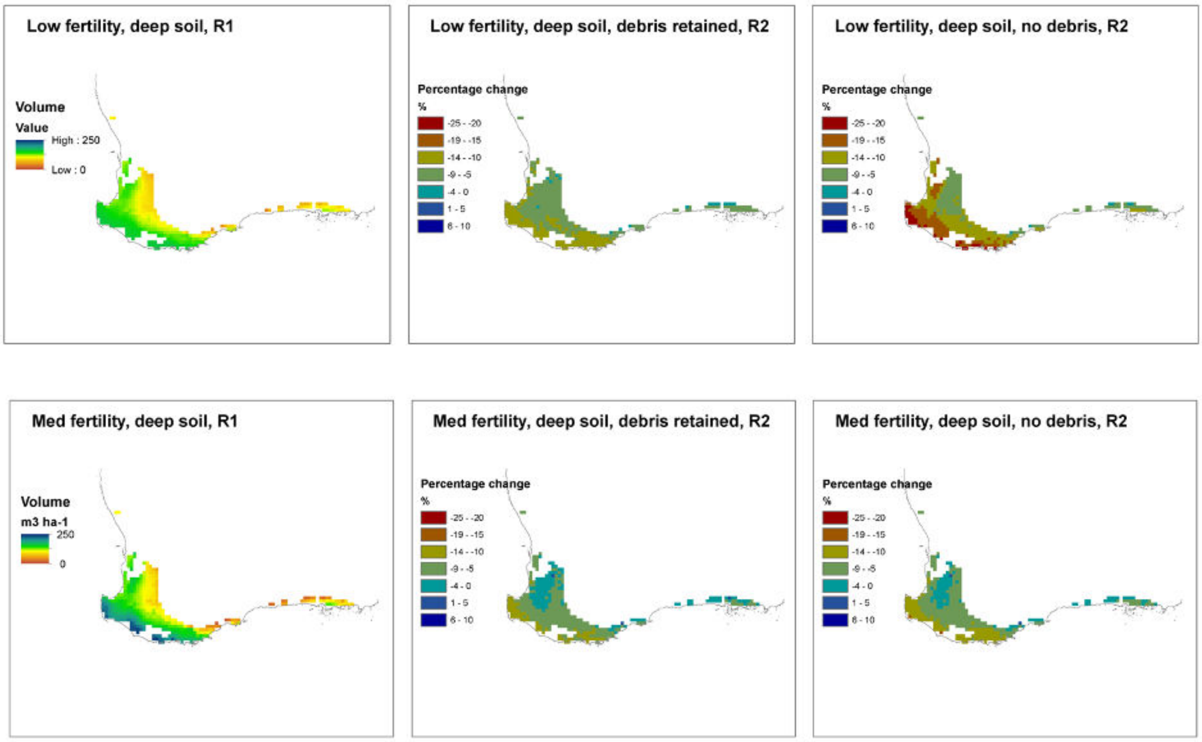


Figure 14 Spatial prediction of 1R production, and change into the second rotation assuming fertility is low (0-10 cm soil organic C=) or moderate (0-10 cm soil organic C=) and soils deep, soil depth 10m), where the logging residues are left distributed on the site or removed (this could be windrow and burnt, or whole tree harvesting).

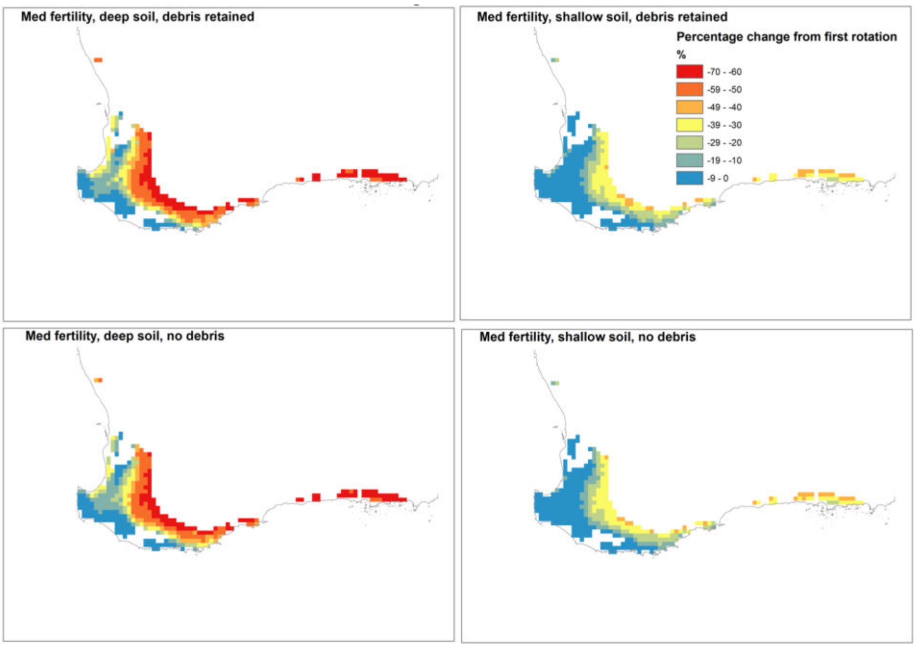


Figure 15 Percentage change in plant available soil water from the start of the first to the start of the second rotation with and without debris retention and on deep and shallow soils.

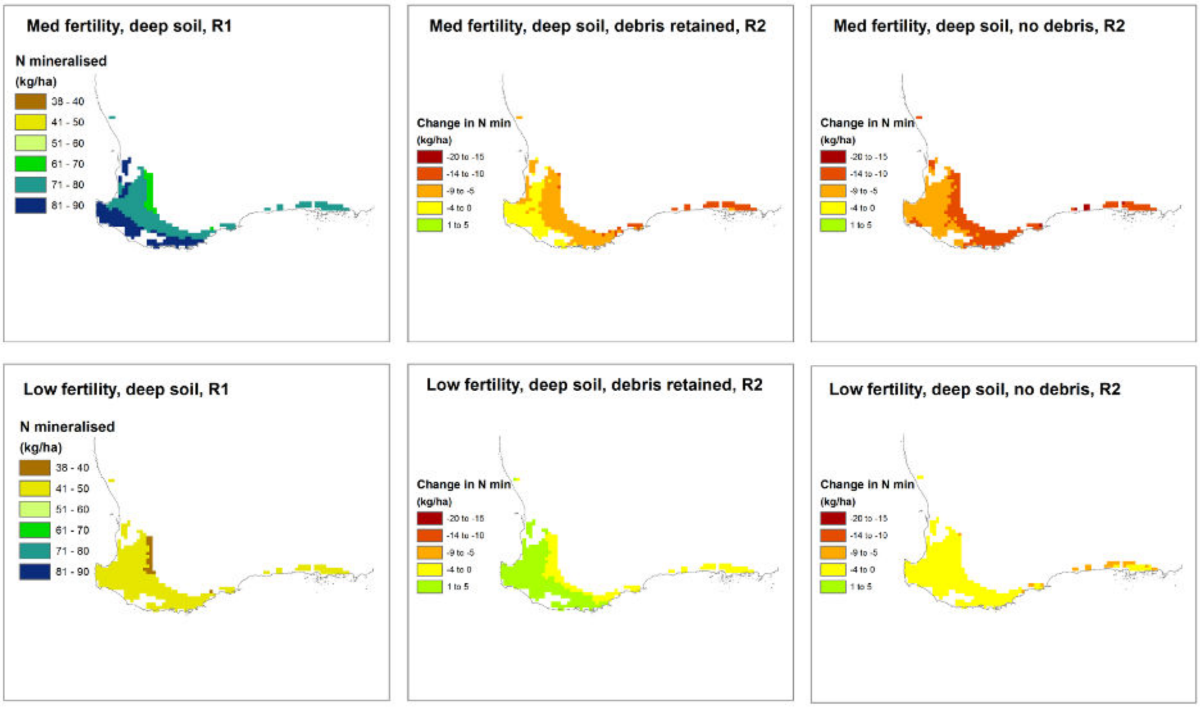


Figure 16 Average annual nitrogen mineralisation (kg N ha^{-1} yr^{-1}) in the first and second rotation with and without slash (debris) retention.

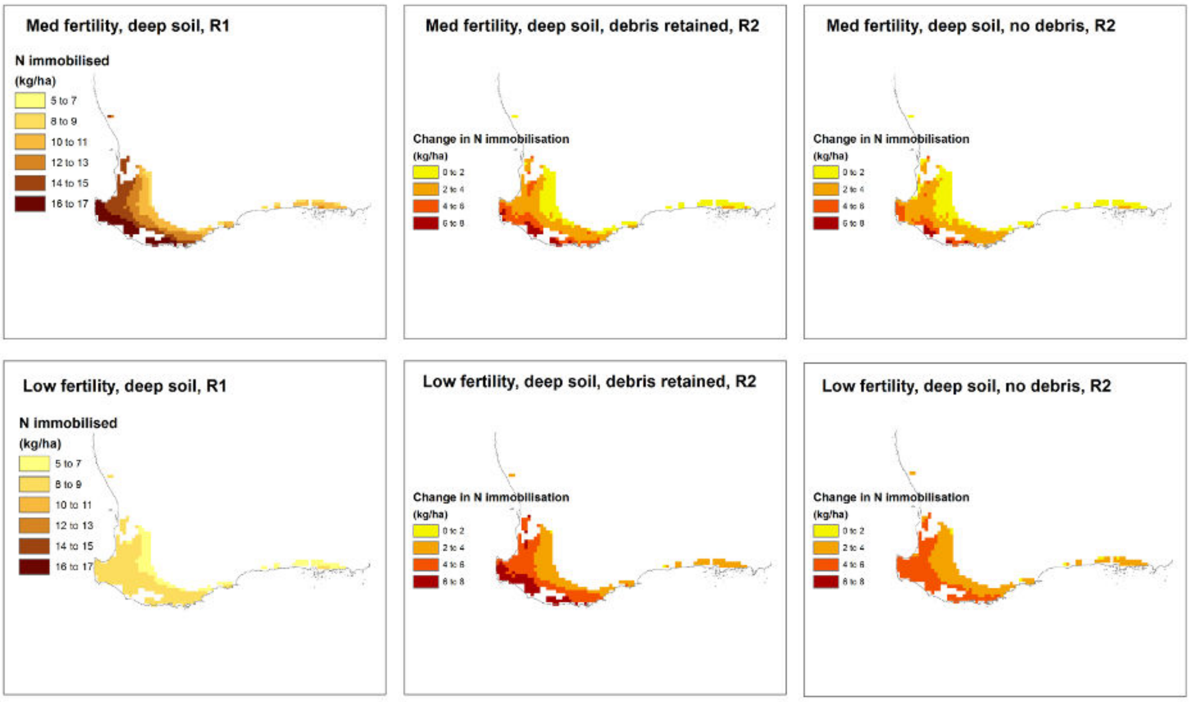


Figure 17 Average annual nitrogen immobilisation (kg N ha^{-1} yr^{-1}) in the first and second rotation with and without slash (debris) retention.

2.3 Decision tools for managing 2R soil water

It is clear from the preceding analysis that inter-rotation changes in soil water storage will impact on second rotation productivity at many sites. However, it has also been shown, here and elsewhere (Menham et al. 2011), that the impact will be dependent on the mean annual rainfall of the site, the productivity of the forest and soil water storage. Mendham et al (2011) suggested that novel management strategies such as fallowing between rotations might allow for soil water replenishment in situations where depletion had occurred in the first rotation. Delaying planting for a year, however, effectively increases the rotation length, and, as a result, reduces the mean annual increment for plantations by a proportion equal to the ratio of the fallow period length to total rotation length (ie. a one year fallow following a 10 year rotation on a site that produces 200 m^3/ha effectively reduces rotation length mean annual increment from 20 to 18, or a 10% reduction). This is clearly an economic decision for the manager: does the extra growth in the second rotation offset the discount to return caused by the longer rotation. To assist this decision making, this section examines the potential maximum growth rate in South Western Australia as a function of soil water, examines likely soil water storage after the first rotation (10 years) for a range of soil depths and mean annual rainfall, and finally examines the rate of soil water recharge under fallow.

Plantation water productivity (as defined by White et al 2014) varies with site fertility and consistent with White et al. (2014), varies from 0.2 g/kg (0.004 m^3/ha per mm of rain+storage) to close to 1g/kg (0.015 m^3/ha per mm of rain+storage) for sites that are moderately fertile, to an upper limit of 2 g/kg (0.04 m^3/ha per mm of rain+storage) for highly fertile sites (Figure 18). While White et al. (2014) records higher water use efficiency (as high as 3.1 g/kg) this is for short periods and not averaged over the rotation as is done here, and in that work the authors note the declining plantation water productivity with increasing stand age. As a reasonable rule of thumb, on a well tended site, Figure 18 that **each mm of increased water storage we can achieve at the start of the second rotation is worth 0.015 m^3/ha of wood** in climates typical of South West Western Australia.

On all but the shallowest sites, substantial soil water deficits are generated at the end of the first rotation (Figure 19). Even where mean annual rainfall is high, some degree of soil water deficit will exist on deep soils one year after the felling of the first rotation. Assuming a site of medium fertility, we can estimate likely lost production if soil water is not allowed to recharge through fallow. At low rainfall, and on sites with deep soil, it can be expected that the second rotation will be at least 10m^3 less in productivity that the first rotation. Seaton Ross from Table 18 would be an example of this type of condition (616 mm rainfall, 9 metre soil depth).

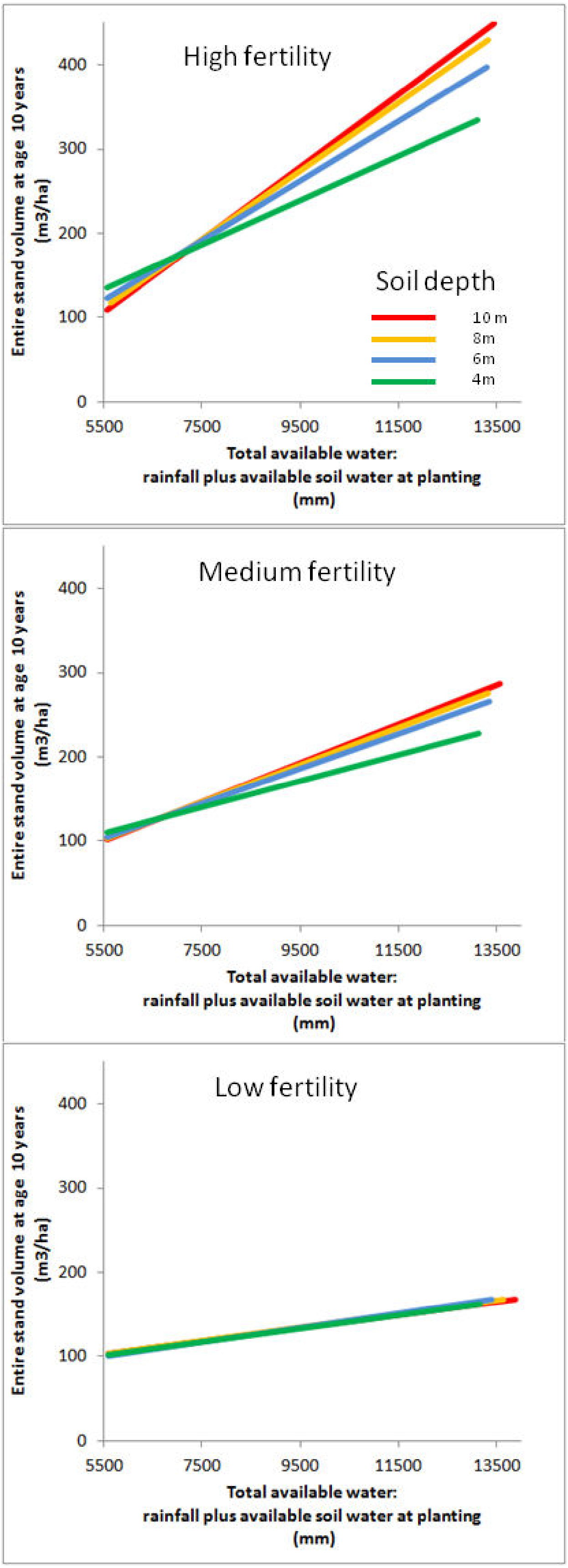


Figure 18 Maximum production (m^3/ha) over the entire 2nd rotation (coppice) modelled for a range of site types under a typical Western Australia climate (Site C in Fig. 19) with different quantities of water (combined soil water and rainfall during the rotation) available for growth across a range of inherent site fertilities.

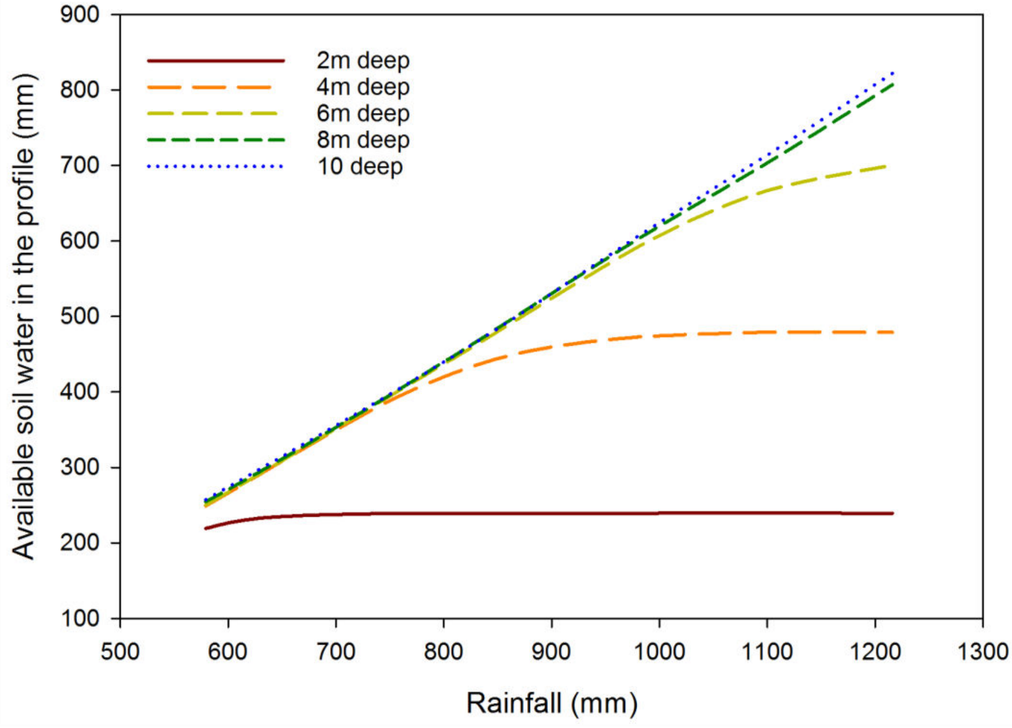
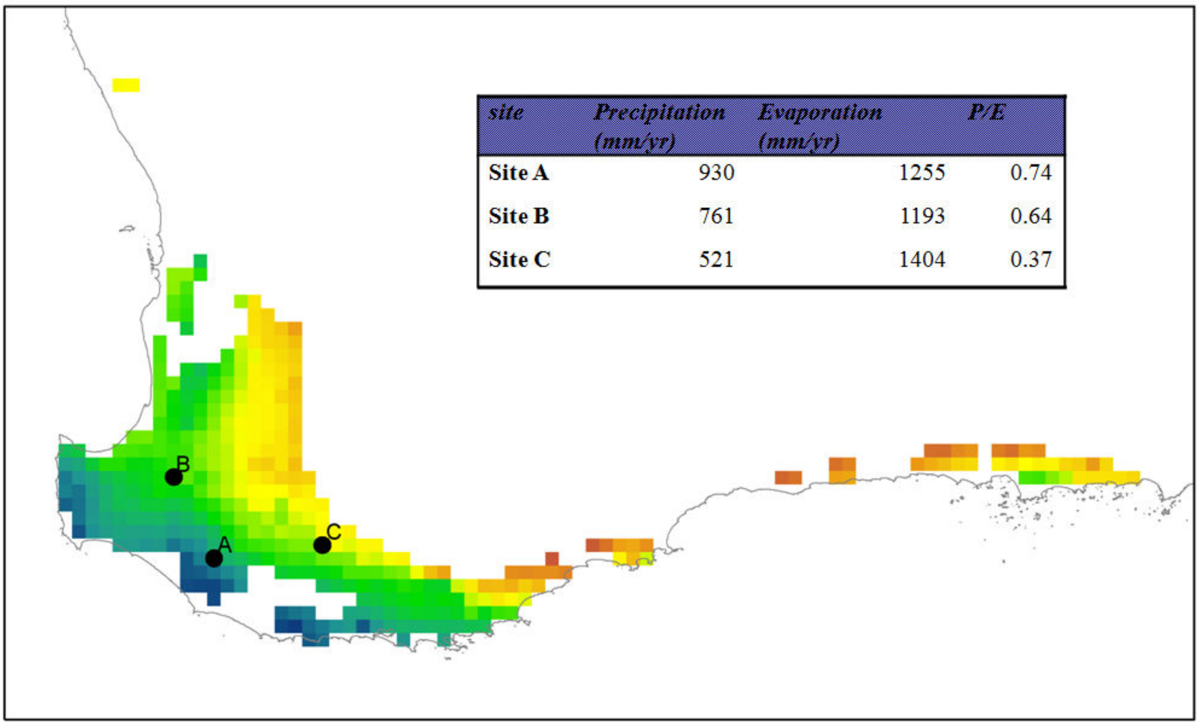


Figure 19 Modelled Available soil water in the profile, 1 year after the felling of a well-tended, first rotation plantation on soils of different depth in areas of different mean annual rainfall. Soils are assumed to hold 110mm of water per metre of soil depth (hence maximum available soil water in the profile at field capacity for the 2 metre deep soil is 220mm and for the 10 metre deep soil it is 1100mm). Radiation and VPD are as per site C in Figure 20.

Table 20 Decrease in production from first rotation to second rotation (m^3/ha) due to decreased soil water storage following first rotation for different soil depths in area of different mean annual rainfall in South West Western Australia (radiation and VPD are that site C from Figure 20).

	rainfall (mm/year)		
soil depth	**700**	**900**	**1100**
2m	0.0	0.0	0.0
4m	1.9	0.3	0.0
6m	4.7	2.4	0.0
8m	8.0	5.0	2.0
10m	11.3	8.3	5.3



site	*Precipitation (mm/yr)*	*Evaporation (mm/yr)*	*P/E*
Site A	930	1255	0.74
Site B	761	1193	0.64
Site C	521	1404	0.37

Figure 20 Location of example plots overlying map of average annual rainfall. Site A (Lat. 34.45 , Long. 116.15) is slightly west of Pemberton, site B (Lat. 33.85 , Long. 115.85) is close to Nannup and Site C (Lat. 34.35 , Long. 116.95) is close to Quinninup.

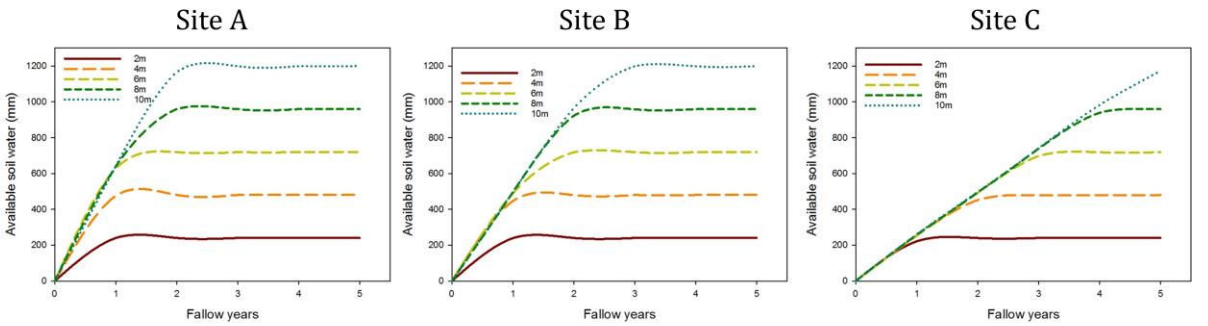


Figure 21 Recharge rates at three example locations is south west Western Australia. Site A (Lat. 34.45 , Long. 116.15) is slightly west of Pemberton with a mean annual rainfall of 930 mm, site B (Lat. 33.85 , Long. 115.85) is close to Nannup with a mean annual rainfall of 761mm and Site C (Lat. 34.35 , Long. 116.95) is close to Quinninup with a mean annual rainfall of 531mm.

To examine soil water recharge rates we used three contrasting sites in the South West of Western Australia (Figure 20). These sites were selected as representing different rain and potential evaporation environments.

At the wettest of the sites full recharge was predicted to occur after 2 years of fallow, as rainfall decreased to 800 mm. Full recharge of soil water on sites with deep soil (10m) was predicted to take 3 years and on dry sites (mean annual rainfall 560mm) full recharge will take at least 5 years of fallow on deep soils (Figure 21). As a general rule, in the absence of a replanted tree crop and where there is no significant weed growth, at sites typical of the water deficit environment (assessed as annual precipitation divided by annual evaporation, P/E) of Site A soil water recharges at a rate of around 500mm/year; at the intermediate site B this occurs around 450mm/year; and on the dry sites typified by site C the recharge rate under fallow is around 200mm/year.

Collectively the data from Figures 18-21 and Table 20 can be used as inputs for decision-making on 2R water management strategy. For example on a deep soiled site (10m) in a 700-800 mm rainfall zone, it is likely that the second rotation will have at least $10m^3$/ha (Table 20) less final stand volume than the first rotation (and if secondary insect attack occurs this reduction is likely to increase). This will occur due to a soil water deficit of 1100 mm at the time of felling and around 750mm at the likely time of planting 12 months later (Figure 19). This could be largely mitigated by an additional year's fallow: at the end of 2 years of fallow following harvest only 100 to 200 mm of soil water deficit would remain (Figure 21).

Taken on its own, a reduction of $10m^3$ suggests that delaying planting by one year or more is unlikely to be economic (ie. $10m^3$ represents about a 10% volume change, but 1 years fallow would represent a 10% increase in rotation length, so that annual productivity taken over the growing time and fallow time would be about the same, and the cash flow potentially worse). However, if secondary insect attack occurs as a result of increased tree water stress (as described in section 2.1.2, it may be a prudent risk management strategy to seek to restore soil water even though the economic outcome in the absence of insect attack may be equivalent or marginally worse.

3. Conclusions and recommendations

3.1 Empirical growth models

We have developed empirical growth models which can be used to predict site index,basal area and volume from two different approaches.

Using the first suite of empirical growth models, gross stand metrics can be estimated if a standardised precipitation evaporation index can be calculated. An alternative approach allows these metrics to be calculated for any age in the second rotation provided 1st rotation site index data is available together with the standardised precipitation evaporation index. While this second approach allows the prediction of important stand metrics for any age it introduces more bias than the first approach which can only be used to predict rotation age stand metrics. **These models have been supplied in spreadsheet form and provide a capacity to predict second rotation productivity.** It should be noted that they are derived from measurements in plantations where management has not yet adapted to the challenges of the second rotation: as second rotation management changes they will become inaccurate and have to be reformulated.

One of the unavoidable problems with any empirical model is that it will be relatively accurate if circumstances remain stable but will become inherently inaccurate if circumstances change. These models have been developed based on data that has been collected at a particular phase of the escalation of insect damage that has been observed on the west coast over the last 6-8 years. This insect attack was initially confined to the lower rainfall zone (e.g. Boyup Bk/Chowerup) but over the last 4-5 years it moved into the medium rainfall zone (e.g. Bridgetown/Greenbushes) and then over the last 2-3 years into quite high rainfall zones (e.g. Manjimup). The highest rainfall zone (e.g. Northcliffe/Scott R/Margaret R) remains relatively unaffected to date. The models are likely to be a very good representation of what was happening 5-10 years ago but with such significant changes in patterns of insect damage since then (which are likely to continue to change i.e. continue to get worse, plateau or start to get better) they are unfortunately very unlikely to be good predictors of what has happened more recently or what will happen in the future. Notwithstanding these considerations the model can allow some immediate assessment of likely changes in 2R production that can be inserted into existing company inventory systems. The evidence from inventory to date, exemplified in these models, is that 2R production will be markedly less and that this will be most acute in low rainfall zones. The most pragmatic approach is to see empirical models as continuous work in progress that need to be reworked constantly as new data becomes available, with great care taken in using them when changes in widespread practice or environmental conditions are evident.

3.2 The severity and causes and potential extent of second rotation decline

3.2.1 Extent and severity

It is clear that the first rotation of bluegum plantations benefited from initial rich site resources in many locations. Years of leguminous-pasture management created ample stores of soil water and nutrients over most of the plantation estate, the exception being those plantations established on ex-bush sites. Without improvement in establishment, tending or harvesting practices, or enhanced tree genetics, **decreased production into the second rotation is inevitable over most of the plantation estate**. In wet areas of high inherent fertility, and conversely of very poor areas, these changes may be so slight as to be undetectable among the noise of plantation variability. **There are site types that will be particularly vulnerable to sharp second rotation decline**: these are sites where substantial soil water stores at the start of the rotation have made a significant contribution to first rotation growth (noting that each mm of soil water store contributes approximately $0.015m^3$/ha at rotation end) and where site fertility is already low so that decreased organic matter quality will markedly impact of soil nutrient supply, to below critical thresholds, in the second rotation. Because we currently lack spatial maps of soil fertility and soil depth for all of SW Western Australia we cannot identify precisely those areas vulnerable to second rotation decline; however in the table below we make some inferences about site type vulnerability.

Table 21 Statement of vulnerability to 2R decline of generalised site types in South West Western Australia.

Site type	Likely risk of 2R decline	Comments
Shallow soil, ex-pasture	**High**	**While high relative impact, absolute impact likely to be low due to low first rotation productivity. High mortality risk from drought in 1R and 2R. Nevertheless if such sites are to be retained in production, careful management of nutrient capital and organic matter inputs is required to sustain site productive potential.**
Shallow soil, ex-bush	**Moderate**	**Managing nutrition and soil organic matter will be critical through multiple rotations, but production will be low. Drought mortality risk moderate, but will increase as site fertility is increased requiring judicious risk management**
Moderate soil depth, ex-pasture	**Moderate**	**Low reliance of first rotation on stored water to drive production may see only modest change, but moderate to high production in first rotation may place significant demands on soil nutrition which may require management into subsequent rotations. Drought mortality and pest risk may be exacerbated into 2R**
Moderate soil depth, ex-	**low**	**Low reliance of first rotation on stored**

Site type	Likely risk of 2R decline	Comments
bush		**water to drive production may see only modest change, and unless fertilisation was high in first rotation, productivity was already nutrient limited. With appropriate residue management, production should not markedly decrease, but with good fertiliser inputs and organic matter management should increase through multiple rotations. Drought mortality and pest risk may be exacerbated into 2R by early water-stress in young plantations.**
Deep soils, ex pasture	**High**	**The first rotation will have significantly benefited from stored soil water and high nutrient capital. Both sets of resources will be depleted moving into the second rotation. Given high productivity of these sites similar percentage changes in production to other sites will result in large absolute changes in production. There is considerable potential to improve both productivity and uniformity of site quality through multiple rotations with best practice management.**
Deep soils, ex bush	**Moderate**	**The first rotation will have significantly benefited from stored soil water but unless significant fertiliser inputs were added production was probably limited by fertility. Realising the site productive potential will require fertiliser inputs and management of soil chemical and physical properties. There is considerable potential to improve both productivity and uniformity of site quality through multiple rotations with best practice management.**

3.2.2 Causes

The most obvious causes of 2R decline might appear to insect attack – our analysis on individual plots shows that volume production has most markedly been reduced in those plantations most severely affected by pests. However, insect pests (especially borers) are likely to be a secondary factor following on from the primary factor of water stress (see for example Pinkard et al 2011; Mitchell et al. 2013). Importantly, the occurrence of attack is not certain, but the probability of pest attack may be increased by primary stress such as drought. In addition to the growing food and habitat base afforded by the expanding plantation resource in Western Australia, two factors are likely to be predisposing second rotation plantations to pest attack; a drying climate and the longer period over the rotation to which trees are exposed to water stress as a result of depletion of soil water in the first rotation, and in particular the increased exposure of young stands to water stress. This is an area of considerable uncertainty, but also complexity, and the situation on the ground is unlikely to be as neatly explained as described here. Pinkard et al (2014) describe pest risk and climate suitability in eucalypt plantations and the drivers of susceptibility.

While our plot analysis suggests that changes in soil nutrition are not likely to be affecting production of stands on ex-pasture sites into the second rotation, both modelling and experience from other plantation systems suggest that nutrient supply will be declining into the second rotation as the nutrient capital from prior agricultural land use is depleted. Modelling suggests that on lower fertility sites this will impact productivity and that, on higher fertility sites, it will impact into future rotations. Declining nutrient resources will be exacerbated by burning or removal of residues. Our modelling shows this as a factor that will markedly impact of future site productivity.

3.3 Conclusion

While the exact balance of factors contributing to 2R decline at any one location is complex and hard to attribute, we do know enough about forest production and sustainability to identify practices to minimise future production loss. Balancing forest production and drought risk combined with careful stewardship of soil resources are fundamental in the south west Western Australian environment to sustaining productivity. Without management of these resources we will not realise the benefits of improved genetics, or forest management technologies. Much of the area planted in south west Western Australia was given a once off ‘freebie’ of soil nutrient and soil water capital. Changes into the second rotation were anticipated. Evidence from the pine sector in Australia and fast growing plantation areas in other parts of the world such as Brazil or South Africa, shows that this capital can be invested through best management practice to realise a dividend from improved genetics and forest management and harvesting technology in increased production realised through multiple rotations, or it can be squandered in a downward spiral of site resource depletion and decreased growth potential.

4. References

Bates D and Maechler M (2010) lme4: Linear Mixed-Effects Models Using S4 Classes, R package version 0.999999-0.

Battaglia M, Bruce J, Brack. C, Baker T (2009) Climate change and Australia's plantation estate: analysis of vulnerability and preliminary investigation of adaptation options. Canberra.

Battaglia, M., P.J. Sands, D. White and D. Mummery 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. Forest Ecology and Management. 193:251-282.

Battaglia, M. and P. J. Sands. 1998. Process-based forest productivity models and their application in forest management. For. Ecol. Management **102**:13-32.

Candy SG (1997) Growth and yield models for Eucalyptus nitens plantations in Tasmania and New Zealand. TasForests 9, 167–198.

Candy SG and Gerrand A (1997) Comparison of financial returns from sawlog regimes for Eucalyptus nitens plantations in Tasmania. TasForests 9, 35–50.

Corbeels, M., R. E. McMurtrie, D. A. Pepper, and A. M. O'Connell. 2005. A process-based model of nitrogen cycling in forest plantations. Part II. Simulating growth and nitrogen mineralisation of Eucalyptus globulus plantations in south-western Australia. Ecological Modelling **187**:449-474.

Crosbie RS, Jolly ID, Leaney FW, Petheram C, Wohling D (2010) Review of Australian groundwater recharge studies. CSIRO Water for a Healthy Country National Research Flagship, Canberra.

CSIRO (2014) State of the climate. http://www.csiro.au/State -of-the -Climate-2014

Evans, J. 1976. Plantations: Productivity and Prospects. Australian Forestry **39**:150-163.

Evelyn, J. 1665. Sylva or discourse on forest trees. Hunter's Edition of 1775, York 1801, op. cit. Evans 1976.

Eyles, A., C. Beadle, K. Barry, A. Francis, M. Glen, and C. Mohammed. 2008. Management of fungal root-rot pathogens in tropical Acacia mangium plantations. Forest Pathology **38**:332-355.

Farquhar, G.D., S.V. Caemmerer and J.A. Berry 1980. A Biochemical-Model of Photosynthetic Co2 Assimilation in Leaves of C-3 Species. Planta. 149:78-90.

Ferguson, I. 2014. Australian plantation inventory: ownership changes, availability and policy. Australian Forestry **77**:25-38.

Flinn DW (1978) Comparison of establishment methods for Pinus radiata on a former P. pinaster site Australian Forestry 41, 167-176.

Franks, P. J., M. A. Adams, J. S. Amthor, M. M. Barbour, J. A. Berry, D. S. Ellsworth, G. D. Farquhar, O. Ghannoum, J. Lloyd, N. McDowell, R. J. Norby, D. T. Tissue, and S. von Caemmerer. 2013. Sensitivity of plants to changing atmospheric CO2 concentration: from the geological past to the next century. New Phytologist **197**:1077-1094.

Harwood CE, Nambiar EKS (2014) Sustainable plantation forestry in Southeast Asia. CSIRO Sustainable Agriculture National Research Flagship, Canberra.

Hennessy KB, Fitzharris B, Bates BC, Harvey N, Howden M, Hughes L, Salinger J, Warrick R (2007) Australia and New Zealand: climate change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge,, UK.

Jones HE, Madeira M, et al. (1999) The effect of organic-matter management on the productivity of Eucalyptus globulus stands in Spain and Portugal: tree growth and harvest residue decomposition in relation to site and treatment. Forest Ecology and Management 122(1–2), 73-86.

Katzensteiner, K., G. Glatzel, M. Kazda, and H. Sterba. 1992. Effects of air pollutants on mineral nutrition of Norway spruce and revitalization of declining stands in Austria. Water, Air, and Soil Pollution **61**:309-322.

Keeves A (1966) Some evidence of loss of productivity with successive rotations of Pinus radiata in the southeast of South Australia. Australian Forestry 30, 51-63.

Lewis, J. D., R. A. Smith, O. Ghannoum, B. A. Logan, N. G. Phillips, and D. T. Tissue. 2013. Industrial-age changes in atmospheric [CO2] and temperature differentially alter responses of faster- and slower-growing Eucalyptus seedlings to short-term drought. Tree Physiology **33**:475-488.

Logan, B. A., C. R. Hricko, J. D. Lewis, O. Ghannoum, N. G. Phillips, R. Smith, J. P. Conroy, and D. T. Tissue. 2010. Examination of pre-industrial and future [CO2] reveals the temperature-dependent CO2 sensitivity of light energy partitioning at PSII in eucalypts. Functional Plant Biology **37**:1041-1049.

Mendham, D. S., A. M. O'Connell, T. S. Grove, and S. J. Rance. 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. For. Ecol. Management **181**:357-372.

McCown, R. L., Z. Hochman, and P. S. Carberry. 2002. Probing the enigma of the decision support system for farmers: Learning from experience and from theory. Agricultural Systems **74**:1-10.

Medlyn, B. E., R. A. Duursma, and M. J. B. Zeppel. 2011. Forest productivity under climate change: a checklist for evaluating model studies. Wiley Interdisciplinary Reviews-Climate Change **2**:332-355.

Mendham, D., M. Battaglia, D. A. White, C. E. Harwood, and S. Abou Arra. 2005. An analysis of 2nd rotation *E. globulus* productivity with variable stocking, rainfall and genetic gain. Client Report, CSIRO Forestry and Forest Products, Canberra.

Mendham DS, Grove TS, O'Connell AM, Rance SJ (2008) 'Impact of inter-rotation site management on soil nutrients and plantation productivity in Euclayptus globulus plantations in south-Western Australia.' (Centre for International Forestry Research).

Mendham DS, Ogden GN, Short T, O'Connell TM, Grove TS, Rance SJ (2014) Repeated harvest residue removal reduces E. globulus productivity in the 3rd rotation in south-western Australia. Forest Ecology and Management 329(0), 279-286.

Mendham DS, White DA, Battaglia M, McGrath JF, Short TM, Ogden GN, Kinal J (2011) Soil water depletion and replenishment during first- and early second-rotation Eucalyptus globulus plantations with deep soil profiles. Agricultural and Forest Meteorology 151(12), 1568-1579.

Miehle, P., M. Battaglia, P. J. Sands, D. I. Forrester, P. M. Feikema, S. J. Livesley, J. D. Morris, and S. K. Arndt. 2009. A comparison of four process-based models and a statistical regression model to predict growth of Eucalyptus globulus plantations. Ecological Modelling **220**:734-746.

Miehle, P., R. Grote, M. Battaglia, P. M. Feikema, and S. K. Arndt. 2010. Evaluation of a process-based ecosystem model for long-term biomass and stand development of Eucalyptus globulus plantations. European Journal of Forest Research **129**:377-391.

Mitchell, P. J., M. Battaglia, and E. A. Pinkard. 2013. Counting the costs of multiple stressors: is the whole greater than the sum of the parts? Tree Physiology **33**:447-450.

Morris, A. R. 2008. Realising the benefit of research in eucalypt plantation management. Southern Forests **70**:119-129.

Musk, R.A. (2011) Calibrating a growth and yield model for Eucalyptus nitens and E. globulus plantations, CRC for Forestry Technical Report 213 June 2011 33pp.

Nambiar, S. 2010. Sustainability of eucalypt plantations in Australia is failing. Australian Forestry **73**:207-208.

Nambiar EKS (2003) Science and technology for sustainable development of plantation forests. Australian Forestry 66(1), 43-50.

Nambiar EKS, Brown AG (1997) 'Management of Soil, Nutrients and Water in Tropical Plantation Forests, .' (Australian Centre for International Agricultural Research: Canberra, Australia.).

Nambiar EKS, Cossalter C, Tiarks A (1999) Site mangement and productivity in tropical plantations. CIFOR, Pietermaritzburg, South Africa.

O'Connell, A. M., T. S. Grove, D. S. Mendham, and S. J. Rance. 2003. Changes in soil N status and N supply rates in agricultural land afforested with eucalypts in south-western Australia. Soil Biology & Biochemistry **35**:1527-1536.

O'Hehir JF, Nambiar EKS (2010) Productivity of three successive rotations of P. radiata plantations in South Australia over a century. Forest Ecology and Management 259(10), 1857-1869.

Petrone KC, Hughes JD, Van Niel TG, Silberstein RP (2010) Streamflow decline in southwestern Australia, 1950–2008. Geophysical Research Letters 37(11), L11401.

Pinkard, E. A., M. Battaglia, J. Bruce, A. Leriche, and D. J. Kriticos. 2010. Process-based modelling of the severity and impact of foliar pest attack on eucalypt plantation productivity under current and future climates. For. Ecol. Management **259**:839-847.

Pinkard EA, Battaglia M, Roxburgh S, O'Grady AP (2011) Estimating forest net primary production under changing climate: adding pests into the equation. Tree Physiology 31, 686-699.

Pinkard EA, Bruce J, Battaglia M, Matthews S, Drew D, Downes G, Crawford D, Ottenschlaeger M (2014) Adaptation strategies to manage risk in Australia's plantations. Forest and Wood Products Australia.

R Development Core Team (2013) R: A language and environment for statistical computing. (R Foundation for Statistical Computing: Vienna, Austria).

Saint-Andre L, Laclau J-P, et al. (2008) 'Slash and litter management effects on Euclayptus productivity: a synthesis using a growth and yeild modelling approach.' (Centre for International Forestry Research).

Squire RO (1983) Review of second rotation silviculture of Pinus radiata plantations in southern Australia: establishment practice and expectations. Australian Forestry 46(2), 83-90.

Squire RO, Farrell PW, Flinn DW, Aeberli BC (1985) Productivity of first and second rotation stands of radiata pine on sandy soils II. Height and volume growth at five years. Australian Forestry 48(2), 127-137.

Squire RO, Flinn DW Site disturbance and nutrient economy of plantations with special reference to radiata pine on sads. In 'Proceedings of the Australian Forest Nutrition Workshop', 1981, Canberra, ACT, pp. 144-161

Squire RO, Flinn DW, Farrell PW (1979) Productivity of first and second rotation stands of radiata pine on sandy soils. 1. Site factors affecting early growth. Australian Forestry 42, 226-235.

Turner J, Lambert M (2014) Analysis of long term productivity and productive capacity of radiata pine plantation on infertile fine textured soils. Forests and Wood Products Association, Melbourne.

Venables WN and Ripley BD (2002) Modern applied statistics with S. Fourth edition. (Springer: New York).

Wang Y and Baker T (2007) A regionalised growth model for Eucalyptus globulus plantations in south-eastern Australia. Australian Forestry 70(2), 93–107.

White, D. A., J. F. McGrath, M. G. Ryan, M. Battaglia, D. S. Mendham, J. Kinal, G. M. Downes, D. S. Crombie, and M. E. Hunt. 2014. Managing for water-use efficient wood production in Eucalyptus globulus plantations. For. Ecol. Management **331**:272-280.

White D, Battaglia M, Bruce J, Benyon R, Beadle C, McGrath J, Kinal J, Crombie S, Doody TM (2009) Water-use efficient plantations-separtaing the wood from the leaves. Forest and Wood Products Australia.

White, D. A., M. Battaglia, D. S. Mendham, D. S. Crombie, J. Kinal, and J. F. McGrath. 2010. Observed and modelled leaf area index in Eucalyptus globulus plantations: tests of optimality and equilibrium hypotheses. Tree Physiology **30**:831-844.

White, D.A. et al. 2011. Climate driven mortality in forest plantations – prediction and effective adaptation. Report to the Department of Agriculture, Fisheries and Forestry. CSIRO, Canberra

Whyte AGD (1973) Productivity of first and second order crops of Pinus radiata on the Moutere gravel soils of Nelson. New Zealand Journal of Forestry Science 18, 87-103.

Williams, M., E.B. Rastetter, D.N. Fernandes, M.L. Goulden, S.C. Wofsy, G.R. Shaver, J.M. Melillo, J.W. Munger, S.W. Fan and K.J. Nadelhoffer 1996. Modelling the soil-plant-atmosphere continuum in a Quercus-Acer stand at Havard Forest: the regulation of stomatal conductance by light, nitrogen and soil/plant hydraulic properties. Plant, Cell and Environment. 19:911-927.

Wong, J., Baker, T.G., Duncan, M.J., Stackpole, D.J. and Stokes, R.C. (1999) Individual Tree Volume Functions for Plantation Eucalypts. Report No. 99/037. Centre for Forest and Tree Technology, Department of Natural Resources and Environment, Victoria.

Acknowledgements

We thank our industry partners for cash and in-kind support for this project and for supplying their inventory and permanent sample plot data. In particular John Weidmann and Sara Mathieson from WAPRES contributed a large amount of time and data without which the project would not have been possible. In addition to FWPA we would also like to thank the CRC for Forestry for a substantial financial contribution, cash and in-kind, to the project. We thank Libby Pinkard, CSIRO, and John Weidmann, WAPRES, for reviewing the document.

APPENDIX 1 CABALA PARAMETERISATION FOR *E. globulus* USED FOR THIS STUDY (CABALA v5.1)

Model section	Symbol or program name	definition	Unit	Values
Leaf conductance parameters	g_0	Minimum stomatal conductance	mol(H20)m^{-2}(ground)s^{-1}	0.01
Leaf conductance parameters	g_1	Determines VPD dependency of water use efficiency	mol(H20)m^{-2}(ground)s^{-1}	2
Leaf conductance parameters	G_B	Maximum tree canopy boundary layer conductance	mol(H20)m^{-2}(ground)s^{-1}	4
Leaf conductance parameters	F_{Y3}	Number of days today's water stress influences conductance	days	8
Leaf conductance parameters	$r_{Q\text{-}C}$	Fraction of radiation that is reflected by crown	dimensionless	0.3
Low temperature effects and hardening	$F_{R\text{-}P}$	Temperature range between 0 and 100% Pn damage from low temp	°C	5
Low temperature effects and hardening	$F_{D\text{-}F\text{-}UH}$	Temperature at which 50% foliar damage in unhardened material	°C	-3
Low temperature effects and hardening	$F_{D\text{-}F\text{-}H}$	Temperature at which 50% foliar damage in fully hardened material	°C	-7
Low temperature effects and hardening	$F_{R\text{-}F}$	Temperature range between 0 and 100% foliar damage from low temp	°C	5
Low temperature effects and hardening	$F_{D\text{-}P\text{-}UH}$	Temperature at which 50% pn damage in unhardened material	°C	0
Low temperature effects and hardening	$F_{D\text{-}P\text{-}H}$	Temperature at which 50% pn damage in fully hardened material	°C	-2
Low temperature effects and hardening	$F_{a\text{-}P}$	Constant in definition of pn frost hardiness	°C	-3
Low temperature effects and hardening	$F_{b\text{-}P}$	Constant in definition of pn frost hardiness	°C	0.5
Low temperature effects and hardening	$F_{c\text{-}P}$	Constant in definition of pn frost hardiness	C	0.03
Low temperature effects and hardening	$F_{a\text{-}F}$	Constant in definition of foliar frost hardiness	°C	-26
Low temperature effects and hardening	$F_{b\text{-}F}$	Constant in definition of foliar frost hardiness	°C	3
Low temperature effects and hardening	$F_{c\text{-}F}$	Constant in definition of foliar frost hardiness	°C	0.02
Low temperature effects and hardening	F_p	Exponent of frost impact factor defining long term pn impact		0.15
Low temperature effects and hardening	F^{+}	Number of days for full pn recovery from long term frost damage	days	14

Model section	**Symbol or program name**	**definition**	**Unit**	**Values**
Low temperature effects and hardening	F_T	Average daily temperature below which pn recovery reduced	°C	15
Photosynthetic parameters	α_0	Value of light use efficiency at base temperature (20oC)	mol(CO2) mol^{-1}(PAR)	0.05
Photosynthetic parameters	α_1 alpha1	Temperature sensitivity of light use efficiency	°C^{-1}	0.016
Photosynthetic parameters	A^*_{opt}	Intracellular CO2 saturated rate of carbon assimilation	μmol (CO2)m^{-2} (leaf) s^{-1}	56
Photosynthetic parameters	T^*_{opt}	Optimum temperature for photosynthesis	°C	15
Photosynthetic parameters	k	Canopy light extinction coefficient	m²(ground) m^{-2}(leaf)	0.5
Photosynthetic parameters	θ	Shape of single-leaf light response curve	dimensionless	0.95
Photosynthetic parameters	$t_{1/2-}$	Determines sensitivity of assimilation to low diurnal temperatures	°C	11
Photosynthetic parameters	$t_{1/2+}$	Determines sensitivity of assimilation to high diurnal temperatures	°C	11
Photosynthetic parameters	Γ	Photosynthetic CO2 compensation point	Pa	59
Photosynthetic parameters	t	Determines extent of seasonal acclimation of Topt	dimensionless	0
Photosynthetic parameters	T_{pref}	Parameter determining seasonal acclimation of Topt	°C	23
Photosynthetic parameters	$t^*_{1/2-}$	Determines acclimation of Aopt to low seasonal temperatures	°C	999
Photosynthetic parameters	$t^*_{1/2+}$	Determines acclimation of Aopt to high seasonal temperatures	°C	999
Photosynthetic parameters	upregulation	Maximum proportional up regulation of photosynthesis following partial defoliation	dimensionless	1.4
Plant nitrogen	N_{FXopt}	Optimum foliage nitrogen concentration at top of canopy	kg(N)kg^{-1}(DM)	0.02
Plant nitrogen	N_0	Minimum foliar N for positive net Pn	kg(N)kg^{-1}(DM)	0.0002
Plant nitrogen	k_N	Attenuation of N through canopy with cumulative LAI	m²(ground) m^{-2}(leaf)	0.5
Plant nitrogen	N_B	Average branch nitrogen concentration	g(N)g^{-1}(DM)	0.002
Plant nitrogen	N_{S_SW}	Average stem sapwood nitrogen concentration	g(N)g^{-1}(DM)	0.001

Model section	**Symbol or program name**	**definition**	**Unit**	**Values**
Plant nitrogen	N_{S_HW}	Average heartwood (root and stem) nitrogen concentration	kg(N)kg^{-1}(DM)	0.0001
Plant nitrogen	N_{Bk}	Average bark nitrogen concentration	kg(N)kg^{-1}(DM)	0.001
Plant nitrogen	N_{fR}	Average fine root nitrogen concentration	kg(N)kg^{-1}(DM)	0.005
Plant nitrogen	N_{CR}	Average coarse root nitrogen concentration	kg(N)kg^{-1}(DM)	0.001
Plant nitrogen	λ	Fraction of nitrogen retranslocated from tissues on senescence	dimensionless	0.5
Plant nitrogen	δN^*	Maximum increase/decrease in foliar N conc. per day	kg(N)kg^{-1}(DM)day^{-1}	2.74E-05
Plant nitrogen	nlowerlimit	Minimum foliar N at which retranslocation effective	kg(N)kg^{-1}(DM)	0.01
Plant nitrogen	Nfixer	Nitrogen fixer	Boolean (0=no, 1=yes)	0
Rainfall interception parameters	I_L	Scalar between lai and interception	kg(H20)m^{-2}(leaf)m^{-2}(ground)	0.3
Rainfall interception parameters	I^*	Maximum proportion of any rainfall event intercepted by closed canopy	dimensionless	0.75
Respiration parameters	k_{day}	Temperature rate constant for foliar respiration	°C^{-1}	0.03
Respiration parameters	r_{d0}	Value of foliar respiration at temperature T=T0	µmol (CO2)m^{-2} (leaf) s^{-1}	1
Respiration parameters	k_{d0}	Value of kdav at temperature T=T0	°C^{-1}	0.09
Respiration parameters	k_{d1}	Temperature sensitivity of kdav	°C^{-1}	0.015
Respiration parameters	R_C	Construction respiration ratio	dimensionless	0.25
Respiration parameters	$R_{0\text{-}cR}$	Specific coarseroot sapwood respiration (kg C/kg N/yr)	kg(C)kg^{-1}(N)yr^{-1}	50
Respiration parameters	$R_{0\text{-}B}$	Specific branch sapwood respiration (kg C/kg N/yr)	kg(C)kg^{-1}(N)yr^{-1}	50
Respiration parameters	$R_{0\text{-}fR}$	Specific fineroot sapwood respiration (kg C/kg N/yr)	kg(C)kg^{-1}(N)yr^{-1}	100
Respiration parameters	$R_{0\text{-}S}$	Specific stem sapwood respiration (kg C/kg N/yr)	kg(C)kg^{-1}(N)yr^{-1}	50
Respiration parameters	Q_{10}	Q10 for respiration	dimensionless	1.3
Soil evaporation parameters	E^*_S	Maximum daily soil evaporation rate; supply side	kg(H20)m^{-2}(ground)day^{-1}	3
Soil evaporation parameters	g_{Bsoil}	Maximum soil boundary layer conductance	mol(H20) m^{-2}(ground)s^{-1}	4

Model section	**Symbol or program name**	**definition**	**Unit**	**Values**
Soil evaporation parameters	g^{*}_{Csoil}	Maximum rate of soil conductance	mol(H20) m^{-2}(ground)s^{-1}	0.1
Soil evaporation parameters	$r_{\mathrm{Q\text{-}S}}$	Fraction of radiation that is reflected by soil	dimensionless	0.3
Water stress	Ψ^{-}	lowest predawn leaf water potential trees reduced to	MPa	-3.5
Water stress	Ψ^{+}	predawn leaf water potential at field capacity	MPa	-0.3
Water stress	K_{a}	predawn water potential at which embolism commences	MPa	-2.5
Water stress	K_{b}	predawn water potential at which embolism to 50% of sapwood conducting area	MPa	-5
Water stress	Ψ_{foliage}	predawn water potential at which new foliage intitiation ceases	MPa	-1
Allometrics and structure	ρ_{w}	Mean density of stem, branch and coarse root wood	kg(DM) m^{-3}	0.5
Allometrics and structure	β_{cR}	Ratio of coarse root biomass to aboveground biomass	kg(DM)kg^{-1}(DM)	0.2
Allometrics and structure	β_{L1}	Multiplier in relationship between SSA and L	kg-1(DM)	1.2
Allometrics and structure	β_{L2}	Exponent in relationship between SSA and Ht	dimensionless	0.8
Allometrics and structure	β_{L3}	Exponent in relationship between SSA and L	dimensionless	0.4
Allometrics and structure	β_{Bk1}	Multiplier in relationship between bark mass and stem mass	dimensionless	10.69
Allometrics and structure	β_{Bk2}	Exponent in relationship between bark mass and stem mass	dimensionless	-0.394
Allometrics and structure	β^{-}_{Bk}	Maximum ratio bark/(bark + stem)	kg(bark)kg^{-1}(stemwood)	0.15
Allometrics and structure	β_{v1}	Multiplier in volume equation	dimensionless	0.6135
Allometrics and structure	β_{v2}	Exponent of ht in volume equation	dimensionless	0.968
Allometrics and structure	β_{v3}	Exponent of ba in volume equation	dimensionless	0.825
Allometrics and structure	β_{W1}	Multiplier in stem ht to diam ratio equation	kg^{-1}	130
Allometrics and structure	β_{W2}	Exponent in stem ht to diam ratio equation	dimensionless	-0.22

Model section	Symbol or program name	definition	Unit	Values
Allometrics and structure	β_{W3}	Exponent stem ht to diameter ratio equation	dimensionless	-0.136
Allometrics and structure	σ_0	Maximum value of SLA	m^2kg^{-1}	12
Allometrics and structure	σ_1	Lower limit of specific leaf area	m^2kg^{-1}	4
Allometrics and structure	b_σ	Rate of change of specific leaf area with leaf nitrogen concentration	$kg(DM)kg^{-1}(N)$	70
Allometrics and structure	ϕ	Average branch angle from the horizontal	degrees	30
Allometrics and structure	x	Volume of branch as proportion of cylinder with same basal diameter and length	dimensionless	1
Allometrics and structure	crownratio	Crown length to width ratio of free grown tree	m (width) m^{-1}(length)	2
Allometrics and structure	$W_{S\ x1000}$	Size of largest possible individual tree(kg) at 1000 spha	kg	300
Biomass loss rates	γ_F	Reciprocal of maximum foliage longevity	yr^{-1}	0.33
Biomass loss rates	γ_{Bk}	Reciprocal of maximum bark longevity	yr^{-1}	0.1
Biomass loss rates	γ_{fR}	Reciprocal of maximum fine root longevity	yr^{-1}	2
Biomass loss rates	γ_{fR}	Reciprocal of maximum coarse root longevity	yr^{-1}	0.05
Composition Fractions	FOLCARB	Breakdown fraction of foliage to soluble carbohydrate	dimensionless	0.3
Composition Fractions	FOLCELL	Breakdown fraction of foliage to cellulose	dimensionless	0.6
Composition Fractions	FOLLIGNIN	Breakdown fraction of foliage to lignin	dimensionless	0.1
Composition Fractions	WOODCARB	Breakdown fraction of wood to soluble carbohydrate	dimensionless	0.05
Composition Fractions	WOODCELL	Breakdown fraction of wood to cellulose	dimensionless	0.45
Composition Fractions	WOODLIGNIN	Breakdown fraction of wood to lignin	dimensionless	0.5
Composition Fractions	FRCARB	Breakdown fraction of fine roots to soluable carbohydrate	dimensionless	0.3
Composition Fractions	FRCELL	Breakdown fraction of fine roots to cellulose	dimensionless	0.6
Composition Fractions	FRLIGNIN	Breakdown fraction of fine roots to lignin	dimensionless	0.1
Composition Fractions	CRCARB	Breakdown fraction of coarse roots to soluable carbohydrate	dimensionless	0.05
Composition Fractions	CRCELL	Breakdown fraction of coarse roots to cellulose	dimensionless	0.45

Model section	**Symbol or program name**	**definition**	**Unit**	**Values**
Composition Fractions	CRLIGNIN	Breakdown fraction of coarse roots to lignin	dimensionless	0.5
Composition Fractions	FCFOM	fraction of carbon in the fresh organic matter	dimensionless	0.4
Litter breakdown rates	BkdnFineRoots	Fraction of fine root litter that breaks down in one month	dimensionless	0.0033333
Litter breakdown rates	BkdnCoarseRoots	Fraction of coarse litter that breaks down in one month	dimensionless	0.0016667
Litter breakdown rates	BkdnFol	Fraction of foliage litter that breaks down in one month	dimensionless	0.0033333
Litter breakdown rates	BkdnBranch	Fraction of branch litter that breaks down in one month	dimensionless	0.0016667
Litter breakdown rates	BkdnBark	Fraction of bark litter that breaks down in one month	dimensionless	0.0033333
Litter breakdown rates	BkdnStems	Fraction of stem litter that breaks down in one month	dimensionless	0.0006667
Soil nitrogen module	ATMOSDEP	daily atmospheric deposition of nitrogen	kg(N) ha^{-1}	0.0068493
Soil nitrogen module	DMINR	non-limited rate of humus mineralisation	day^{-1}	8.333E-05
Soil nitrogen module	upperlimit	pH at which NH4 conversion to NO3 not pH limited	pH	6
Soil nitrogen module	lowerlimit	pH at which no NH4 conversion to NO3	pH	3
Soil nitrogen module	MicroEff	biological efficiency of carbon turnover by microbes	kg(DW)$^{-1}$	0.4
Soil nitrogen module	EF_HUM	proportion of N release in litter incorporated into humus	dimensionless	0.8
Soil nitrogen module	Ncmicrobes	N:C ratio of microbes	kg(N)kg(C)$^{-1}$	0.125
Soil nitrogen module	HUMDCMPTOPT	optimum temperature for humus decomposition	C	35
Soil nitrogen module	HUMDCMPTLOW	lower temperature limit for humus decompostion	C	5
Soil nitrogen module	nleachlimit	% H20 layer in excess of field cap before leach of N	dimensionless	0.05
Soil nitrogen module	CECFAC	fraction of ammonium in liquid phase	dimensionless	0.1
Soil resource capture	krn	Shape parameter in Wfr-Nuptake relationship	kg(N)kg^{-1}(DM)day^{-1}	0.5
Soil resource capture	maxtranspiration	Potential maximum rate of stand water use	kg(H20)m^{-2}(ground)day^{-1}	10
Soil resource capture	krw	Shape parameter in Wfr-Nuptake relationship	kg(H20)kg^{-1}(DM)day^{-1}	1

Model section	**Symbol or program name**	**definition**	**Unit**	**Values**
Soil resource capture	rootExtensionRate	Potential maximum annual vertical root growth	cm yr^{-1}	250
Substance decomposition rates	RDECR1	Fractional decomposition per day of carbohydrate pool	days^{-1}	0.8
Substance decomposition rates	RDECR2	Fractional decomposition per day of cellulose pool	days^{-1}	0.05
Substance decomposition rates	RDECR3	Fractional decomposition per day of lignin pool	days^{-1}	0.0095
Substance decomposition rates	kdecomp	Rate parameter for lignin:N ratio impact on decompostion rate	dimensionless	0.01
Substance decomposition rates	ligninNopt	lignin:N ratio below which no effect on decompostion rate	kg(Lignin)kg(N)$^{-1}$	15
Substance decomposition rates	optTdecomp	optimum temperature for litter decompostion	°C	20
Risk Thresholds	txHotDay	Threshold temperature for a hot day	°C	35
Risk Thresholds	MinMonthPredawnDryDay	Threshold pre-dawn water potential for a hot day	MPa	-3.2
Hydraulics	mindeltapsi	maximum difference between leaf and soil water potential	MPa	0.5
Hydraulics	Ψ_{TLP}	turgor loss point	MPa	-2.7
Hydraulics	Ψ_{crit}	water potential at which tree dies of hydraulic failure	MPa	-3.9
Hydraulics	C_L	capacitance per unit leaf area	kg(H_2O)	50
Hydraulics	kmaxintercept	maximum hydraulic conductivity	Kg(H2O) m-2(sapwood) s-1 MPa-1	0.08
Hydraulics	kmaxslope	rate of change of hydraulic conductivity with predawn water potential	MPa^{-1}	0.02
Leaf Temperature	windspeed	average wind speed	m s^{-1}	3
Leaf Temperature	laminarwidth	leaf laminar width	m	0.04
Leaf Temperature	lethaltemperature	lethal temperature for leaves	k	311
Temperature response jmax	edvj	Michelis menton temperature dependence paramter	J mol-1	200000
Temperature response jmax	eavj	Activation energy for RUBP regeneration	J mol-1	43790
Temperature response jmax	delsj	Entropy factor	J mol-1	644.4338
Temperature response jmax	jmax25	maximal photosynthetic electron transfer rate	μmol (CO2)m^{-2} (leaf) s^{-1}	180

Model section	**Symbol or program name**	**definition**	**Unit**	**Values**
Temperature response vcmax	vcmax25	maximal carboxylation rate	μmol (CO2)m^{-2} (leaf) s^{-1}	80
Temperature response vcmax	eavc	Activation energy for carboxylation	J mol-1	51560
Temperature response vcmax	delsc	Temperature dependence of vcmax	J mol-1	0
Temperature response vcmax	edvc	Michelis menton temperature dependence paramter	J mol-1	0
Respiration	dayresp	proportion of dark respiration observed in light	dimensionless	0.6
Respiration	tbelow	lower temp threshhold for respiration	C	0
Respiration	rtemp	temperate at which resp=rd0	C	20
Respiration	Q_{10f}	q10 of foliar daytime respiration	dimensionless	0.0575
General	AJQ	quantum efficiency	mol (electrons) mol^{-1}(photons)	0.324
General	θ_f thetaf	curvature of quantum efficiency with light	dimensionless	0.7
General	koea	temp response of ko	μmol mol^{-1}	3600
General	oi	oxygen partial pressure	mol mol^{-1}	205000
General	kc25	Michaelis-Menten coefficient of Rubisco for CO$_2$	μmol mol^{-1}	404
General	ko25	Michaelis-Menten coefficient of Rubisco for O$_2$	μmol mol^{-1}	248000
General	kcea	temp response of kc	J mol-1	59400
Down-regulation to eCO2	doublepropchange jmax	proportional reduction in V$_{Cmax}$ at double referenceCa	dimensionless	0.05
Down-regulation to eCO2	referenceCa	referenceCa	ppm	350
Down-regulation to eCO2	doublepropchange vcmax	proportional reduction in vcmax at double referenceCa	dimensionless	0.1