ANALYSIS OF SPACING FOR SPOTTED GUM PLANTATIONS FOR MAXIMISING MERCHANTABLE LOGS' VOLUME IN SOUTH EAST QUEENSLAND, AUSTRALIA

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ABSTRACT

Spotted gum (*Corymbia citriodora* subspecies *Variegata*) has the potential to be the major hardwood species for large-scale plantations in South East Queensland, Australia, but production research is limited due to the lack of age of research plots. Optimal spacing is a major subject of concern. Based on time series data from a spotted gum experiment site, growth performance is analysed for five spacing levels: —11.3 m x 11.3 m (78 stems per hectare), 7.4 m x 7.4 m (182 sph), 5.4 m x 5.4 m (343 sph), 3.6 m x 3.6 m (771 sph) and 2.9 m x 2.9 m (1189 sph). The major objective was assumed to be to maximise total merchantable log volume. A growth model was produced, and the mean diameter at breast height (dbh) and total merchantable log volume for each spacing levels at a range of harvesting ages was estimated. From the analysis, the spacing level of 5.4 m x 5.4 m was found to be optimal for maximising merchantable log volume to 10 cm small-end diameter. Further analysis of mean dbh, height and volume of the largest 200 and 250 trees from this spacing level indicates that merchantable log volume could be maximised by retaining the 250 largest trees per hectare. The total financial revenue from the best spacing level in 25 and 30 years are predicted to be $13,637 and $17,779 per hectare, respectively. If full rotation data could be obtained, more reliable models could be produced, and a more accurate financial estimate could be made.

Keywords: spotted gum, spacings, merchantable log volume, Southeast Queensland

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INTRODUCTION

Forest clearing was part of the drive to civilisation. The process is still continuing in many parts of the world, as people perceive that the natural forest is of less economic value than alternative uses (Filho 2004). If the world trend of forest clearing continues, an additional 10 billion hectares (about 1.3 times the size of Australia) of natural ecosystem could be converted to agriculture by 2050 (Tilman *et al*. 2001). In Australia, forest has been extensively cleared for cropping and grazing. Although the rate of clearing decreased from 546,000 ha/year in 1988 to 187,000 ha/year during 2000 to 2003, it is still relatively high (AGO 2000, BRS 2005). Therefore, unlike Europe, the USA and Canada, Australia had a net source of carbon (37.2 $MtCO_2e$) from the land-use sector in 2000 (Van Kooten 2004, Mitchell and Skjemstad 2004). Forest clearing alone accounted for 12% of the total emissions in Australia (AGO 2000).

About 80% of total land clearing in Australia has occurred in the state of Queensland. There have been many motivating factors for forest clearing in Queensland, but the driving force was economic return, availability of low-priced land, immediate profit by crop production, and long-term profit by increased land value (AGO 2000). Clearing was perceived as development and land was considered wasted unless it was developed. In fact, clearing in Queensland was accelerated in the second half of the 20th century under a government-sponsored development scheme, where low-cost land and low-interest loans were offered under the condition that landholders improve the land by clearing (Fensham and Fairfax 2003). Tax concessions, deduction of full clearing costs from the tax, and low-cost finance are other accessory factors of clearing (AGO 2000).

The cleared land was predominantly used for the grazing of livestock. However, in particular areas with favourable climatic and topographic factors (including inland south-east Queensland), much of the cleared land was used for crop production. By the 1980s, increasing costs of production and decreasing commodity prices, especially of the major cereals, created financial pressure for farmers (Zammit *et al*. 2001). Technological innovation did not keep pace with increasing cost. This caused a shift in land use around the 1980s from cultivation to grazed pasture in less productive or degraded cropping land (Zammit *et al.* 2001, Maraseni *et al.* 2006). Recently, due to increased environmental concerns focusing on land degradation and the risk of dryland salinity, the Queensland government has encouraged farmers to establish hardwood plantations on some degraded ex-cultivation and pasture areas (DPI&F and DNR 1999, DPI&F 2000, Brown 2002).

The national policy statement '*Plantation for Australia: The 2020 Vision*' has targeted trebling the national plantation estate to about 3 M ha by the year 2020 (Kirschbaum 2003). In order to support this target, the Queensland government committed to increase the plantation estate by 320,000 ha from 1996 to 2020 (DPI&F 2000). A 20-year Federal-State agreement, known as the Southeast Queensland Regional Forest Agreement (SEQRFA), was implemented in 1996 for native forest conservation and timber resources management in south-east Queensland (SEQ) (Brown, 2002). As a part of this SEQRFA program, the Queensland Government approved a $30 M plan to increase the area of hardwood plantations, especially of spotted gum (*Corymbia citriodora* subspecies *Variegata*), in SEQ (DPI&F 2004b).

What spacing is most appropriate for maximum merchantable log volume is the major subject of concern, because it may leads towards maximisation of financial return. However, lack of full-rotation plantation growth data for spotted gum, a highly recommended hardwood species for plantations, is the major impediment in this direction (Huth *et al.* 2004). The main aim of this study is to determine the tree spacing for spotted gum which will maximise merchantable log volume to 10 cm top diameter. The study further estimates the financial return from spotted gum at harvesting age of 25 and 30 years.

This article is further divided into five sections. The recent policy and plantations trend is first discussed and then the reasons for popularity of spotted gum are examined. The research method is then outlined, followed by yield prediction. A discussion of the results and conclusions follow.

RECENT POLICIES AND PLANTATION TRENDS

Apart from the '*the Vision 2020*' national plantation policy, Australia has laws in place to slow down the forest clearing rate and increase the plantation estate area. Regarding land-use decisions, the Queensland government has the sole responsibility; however, the provisions of the *Australian Heritage Commissions Act 1975* and the *Environmental Protection Act 1974* of the Federal Government must be met (AGO 2000). Before 1990, there was no legislation in Queensland controlling native forest management on all land title types. The *Land Act 1994* makes provision for seeking permission for native vegetation clearing on leasehold land, but not for previously cleared land (AGO 2000). However, after the recent implementation of a native vegetation management framework, the legislation applies to all tenures (AGO 2000). Other states have been more pro-active in this regard. For example, the Victorian government has implemented the Bush Tender initiative through which landholders have been paid to conserve any areas of native species on their properties. New South Wales has followed this with an Environmental Service Scheme in which landholders will receive payments for changing their land-use practices and improving the environmental services they provide through their properties (Cacho *et al*. 2003).

The federal and state governments have recommended native hardwood species for plantations (DPI&F and DNR 1999, DPI&F 2000). These species are more environmentally friendly than exotic pine species (Turner *et al*. 1999). Moreover, there is a difference in the soil carbon sequestration amount under the soil of hardwood and pine plantation on ex-agriculture lands. A study at the Billy Billy field site near Canberra has shown that conversion of ex-pasture to pine has resulted in a 15% loss of soil carbon (CRC for GA 2004) whereas afforestation of hardwood on ex-agricultural land is likely to increase soil carbon (Paul *et al*. 2002, Paul *et al*. 2003, Saffigna *et al*. 2004, Maraseni *et al*. 2006).

In Australia, plantation history began with softwood (pine) plantations in 1867 to meet the growing domestic softwood demand. Until after World War 2, decisions on plantation establishment were not made on financial returns and plantations were established on many sites not suitable for cropping. The major focus was to reduce unemployment and to furnish raw material for small scale industries (Turner *et al.* 1999). Soft loans were provided by the Commonwealth to the states with the objective of Australian becoming self-reliant in timber supply, which facilitated the conversion of native forests to pine plantations. In the 1980s, due to environmental pressure, commercialisation of forest services and reduced land availability in some areas, site-specific management was commenced. Since then, pressure has been mounted on the government authorities to reduce the area of exotic pines, especially *Pinus radiata* (Turner *et al.* 1999).

While analysing the plantation history in Australia, two major changes are apparent: shifting from softwood to hardwood, and shifting from public to private plantations. The current total plantation area in Australia includes 675,962 ha (41%) hardwood species (mainly eucalypts) and 988,223 ha (59%) of softwood species (mainly *Pinus radiata*) (BRS 2005). The average annual plantation area during the period 2000-2004 was 74,000 ha (BRS 2005). Of the total area planted in 2003, 74% was hardwood and 26% was softwood. The hardwood proportion increased from 15% in 1994 to 74% in 2003. Similarly, the proportion of private plantations was 46% in 1999, but in 2003, about 71% of the new plantations were privately owned and another 11% were jointly owned (National Forest Inventory 2004). Although the plantations area in Queensland is small compared to the national plantations area (about 13% or 214,585 ha out of 1,664,185 ha), the general pattern of plantations is similar. Until 2004, only around 16% of total planted area was hardwood and 84% was softwood. However, in 2004, the trend was reversed; of the total planted area of 5,470 ha, more than 84% (4,618 ha) was hardwood and about 16% (852 ha) was softwood (BRS 2005).

The current trends in plantations both at state and national levels show some positive connection with government policy, but the annual rate of 70,000 ha plantations falls short by about 100,000 ha towards meeting the plantation target of '*the Vision 2020*'. In order to meet this goal, inland medium low rainfall areas will need to be targeted, which is the focus area of this research. As this research focuses on the maximisation of return by recommending optimal spacing of spotted gum, it would help toward achieving the planting target.

REASONS OF POPULARITY OF SPOTTED GUM

One of the main hardwood species being promoted by government agencies in south-east Queensland is spotted gum. This species accounts for over 60% of the native hardwood volume harvested in Queensland (DPI&F, 2004a) and also is the most prioritised (over 60%) hardwood tree species for plantation in Queensland (Huth *et al*. 2004). There are a number of reasons for its popularity: 1) Over time, large areas of SEQ were World Heritage listed, became National Parks or had tenure restricted. This reduced the supply of native timber including spotted gum, but demand is still increasing by two to three percent every year (DPI&F and DNR 1999). 2) Although full rotation plantation data are not available, the early-age performance of spotted gum is encouraging (Huth *et al*. 2004). 3) Preliminary results of the genetic improvement program of spotted gum are promising, the seedlings having vegetative propagative capacity, and frost tolerance and *Ramularia* shoot blight resistance (Lee, 2005). 4) The timber is highly valued for its durability, hardness and pale colour (Huth *et al.* 2004). 5) Of the 3.42 M ha of cleared land evaluated for plantation in the South East Queensland Regional Forest Agreement (SEQRFA) region, 2.72 M ha met the slope (<20%) and size (>10 ha) constraint, and 73% of that land was found suitable for spotted gum (Queensland CRA/FRA Steering Committee 1998).

RESEARCH METHOD

Species Description for Spotted Gum

The word 'spotted' for the spotted gum refers to the 'spots' on the bark. The species is widely distributed in south-east Queensland. Naturally, it predominates between 25°S to 38°S latitude. In Queensland, it extends up to 400 km inland and up to 950 m altitude from sea level (Boland *et al.* 1984). Trees attain heights of 35-45 m and diameter at breast height of 1-1.3 m (Boland 1984); the greater dimensions are reached towards the southern limits of the species' range in New South Wales (Huth *et al.* 2004). Spotted gum may grow up to 20-35 m in height and 0.7-1.2 m in diameter, even in dryer and poorer sites (Boland 1984). This species has high site adaptability, and copes well with soils that have low to high fertility, annual rainfall exceeding 600 mm, low to medium salinity; low to moderately high pH, and sites that experience a moderate frequency of non-severe frost (DPI&F 2004c). In a native forest environment, it is usually found with many associates, some examples being narrow-leaved red iron bark (*Eucalyptus crebra*), blackbutt (*E. pilularis*), tallowwood (*E. microcorys*), grey gum (*E. propinqua*), and grey iron box (*E. paniculata*) (Boland, 1984). The timber is hard, durable and resistant to decay (DPI&F 2004c, Lee 2005), and is used for heavy and general building construction, decking and flooring. Spotted gum is also used for preservative-treated poles and tool handles (Queensland CRA/RFA Steering Committee 1998).

Site Description and Experimental Design

The primary data sources are the hardwood experimental plots located at Warril View, near Ipswich, Queensland. The Warril View hardwood experiment site is the oldest spotted gum experimental site in south-east Queensland. The soil is of medium fertility. The spotted gum seedlings were planted on 31 May 1990 at five planting densities – 'A' (11.3 m x 11.3 m=78 stems per hectare), 'B' (7.4 m x 7.4 m=182 sph), 'C' (5.4 m x 5.4 m=343 sph), 'D' (3.6 m x 3.6 m =771 sph) and 'E' (2.9 m x 2.9 m=1189 sph). Each treatment had three replicates. No artificial thinning was done but natural thinning was probably occurring in all spacing levels except spacing level 'A', which had a zero mortality rate. The number of trees at the last measurement (15.16 years after planting) at spacing level 'B', 'C', 'D' and 'E' were reduced to 161 (by 21), 302 (by 41), 724 (by 47) and 1093 (by 97) sph, respectively.

Measurement of Tree Diameter and Height

Diameter at breast height (dbh at 130 cm) and height of all trees were measured at the age of 0.07, 0.51, 1.01, 1.51, 2.01, 3.12, 4.02, 5, 6.02, 7, 8.04, 11.01, and 15.16 years. However, because of their smaller height there was no dbh measured until the age of 4.02 years. A 1.3 m stick and diameter tape was used for the dbh measurement. Before taking dbh, all dead bark was removed. A Vertex Hypsometer was used for height measurement and a Husky Hunter 16 was used for data entry.

Growth Model Development for Full Rotation Performances

Forest growth models are nonlinear and sigmoid in shape and have points of inflection. Because the Von Bertlanffy, Chapman-Richards, Logistic and Gompertz growth equations have these characteristics, they are widely used for forest growth model development (Fekedulegn *et al.* 1999). For the development of the growth model of this study, the von Bertalanffy growth equation was used (a description of which can be found in Fekedulegn *et al.* 1999, Williams *et al.* 1991 and Vanclay 1994). As suggested by Fekedulegn *et al.* (1999), the formula can be written in simple form as:

$$\mathrm{DBH} = \left[\mathrm{b}_0^{(1-\mathrm{b}_3)} - b_1 * \exp(-b_2 * \mathrm{T}) \right]^{1/(1-b_3)} \qquad (1)$$

where, 'DBH' is the dependent growth variable, 'T' is tree age in years, and 'exp' is the base of a natural logarithm. 'b_0', 'b_1', 'b_2' and 'b_3' are regression parameters to be estimated. 'b_0' refers to the asymptote or potential maximum of the response variable (DBH), 'b_1' is the biological constant,

'b_2' is the parameter governing the rate at which the DBH (or volume) approaches its potential maximum, and 'b_3' is the allometric constant.

The regression parameters (b_0, b_1, b_2 and b_3) were determined iteratively using the STATISTICA software package. However, for the iteration to be initiated starting values for b_0, b_1, b_2 and b_3 were needed. This was the most difficult part in modelling. Fekeldulegn *et al.* (1999) was followed for the estimation of starting values. A demonstrated example is given for spacing level 'C' (5.4 m x 5.4 m=343 sph). As per a suggestion from Fekedulegn *et al.* (1999), a negligible value of dbh (0.0001 cm) for age 0.001 year was assumed, which improved the predictive power of the model. The same method was applied for all spacing levels.

Table 1. Age and Mean DBH of Spacing Level 'C'

Age (yrs)	0.001	4.02	5.00	6.02	7.00	8.04	11.01	15.16
DBH (cm)	0.001	5.690	7.720	10.060	12.180	13.650	18.230	23.21

b_0 = Maximum dbh = 23.21
b_3 = 0.5 (positive, less than 1 value assumed).

Calculation for b_1:

$$\text{DBH (at 0 yr age)} = b_0\ (1-b_1)^{1/(1-b_3)} \quad \ldots\ldots(2)$$

Dbh for '0' age is also assumed to be 0.001 cm, b_0 = 23.21 and b_3 = 0.5 then
b_1= 0.9934

Calculation for b_2:

$$b_2 = \frac{\{\text{DBH(last)} - \text{DBH(first)}\}/\{\text{Age(last)} - \text{Age(first)}\}}{b_0} \quad \ldots\ldots(3)$$

$$b_2 = \frac{\{(23.21\ \text{cm} - 0.001\ \text{cm})/(15.16 - 0.001)\}}{23.21\ \text{cm}} = 0.06596$$

After entering these starting values for b_0, b_1, b_2 and b_3 regression parameters, the non-linear estimation module of STATISTICA software was run. The starting values were replaced by values produced by the model in an iterative fashion until the lowest and constant root mean square error (RMSE) and highest of proportion of variance explained (R^2) were obtained. The RMSE was also used because it is easier to interpret and explain than mean square error and is also the most compatible with the statistical concepts of standard deviation. During the process of building model, the step size, convergence criterion and iteration number were adjusted until the model of best fit was obtained. The final (best) models for each spacing level were used to predict the diameter if trees of various ages. Then the dbhs were used in the calculation of volume by using the allometric equation developed for spotted gum by Margules Poyry (1998). This equation is:

$$Volume(m^3) = [\{9.1944 * 3.14 * (DBH)^2 / 4\} - 0.1167]/1000 \quad \ldots\ldots(4)$$

After selecting the optimal tree spacing from among the five treatments, further analysis on the selected 'optimal spacing level' was done to determine which spacing was the most profitable option, out of keeping all the trees for the whole rotation or thinning some trees before harvest.

Financial Analysis of Investment in Plantations

In Australia, the possible harvesting age of hardwood species for logs is assumed to be 25 to 30 years (Venn 2005). The composition of various types of forest products (pole, sawlog and low-value log) at age 25 to 30 and their stumpage prices were taken from Venn (2005), as reported in Table 2. After finding the merchantable log volumes at 25 and 30 years from the best tree spacing, the financial return of plantations, on a per hectare basis, was estimated by developing the following logs volume, composition and price related formula (Equation 5):

$$Income = \frac{V}{100}\sum_{i,j=1}^{i,j=3}(C_i * P_j) \qquad (5)$$

where 'V' is the volume of logs, 'C_i' and 'P_j' are composition and prices of different types of logs, respectively; and 'i' and 'j' go from one to three.

Table 2. Composition and prices by log type for harvesting ages of 25 to 30 years

Log type	Percentage of composition	Price ($/m^3)
Pole	20	70
Sawlog	60	55
Low-value log	20	20

Source: Venn (2005).

RESULTS AND DISCUSSION

Average Diameter of Trees at Various Spacings

Since the diameter is squared for the estimation of volume (Volume = π * DBH^2/4 x height) of the log, the diameter plays the dominant role in volume determination. Moreover, in spotted gum, height is not generally a concern, because this species has good height and bole form. Because of these characteristics, spotted gum has been referred to as the 'Lady of the Woods' (Wilson quoted in Huth *et al.* 2004). The dbh, therefore, is the main parameter of interest. The mean dbh of all trees and the largest 50 trees planted at five spacing levels (treatments A to E) were compared. The graph between age and the mean dbhof the largest 50 trees is given in Figure 1.

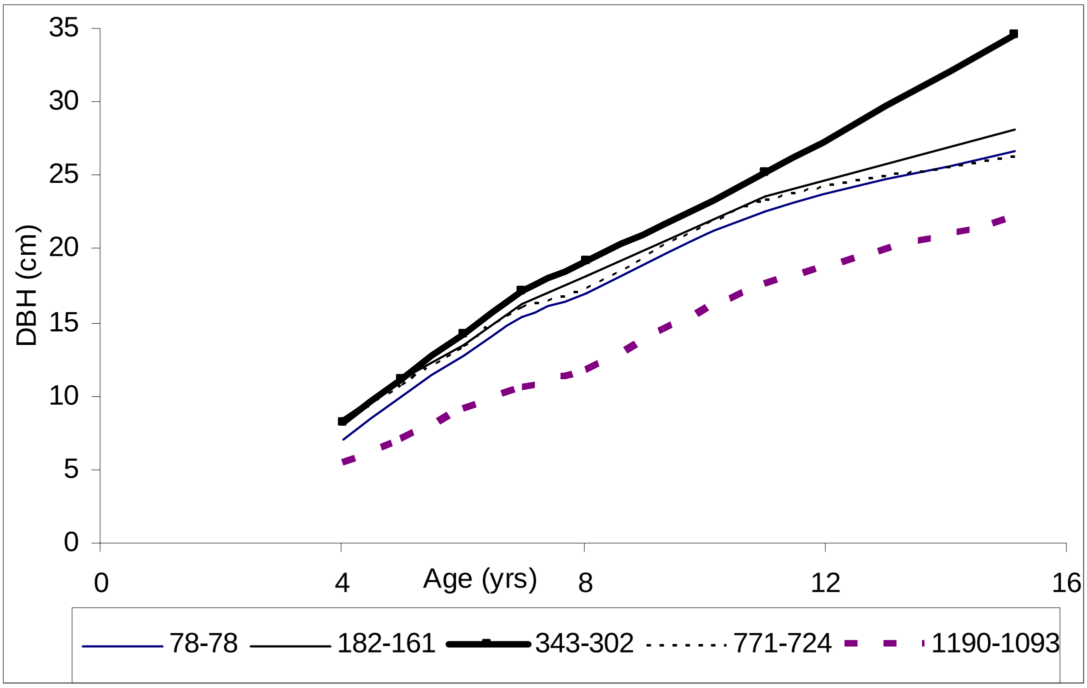

Figure 1. Average diameter of 50 largest spotted gum trees for each hectare, Warril View, Queensland

Note: Legend shows the stand density at the time of planting and at 15.16 years.

As indicated in Figure 1, average diameter at year 15.16 for spacing C is much greater (34.62 cm) than for the other spacing levels. At age 4, the average diameter is lower for spacing C than spacing B, but became the higher from the fifth year. Institutively it would be expected because of the large spacing level, the average diameter for spacing levels 'A' and 'B' would be higher than for spacing 'C'. But selecting the 50 largest trees from the small number of trees for spacing 'A' and 'B' might have resulted in lower than expected mean diameter. Therefore, from the analysis of DBH of the 50 largest trees, it was obvious that spacing 'C' leads to higher tree diameter than the others. But a high amount of cost on plantation could not be compensated for from 50 the 50 largest trees in a hectare. This demands further analysis of the diameter of all trees. While comparing the average diameter of all trees at five spacing levels, there was not much difference in diameter between the spacing levels 'A', 'B' and 'C' at year 15.16 (Figure 2). However, the spacing levels 'D' and 'E' had much lower mean DBH than the other spacing levels.

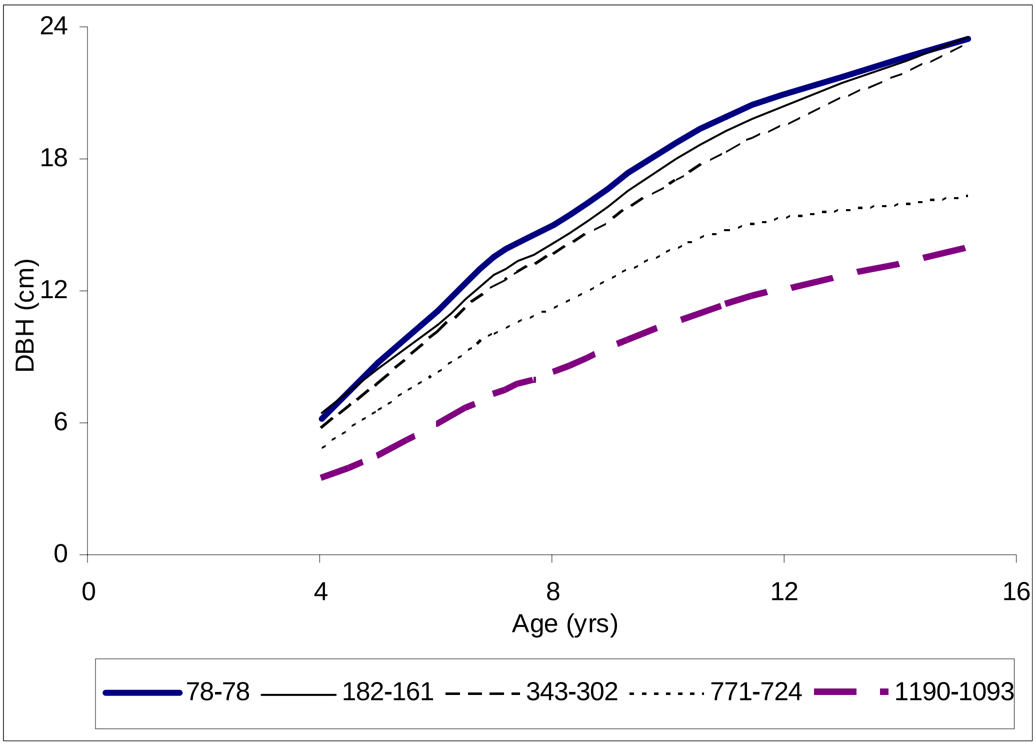

Figure 2. Average diameter of all spotted gum trees of various spacings, Warril View, Queensland
Note: The legends indicate stand densities at the time of planting and at 15.16 yrs.

Since there was a higher number of trees (302 sph) in spacing 'C', the similar mean to spacing 'A' (78 sph) and 'B' (161 sph) confirms the superiority of spacing C. However, it is necessary to also analyse the mean height of all trees.

Mean Height of Trees at Various Spacings

The mean height of all trees at spacing 'D' is higher than at other spacings (Figure 3). However, the difference in mean height between spacing 'C' (17.12 m) and 'D' (17.27 m) is relatively small. The mean diameter of spacing levels 'A' (14.95 m) and 'B' (15.11 m) is much lower than of spacing 'C' (23.21 cm). Because the number of trees per hectare in spacing levels 'A' and 'B' are lower than for the other spacings, the lower mean height is expected at spacing 'A' and 'B' . This is due to the open canopy and therefore lower level of competition for light among the trees. Figure 3 shows that the increasing rate of mean height decreases at an age of about 9-12 years (inflection point) at all spacing levels. This has a major implication for silvicultural treatment because from this age, the tree will have more crown and diameter growth, rather than on height growth. Initially trees compete for light and therefore the height will grow more than crown and diameter. Once tree height approached the inflection point, the trees target changes to diameter and crown cover. Therefore, this is the age at which farmers need to carry out a second thinning to promote diameter growth.

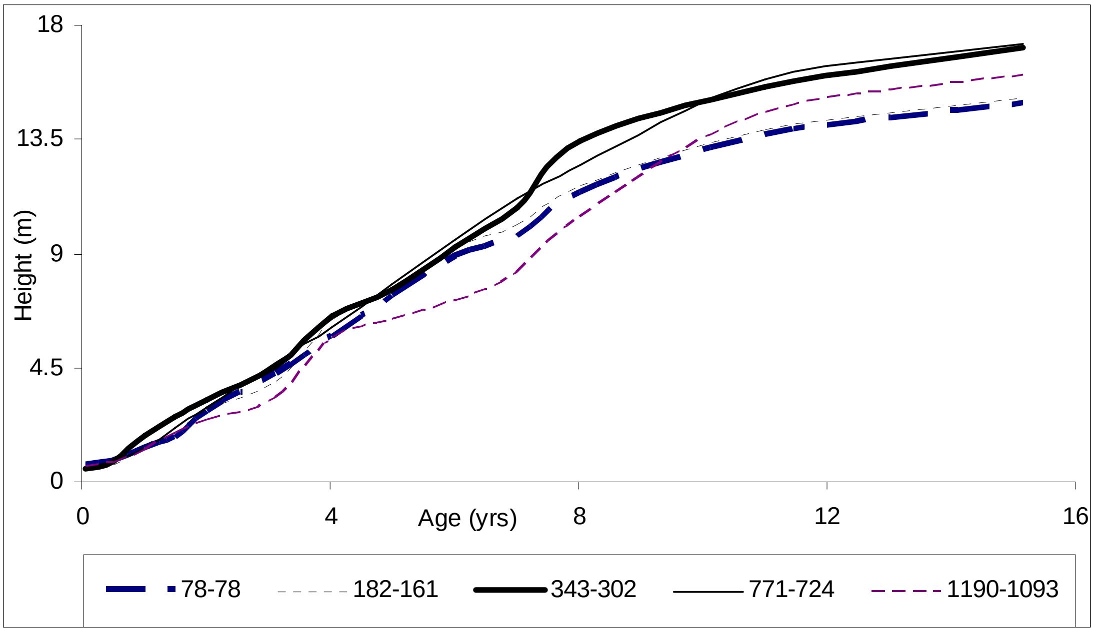

Figure 3. Average height of all spotted gum trees of different spacings at Warril View, Queensland

The analysis of growth over time of mean diameter of the 50 largest trees, and mean height and mean diameter of all trees, suggests the superiority of spacing 'C' over other spacings. However, this result is only up to the age of 15.16 year and not up to harvest age. There are several questions to be resolved to arrive at a final conclusion about the best spacing. What will the mean diameter of all trees at ages of up to say 60 years, be in a 'business as usual' scenario and under each thinning scenario? What age will be the best to achieve the greatest tree diameter (of maybe 40 to 60 cm) for various spacing levels? This requires the analysis and simulation of growth models.

Estimation of Growth Models

The estimated regression parameters (b_0, b_1, b2 and b_3) of growth models of each spacing level are given in Table 3. The lower root mean square value and higher coefficient of determination (R^2) value show that the models were fitted well to the observed values. The potential maximum mean dbh (that is b_0) has a big implication for model calibration. Differences in the values of b0 at each spacing levels show that the potential maximum mean diameter at each spacing level would be different. For example, if the number of trees kept as is at spacing level 'D' (724 sph), the maximum mean potential diameter of the trees would be only about 55 cm (Table 3). Spacing levels 'A', 'B' and 'C' have a similar value of b_0 (around 81 cm). This suggests that there would not be much difference in the maximum potential mean diameter among spacing levels.

Table 3. Estimated model parameters and accuracy measures of growth models for the five planting densities

Spacing level (sph)	b_0	b_1	b_2	b_3	RMSE (cm)	Explained variance
A (78-78)	81.0492	89.3834	0.0231	-0.0223	0.867	98.47%
B (182-161)	80.9800	89.0258	0.0227	-0.0216	0.577	99.30%
C (343-302)	81.0509	88.6978	0.0216	-0.0205	0.651	99.08%
Largest 200 trees	98.4523	89.6975	0.0221	0.0203	0.712	99.16%
Largest 250 trees	90.6030	90.3706	0.0221	0.0006	0.667	99.19%
D (771-724)	54.9980	81.6793	0.0220	-0.0987	0.789	98.72%

Note: The first and second values in parentheses in the first column represent the stand density at the time of planting and at 15.16 years respectively, and RMSE is the root mean squared error.

Estimation of Mean DBH and Volume at Various Ages

Using the estimated regression parameters for all spacing levels and the von Bertalanffy growth equation, mean diameter has been estimated for various tree ages (Table 4). Prediction from the growth equations show that the harvesting age of trees for a given dbh could be reduced by increasing the spacing levels. For example, a 40 cm mean DBH could be achieved at 29, 30, 31 and 56 years by keeping trees at 'A' (11.3 m x 11.3 m), 'B' (7.4 m x 7.4 m), 'C' (5.4 m x 5.4 m) and 'D' (3.6 m x 3.6 m) spacing levels, respectively. However, there is little difference in age to have a 40 cm mean DBH at 'A', 'B' and 'C' spacing levels. The difference in age increases for a higher mean diameter. If the spacing level at 'D' is fixed there would never be a 55 cm mean dbh (maximum potential dbh is less than 55 cm, Table 3). Therefore, the spacing level 'D' was not considered for further analysis.

Table 4. Mean diameter and merchantable log volume up to 10cm top diameter at various ages, for five spacing levels

Tree age (yrs)	Spacing level 'A'		Spacing level 'B'		Breakdown of spacing level 'C' into three different scenarios					
	78 sph		161 sph		200 sph		250 sph		302 sph	
	DBH	Vol	DBH	Vol	DBH	Vol	DBH	Vol	DBH	Vol
25	36.2	73.8	35.7	147.9	41.1	243.9	38.5	267.4	34.37	257.6
30	41.1	95.3	40.6	191.3	47.1	319.7	43.9	348.6	39.18	334.8
35	45.5	116.7	44.9	234.6	52.4	396.4	48.8	430.5	43.49	412.5
40	49.4	137.5	48.8	277.0	57.2	472.3	53.2	511.1	47.35	489.1

Since the number of trees was greater at spacing 'C' (302) than spacing 'A' (78) and 'B' (161), a greater merchantable log volume would be obtained under spacing 'C' than 'A' and 'B'. In order to estimate merchantable log volume (in m^3/ha), the mean diameter of trees of various ages was predicted. The total merchantable volume at spacing 'C' was found to be much higher than for spacings 'A' and 'B' (Table 4).

Thinning Scenario Analysis at Spacing 'C'

The above analysis has not addressed the question: 'What would be the wisest decision: keeping all 302 trees for the whole rotation, or thinning some trees at some stage?' In order to answer this question, two more simulations were undertaken. A similar analysis, as discussed above, was performed by taking the time series data of the mean diameter of the 200 and 250 largest trees per hectare from spacing 'C'. The regression parameters produced from modelling are reported in Table 3. From modelling, it was revealed that if the 200 and 250 best trees per hectare were retained, the maximum potential mean diameter (B0) would be increased to 98 and 91 cm (from 81.04 cm of business-as-usual scenario of level 'C'), respectively (Table 3).

The predicted mean diameter and volume of three different scenarios from level 'C' at different ages are presented in Table 4. It was found that the time to reach a desirable dbh can be reduced dramatically by retaining the largest 200 and 250 trees per hectare. For example, instead of waiting 44 years for 50 cm mean diameter by using the business-as-usual scenario, the same mean dbh will be achieved in 33 years by retaining the 200 best trees and 37 years by keeping the 250 best trees, for one hectare. The analysis shows that the merchantable logs volume at each potential harvesting age would be higher than in other cases, if keep 250 trees per hectare were retained (Table 4). A smaller number of trees associated with a higher amount of merchantable log volume is highly desirable for farmers because it may produce a larger amount of sawn timber volume. Therefore, retaining about 250 sph would be the most profitable option.

Due to the limited research plot age, extrapolation of growth performance was necessary for this study. However, the potential maximum response variable (b_0) provides an important clue about the model. Boland (1984) and Huth *et al.* (2004) were of the view that even in relatively lower rainfall sites, spotted gum may reach from 70 to 120 cm DBH. An intensive inventory of spotted gum in similar rainfall sites found some trees between 80 cm and 84 cm DBH (Margules 1998). Since the estimated 'b_0's from the five spacing levels are within the range of the abovementioned values, they seem reasonable estimates. Moreover, the root mean square error (RMSE) and coefficient of determination (R^2) of all models are acceptable. This evidence suggest that the models are reliable in the given limited data environment.

Financial Analysis of Plantations

Estimated merchantable logs volumes at 250 sph of spacing ‘C’, a most profitable spacing, at a range of ages are reported in Table 4. The total financial revenue per hectare from plantations in 25 and 30 years would be $13637 and $17779 respectively (Table 5). At a 6% discount rate, the net present revenue of plantations in age of 25 and 30 would be $31776 and $3095 per hectare, respectively.

Table 5. Financial revenue (not discounted) from spotted gum plantation at harvesting ages of 25 and 30 years

Log type	Composition	Price ($/m^3)	Revenue in age 25	Revenue in Age 30
Pole	20%	70	3743.6	4880.4
Sawlog	60%	55	8824.2	11503.8
Low-value log	20%	20	1069.6	1394.4
Total revenue			13637.4	17778.6
NPR (present value of final revenue)			3177.5	3095.43

Note: Volumes of logs in age 25 and 30 are 267.4 and 348.6 m^3/ha, respectively. NPR is net present revenue from plantation at 6% discount rate.

Venn (2005) reported the establishment cost of hardwood plantations in REQRFA areas would be $1900/ha. If establishment cost and all recurrent costs are taken into account, the revenue from plantations reported in the Table 5 would not be attractive for farmers. Moreover, if the overhead costs are considered, the attraction of plantations would reduce. Unless farmers are convinced of a higher financial return they will not transform their land use. If a plantation is managed as a silvipastoral system and livestock and carbon values are considered, plantations could be an attractive enterprise.

Some value-adding options on spotted gum plantations could be possible. Aboriginal people have traditionally used the leaves of the spotted gum species. Even with current knowledge, it is used for food additives and perfume, curing food poisoning, acne and athlete’s foot caused by microbial activities (Takahashi et al., 2004), controlling leaf cutting ants (Marsaro et al. 2004) and leaf oil (Asante *et al*. 2001). If these benefits are commercialised, it would help to increase financial returns from spotted gum plantations. Moreover, if markets for forest ecosystem services such as biodiversity, aesthetics and hunting can develop, the plantation benefits could be much higher than the currently estimated amount.

CONCLUSIONS AND RECOMMENDATIONS

This article demonstrates how the optimal spacing level of plantations can be determined in a limited data environment, and how the regression parameter ‘b_0’ (potential maximum DBH), could be an important clue for model verification. From the analysis, the spacing level ‘C’ (5.4 m x 5.4 m, 343 sph) was found to be the most profitable than higher and lower spacings tested. Further analysis of the mean diameter and height of the largest 200 and 250 trees per hectare from spacing ‘C’ reveals that the merchantable volume of logs could be maximised by retaining the 250 largest trees.

The total financial revenue from plantations in 25 years is much lower than that for a 30-year rotation. However, at a 6% discount rate the net present revenue of spotted gum plantations harvested at age 25 is higher than for harvest at 30 years. If all variable and overhead costs are taken into account, timber-alone plantations would not be financially viable in the study area in south-east Queensland. These would have serious implications for attempts to increase the plantation estate to 3 M ha by 2020, through policy frameworks including the Australian Government’s ‘*Vision 2020*’. Therefore, in order to make plantations more attractive, other payment for ecosystem services such as a silvipastoral system, carbon trading, salinity trading and commercialisation of non-timber benefits could be considered.

This analysis is based on the current state of knowledge and limited data. It could be applicable for broadscale financial and economic planning in similar climatic, edaphic and topographic conditions as the experimental site. If full rotation data were available, a more reliable model could be produced thereby a more accurate financial estimate could be made following the methodology presented here.

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REFERENCES

Asante, KS, Brophy, JJ, Doran, JC, Goldsack, RJ, Hibbert, BD & Larmour, JS 2001, 'A Comparative Study of the Seedling Leaf Oils of the Spotted Gums: Species of the Corymbia (Myrtaceae), Section Politaria', *Australian Journal of Botany*, vol. 49, pp. 55-66.

Australian Greenhouse Office (AGO) 2000, 'Land Clearing: A Social History', National Carbon Accounting System, Technical Report No. 4, Canberra.

Boland, D., Brooker, M., Chippendale, G., Hall, N., Hyland, B., Johnston, R., Kleinig, D. and Turner, J. (1984), *Forest Trees of Australia*, Nelson, CSIRO, Australia.

Brown, A.J. (2002), 'Collaborative governance versus constitutional politics: Decision rules for sustainability from Australia's South East Queensland Forest Agreement', *Environmental Science and Policy,* 5(1): 19-32.

BRS (Bureau of Rural Science) (2005), 'National Plantation Inventory Australia: 2005 Updates', http://affashop.gov.au/PdfFiles/, accessed 10 September 2006.

Cacho, O.J., Hean, R.L. and Wise, R.M. (2003), 'Carbon accounting methods and reforestation incentives', *The Australian Journal of Agricultural and Resource Economics*, 47(2): 153-79.

CRC for GA (Cooperative Research Centre for Greenhouse Gas Accounting) (2004), *Annual Report 2003-2004*, ttp://www.greenhouse.crc.org.au/crc/ecarbon/publications/ accessed 6/6/2005.

Department of Primary Industries and Fisheries (DPI&F) (2000), 'Investigating in Queensland's Private Plantations', Brisbane.

Department of Primary Industries and Fisheries (DPI&F) (2004a), 'Forestry, Timber and Wood', Hardwood Queensland: Species List: Spotted Gum, http//:www.dpi.qld.gov.au/hardwoodsqld/7581.html, accessed 3 April 2005.

Department of Primary Industries and Fisheries (DPI&F) (2004b), 'The Queensland Forestry Industry: An Overview of the Commercial Growing, Management and Processing of Forest Products in Queensland', Queensland Government, Department of Primary Industries and Fisheries, Brisbane.

Department of Primary Industries and Fisheries (DPI&F) (2004c), 'Hardwood Advice: Plantation Species Profile', Queensland Government, Department of Primary Industries and Fisheries, Brisbane.

Department of Primary Industries and Fisheries and Department of Natural Resources (DPI&F and DNR) (1999), 'Moving towards Hardwood Plantation', Between the Leaves: www.forests.qld.gov.au/educat/btl/hardwood.htm, accessed 21 October 2004.

Fekedulegn, D., Siurtain, A. and Colbert, J. 1999, 'Parameter Estimation of Nonlinear Growth Models in Forestry', *Silva Fennica*, 33(4): 327-36.

Fensham, RJ and Fairfax, RJ 2003, 'Assessing woody vegetation cover change in north-west Australian savannas using aerial photography', *International Journal of Wildland Forest*, vol. 12 (4), pp. 359-67.

Filho, MS 2004, 'Opening Address', paper presented to Climate Change and Forest Sector: Clean Development Mechanism in Tropical Countries, September 21-23, 2004, Seoul, Korea.

Greenfield Resource Options Pty Ltd (GRO) 1999, 'Silviculture, Management and Infrastructure Requirements for Hardwood Plantations in South East Queensland', Main Report, Bureau of Resources Sciences, Canberra, Australia.

Huth, J, Lee, D, Lawson, S and Smith, T 2004. 'Hardwood Plantation Research Field Tour: Tour of hardwood trials in Wide Bay-Burnett region of Queensland', Queensland Government, Department of Primary Industries and Fisheries.

Kirschbaum, MUF 2003, 'The Clean Development Mechanism', paper presented to international Workshop in 'Facilitating International Carbon Accounting in Forests, CSIRO Forestry and Forest Products, Canberra, 24 February 2003.

Kooten, GC 2004, Climate Change Economics, Why International Accord Fail, Edward Elgar Publishing Ltd, UK.

Lee, D 2005, Hybrids: Spearheading Hardwood Plantation Establishment, A Leaflet Distributed in IUFRO World Forestry Congress, Queensland Government, Department of Primary Industries and Fisheries.

Maraseni, TN, Mathers, NJ, Harms, B, Cockfield, G and Apan, A 2006, 'Comparing and Predicting Soil Carbon Quantities under Different Land Use Systems on the Red Ferrosol Soils of Southeast Queensland', paper presented to International Workshop on Development of Models and Forest Soil Surveys for Monitoring of Soil Carbon, Koli, Finland.

Margules Poyry Pty Ltd 1998, 'Wood Fibre Yields For South East Queensland RFA Region' (Draft Report), Prepared for CRA Unit, Department of Natural Resources, Brisbane and BRS, DPIE, Canberra, Australia.

Marsaro Jr, AL, Souza, RC, Lucia, DTMC, Fernandes, JB, Silva, MFGF & Vieira, PC 2004, 'Behavioral Changes in Workers of the Leaf-Cutting Ant *Atta sexdens rubropilosa* Induced by Chemical Components of *Eucalyptus maculata* Leaves', *Journal of Chemical Ecology*, vol. 30 (9), pp. 1771-80.

Mitchell, C and Skjemstad, J 2004, 'Greenhouse Chemistry not only in the Atmosphere', *Chemistry in Australia*, vol. 17, pp. 12-16.

National Forest Inventory 2004, *National Plantation Inventory Update-March 2004*, Bureau of Rural Sciences, Canberra.

Paul, K, Polglase, P and Ricchards, GP 2003, 'Sensitivity Analysis of Predicted Change in Soil Carbon Following Afforestation', *Ecological Modelling*, vol. 164 (2-3), pp. 137-52.

Paul, K, Polglase, P, Nyakuengama, JG and Khanna, PK 2002, 'Change in Soil Carbon Following Afforestation', *Forest Ecology and Management*, vol. 168 (1-3), pp. 241-57.

Queensland CRA/RFA Steering Committee 1998, 'Commercial Plantation Land Capability Analysis of South East Queensland', Queensland CRA/FRA Steering Committee, Queensland, Brisbane.

Saffigna, P.G., Moody, P.M. and Mathers, N.J. (2004). Impact of cropping on the soil C and N, and the potential for C sequestration under hardwood forest plantations in subtropical Queensland, Australia. In Conserving Soil and Water for Society: Sharing Solutions. Proceedings of the 13th International Soil Conservation Organisation Conference, (Eds. S.R. Raine, A.J.W. Biggs, N.W. Menzies, D.M. Freebairn and P.E. Tolmie), 4-8 July 2004, Brisbane, paper 435.

Takahashi, T, Kokubo, R & Sakaino, M 2004, 'Antimicrobial Activities of Eucalyptus Leaf Extracts and Flavonoids from *Eucalyptus maculata*', *The Society for Applied Microbiology*, vol. 39, pp. 60-4

Tilman, D, Fargione, J, Wolff. B, D'Antonio, C, Dobson, A, Howarth, R, Schindler, D, Schlesinger, W, Simberloff, D and Swackhamer, D 2001, 'Forecasting Agriculturally Driven Global Environmental Change', *Science*, vol. 292, pp. 281-84.

Turner, J, Gessel, S and Lambart, M 1999, 'Sustainable Management of Native and Exotic Plantation in Australia', *New Forests*, vol. 18, pp. 17-32.

Vanclay, JK 1994, 'Modeling Forest Growth and Yield', CAB International, Wallingford, UK.

Venn, TJ 2005, 'Financial and Economic Performance of Long-rotation Hardwood Plantation Investments in Queensland, Australia', *Forest Policy and Economics*, vol. 7 (3), pp. 437-54.

Williams, K, Ryan, P, Ross, Y, Venn, TJ and Norman, P 1999, 'Calibrating Empirical Models for Wood Volume and Yield as Inputs for Financial Planning in Agroforestry', Queensland Department of Natural Resources, Indooroopilly, Brisbane, Australia.

Zammit, C, Apan, A, Cockfield, G, Brocque, AL and Bouldin, MR 2001, Prospects for Regional Sustainability: Land Use Change in the Eastern Darling Downs*, 1975-2001* http://www.usq.edu.au/users/apana/landuse.pdf, *accessed 9 July 2005.*