Forest Ecology and Management 406 (2017) 361–369

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

The economic impact of optimising final stand density for structural saw log production on the value of the New Zealand plantation estate

Michael S. Watt[a,*], Mark O. Kimberley[b], Jonathan P. Dash[b], Duncan Harrison[b], Juan J. Monge[b], Les Dowling[b]

[a] Scion, P.O. Box 29237, Christchurch, New Zealand
[b] Scion, Private Bag 3020, Rotorua, New Zealand

ARTICLE INFO

Keywords:
IRR
NPV
Radiata pine
Stocking

ABSTRACT

Final crop stand density is an important determinant of plantation value. A relatively simple model, based on productivity indices, has recently been developed that can spatially optimise final crop stand density S_{opt}, of the widely planted plantation species *Pinus radiata* D. Don for stands grown for structural grade timber. When applied to New Zealand this model shows S_{opt} to be *ca.* 100 stems ha^{-1} higher than the current final stand densities. Using a comprehensive set of model simulations, the objectives of this research were to (i) examine the accuracy of predictions of S_{opt} from the simple model and (ii) determine the potential economic gain of thinning structural grade regimes to optimal stand densities.

Simulations included 15 combinations of the metrics Site Index and 300 Index that cover the productivity envelope occupied by New Zealand plantations and assumed a rotation age of 28 years. For each combination of Site Index and 300 Index, simulations included S_{opt} and eight stand densities that were 200, 150, 100 and 50 stems ha^{-1} lower and higher than S_{opt}.

Composite financial metrics, weighted by the proportion of the plantation estate in each productivity class, showed marked increases from stand densities 200 stems ha^{-1} lower than S_{opt} to S_{opt} which levelled off above S_{opt}. This levelling off after S_{opt} suggests that the simple model provides an accurate estimate of S_{opt}. Gains in gross value, net value, internal rate of return and net present value that could be realised through increasing stand density by 100 stems ha^{-1} were, respectively, \$5183 ha^{-1} (\$77,891–\$83,074 ha^{-1}), \$2319 ha^{-1} (\$28,740–\$31,059 ha^{-1}), 0.44% (8.05–8.49%) and \$294 ha^{-1} (\$108–\$402 ha^{-1}). When scaled up to the plantation estate potential gains in net and gross value that could be realised through thinning to S_{opt} were respectively, \$1.7 and \$3.8B, which when discounted back to the current time equate to respective gains of \$156 and \$349 M.

1. Introduction

Within the southern hemisphere *Pinus radiata* D. Don is amongst the most economically important plantation species. Selection of the final crop stand density is a key silvicultural decision that is predominantly driven by financial considerations. The most common form of thinning is thinning from below (Lewis and Ferguson, 1993) where smaller trees with defects are removed to ensure that remaining final crop trees are evenly spaced and of good form and vigour. Within New Zealand, 47% of the *P. radiata* plantation resource is grown for structural grade timber with the remainder of the resource grown for clearwood (NZFOA, 2016). Almost all thinning within structural grade regimes in New Zealand is to waste, rather than production thinning (NZFOA, 2016). Typically, there are one or two thinnings to a residual final stand density of *ca.* 500 stems/ha (Watt et al., 2017).

Growth modelling approaches have been widely used to optimise stand density. Although the simpler forms of process based models are occasionally used by forest managers (Landsberg and Waring, 1997) almost all growth models used for the prediction of future stand development are empirical models. Site productivity has been most often described within empirical growth models using Site Index (*SI*). This parameter, which expresses the height of dominant and/or co-dominant trees at a given index age, is a useful measurement as it is relatively unaffected by stand density (Skovsgaard and Vanclay, 2008). However, as stand height does not account for variation in basal area (Kennel, 1973; Hasenauer et al., 1994; Vanclay et al., 1995; Skovsgaard and Vanclay, 2008), *SI* does not fully describe site productivity. Consequently, alternative productivity indicators have been developed for

* Corresponding author.
E-mail address: michael.watt@scionresearch.com (M.S. Watt).

http://dx.doi.org/10.1016/j.foreco.2017.07.044
Received 11 June 2017; Received in revised form 12 July 2017; Accepted 24 July 2017
Available online 18 October 2017
0378-1127/

many plantation species that quantify volume increment at a given age under a standardised silvicultural regime. The productivity indicator for *P. radiata* is the 300 Index (I_{300}) (Kimberley et al., 2005; Watt et al., 2017).

Although growth models allow for stand level optimisation of stand density, large scale spatial surfaces of optimal final crop stand density (S_{opt}) are potentially more useful to forest managers for stratification and broad level planning. A major impediment to developing spatial predictions of S_{opt} from empirical growth models is that estimates of site productivity are typically only available at the stand level from plot measurements. However, the recent proliferation of environmental surfaces and remotely sensed data has allowed both *SI* and I_{300} to be accurately predicted across the landscape, at a range of scales, ranging from regional to national (Palmer et al., 2009; Watt et al., 2009, 2010; Palmer et al., 2012; Watt et al., 2015b, 2016). This approach has been recently refined through use of data from airborne light detection and ranging (LiDAR) which has been found to provide more accurate estimates of site productivity than environmental surfaces or satellite imagery (Watt et al., 2015b, 2016). The increasing rate of LiDAR acquisition, combined with advances in processing speed of this high density data, may allow regional use of LiDAR for prediction of *SI* and I_{300} in the near future.

Recent research has developed a relatively simple model to predict spatial variation in S_{opt} for structural grade regimes from surfaces that describe site productivity (Watt et al., 2017). This model optimises S_{opt} through maximising the volume of the highest value sawlog, which has a large small end diameter and relatively fine branches. Using this model wide variation in predicted S_{opt} was found throughout New Zealand plantations (200–700 stems ha^{-1}) and this variation was mainly attributable to variation in two of the key driving variables in the model, SI and I_{300}. Values of S_{opt} increased as I_{300} increased and for a given value of I_{300} reductions in S_{opt} were predicted with increasing *SI*. Within New Zealand plantations the mean predicted S_{opt} was 614 stems ha^{-1} which exceeds the mean final crop stand density in stands managed under structural grade regimes of *ca.* 500 stems ha^{-1} (Watt et al., 2017). This disparity indicated that optimising final stand density based on site characteristics could significantly increase the value of the New Zealand *P. radiata* plantation estate. It would be useful to further investigate the robustness of this simple model as this approach optimises stand density through maximising the volume of only the most valuable log grade. Further research should investigate whether total log value is also optimised when the most valuable log grade is optimised.

Using a comprehensive set of simulations that examined the influence of final crop stand density on the value of all merchantable log grades, the objectives of this research were to (i) examine the accuracy of predictions of S_{opt} from the simple model and (ii) determine the potential economic gain to thinning structural grade regimes to optimal stand densities.

2. Methods

2.1. Description of the modelling approach

This study used Forecaster, a flexible forest stand level growth and yield simulation system. Forecaster can be used to predict growth and potential log yield of a forest stand (West et al., 2013) and to predict log product volumes for a range of site types, stand densities and rotation lengths in *P. radiata* plantations. Numerous component models are implemented in Forecaster including growth models, models for predicting branch size, and log bucking algorithms. Forecaster uses a stem list as a model of a crop of trees growing on a site, with each stem having attributes including diameter at breast height (DBH) and height, and a weighting indicating the number of stems per hectare. Stem DBH and height are grown to a specified felling age using a growth model, while stem weights are adjusted to account for thinning events and for mortality using a mortality model. At felling, sweep and forking defects are simulated and stems are cut into logs using a log-bucking algorithm, and under-bark volume of logs cut from each stem are calculated from the DBH, height and position of the log within the stem using an individual-tree volume and taper function. Other stem attributes such as branch diameter are predicted using sub-models within the system. Logs are graded into log products using log product definitions supplied by the user.

A key component model within Forecaster used in this study was the I_{300} growth model which was used to predict DBH growth, height growth, and mortality. This model has been described previously (Kimberley et al., 2005; Watt et al., 2017) and a brief summary is given below. This empirical stand level model comprises a number of sub-models including a height/age model, a model for predicting DBH growth and mortality function. The I_{300} growth model can be used to predict growth and yield across the range of site types and management regimes typical of *P. radiata* plantations in New Zealand with site characteristics specified in terms of both I_{300} and *SI*. The height/age model predicts height consistent with the specified *SI* while the DBH model predicts DBH as a function of age and stand density, using a family of curves that vary according to site productivity as defined by *SI* and I_{300}. The model accounts for thinning events using the age-shift approach (Watt et al., 2015a) while the mortality function used in the I_{300} model is based on Reineke's 'line of self-thinning' concept (Reineke, 1933). The I_{300} model is conditioned so that when it is applied to the 300 Index reference regime (300 stems ha^{-1} grown to age 30 years) for a particular site characterised by its *SI* and I_{300}, and used in combination with a national stand-level volume function (Kimberley and Beets, 2007), it predicts mean top height at age 20 years equal to the specified *SI*, and mean annual volume increment at age 30 years equal to the specified I_{300}. The branch diameter model used in this study has been described in full previously (Inglis and Cleland, 1982; Watt et al., 2017).

2.2. Forecaster simulations

2.2.1. Model input

Forecaster runs were undertaken to model the influence of final stand density on volume, log grade out-turn and value for 15 combinations of *SI* and I_{300}. These site productivity combinations included 5 levels of I_{300} and 3 levels of *SI* at each I_{300} (Table 1) and the ranges of *SI* and I_{300} that these 15 combinations represent are given in Appendix 1. For instance the class that has I_{300} of 25 m^3 ha^{-1} yr^{-1} and *SI* of 30 m represents sites with a range in I_{300} of 21.25–28.75 m^3 ha^{-1} yr^{-1} and a range in *SI* of 26.5–33.5 m (Appendix 1). Although the two productivity indices tend to be positively related there is a considerable range in *SI* for a given I_{300}.

Table 1
Variation in optimal stand density (S_{opt}) as a function of the 15 combinations of 300 Index and Site Index used within this study.

300 Index (m^3 ha^{-1})	Site Index (m)	S_{opt} (stems ha^{-1})
10.0	18	290
10.0	22	200
10.0	26	200
17.5	19	700
17.5	26	434
17.5	33	253
25.0	23	700
25.0	30	526
25.0	37	319
32.5	26	700
32.5	33	647
32.5	40	398
40.0	30	700
40.0	37	700
40.0	44	451