Research paper

Stand Growth Simulation of a Taiwania Plantation in the Liouguei Area

Dar-Hsiung Wang,[1,2] Han-Ching Hsieh,[1] Shyh-Chian Tang,[1]
Chih-Hsing Chung[1]

【Summary】

Taiwania cryptomerioides is a quite important endemic species in Taiwan, and is the most abundant species in plantations in the Liouguei Experimental Forest, southern Taiwan. Using the concept of compatibility and numeric equivalence among stand-level attributes, this study established a growth and yield stand simulator for Taiwania plantations in the Liouguei area. Based on data from permanent plots of Taiwania plantations in the experiment forest, the components of a growth and yield model such as diameter, tree height, stand density, and stand structure modules were separately fitted in sequence and then integrated, and finally computer software (TCSIM) was coded to implement the integrated growth and yield simulator. As an adjunct to the stand-level equations, compatible stand/stock tables were derived by solving for the parameters of the Weibull distribution from attributes predicted with the stand-level equations. The results indicated that the goodness of fit for all equations were good ($R^2 > 0.82$) except for the tree density equation and basal removal function. By inputting the current stand age, tree density, basal area, projection length, and management options into TCSIM, dynamic changes for a given stand can effectively be evaluated.

Key words: stand growth simulator, compatibility, *Taiwania cryptomerioides*.

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[1] Forest Management Division, Taiwan Forestry Research Institute, 53 Nanhai Rd., Taipei 10066, Taiwan. 林業試驗所森林經營組，10066台北市南海路53號。

[2] Corresponding author, e-mail:dhwang@tfri.gov.tw 通訊作者。

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研究報告

六龜地區台灣杉人工林林分生長模擬之研究

汪大雄[1,2)] 謝漢欽[1)] 湯適謙[1)] 鍾智昕[1)]

摘 要

台灣杉(*Taiwania cryptomerioides*)是台灣重要之本土樹種，亦是林業試驗所六龜試驗林最主要之造林樹種。本研究從林分之觀點，以有系統方式將影響台灣杉生長之各項因素(如林齡，地位，密度等)，納入台灣杉各項生長(如胸徑生長，斷面積生長，材積生長，林分密度和結構改變)，並進行各項生長之整合，發展出台灣杉林分生長模擬器。使用相容性之概念發展林分斷面積和林分材積生長模式，再配合六龜試驗林永久樣區之台灣杉生長資料，推導出各項生長模式。整體言之，由於林分株數之變異較大導致林分株數模式之配置效果較差外，其餘大部份之各項生長模式配置結果均佳(R^2 > 0.82)，顯示本研究模式得到良好之配置結果。林分經營者可就某一現實林分輸入必要之資料透過台灣杉林分生長模擬器(TCSIM)，進行不同經營撫育策略下林分未來可能變化之模擬，以掌握林分之動態變化。

關鍵詞：林分生長模擬、相容性、台灣杉。

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INTRODUCTION

For a long time, research focused on growth modeling aimed at describing stand evolution through the construction of yield tables or growth models for even- or uneven-aged stands (Pauwels et al. 2007). Forest growth and yield models of varying degrees of complexity and detail, ranging from whole-stand to individual-tree resolutions, were developed to fulfill the different information requirements for decision making (Zhang et al. 1993, Davis et al. 2001). During the past several decades, a number of stand-level and individual-tree growth models and simulations were developed (Stage 1973, Daniels and Burkhart 1975, Zhang et al. 1996).

The history of growth and yield studies can be traced back to early models from studies of healthy natural stands and published as bulletins full of tables and graphs and called, appropriately, fully stocked or normal yield tables (McCarthy 1933). Later, with the increasing capability in evaluating stands with different levels of stand density, the complexity grew as sets of equations, leaving it up to the user to solve the questions (Bennett 1970). The final evolution was to more-complex models, particularly individual tree models, written as computer software for the facility of users (Clutter et al. 1983, Davis and Johnson 1987).

Early studies of growth and yield were done separately. Buckman (1962) and Clutter (1963) were the first pioneers to explicitly recognize the mathematical relationships between growth and yield in the US (Burkhart and Sprinz 1984). An algebraic form of the yield model that was derived by mathematical integration of the growth model in loblolly pine was proposed, and the resulting analytical models were called compatible growth and yield models (Clutter 1963). Since then, many studies adopting the compatibility concept were conducted in modeling growth and yield events (Sullivan and Clutter 1972, Matney and Sullivan 1982, Burkhart and Sprinz 1984).

Munro (1974) suggested that the empirical growth models be classified into 2 broad categories of stand-level and tree-level models. The basic distinction between these 2 types is that the predictor variables and output variables in stand-level models are stand statistics, but at least some of the predictor variables and output variables in any tree-level model are individual tree statistics. While some stand-level models (diameter distribution models) produce tree-level outputs (frequencies and average heights by diameter at breast height (DBH) classes), they are still classified as stand-level models because the inputs are stand-level statistics (Clutter et al. 1983).

Several models and functions must be integrated to build an integrated stand-level growth and yield simulation system: (1) an assessment of forestland site potential capacity, usually expressed by site index, (2) a density function to express demographic changes in the tree population, (3) a tree height-diameter model quantitatively expressing the relationship between tree height and DBH, and (4) an individual tree volume function to calculate the tree volume by measuring tree height and DBH. An additional model that has to be added for the diameter distribution model is the tree diameter distribution function expressing the diameter structure in the stand (Biging 1985, Hann and Ritchie 1988, Hann and Wang 1990, Smith and Hann 1984).

The intensive management of Taiwania (*Taiwania cryptomerioides*) plantations needs accurate estimations of current state and precise projections of plantations that undergo alternative silvicultural practices. In the Liouguei area, while several studies related to Taiwania plantation growth were done in the past (Hung 1974, Lin 1975, Liu et al. 1984, Lin and Horng 1991, Liu and Chung 1993, Chen et al. 1996, 1997, Wang et al. 2008), none of them attempted to integrate different stand attributes growth together. Therefore, the purposes of this paper were (1) to develop an integrated stand-level growth and yield model to simulate the evolution of Taiwania plantation in the Liouguei area, and (2) to derive diameter distributions from the predicted stand attributes using the parameters recovery methods.

MATERIALS AND METHODS

Data for this study came from Taiwanian plantations in the Liouguei Experimental Forest of TFRI. Permanent plots of Taiwania plantations in compartment 3, 10, 12, 14, 18, 20, and 24 were used to establish the Taiwania plantation simulation model. At each plot, trees were tagged, and stand attributes were calculated following the different periods of surveying. In each plot, data for each survey were considered 1 observation in the dataset for model fitting. In total, 228 observations were used to construct the growth and yield equations. Among them, 146 were from plots with no thinning treatment, and 82 from plots with 1 thinning practice. Validation was done using observations randomly picked out from the dataset.

The growth and yield simulation system for Taiwania plantations (*Taiwania cryptomerioides* Simulator, TCSIM) was developed in 3 stages. In the 1st stage, equations to predict stand-level attributes (e.g., site index, dominant tree height growth, DBH growth, basal area, and volume growth) were obtained and fitted to observed data, respectively. In the 2nd stage, stand tables were derived from the whole-stand attributes to calculate parameters of the Weibull diameter distribution function using parameter recovery methods to assure the compatibility between the whole stand and diameter distribution estimates of the stand-level attributes. Finally, all equations were integrated and coded into a computer simulator to be used by forest managers.

Site index models and the dominant height growth function used were obtained from a study of the site index model in the Liouguei area (Wang et al. 2008) as equations (1) and (2):

$S = 43.3419\ H_d^{-0.0935}[1 - \exp(-0.033\ A_0)]^P$; ....(1)

where S is the site index (m), A_0 is the base age (yr), H_d is the average dominant tree height in stand at age A (m), A is the tree age (yr), and $P = \ln(H_d/43.3419\ H_d^{-0.0935}) / \ln[1 - \exp(-0.033A)]$.

$H_d = 2.6462\ S^{0.7704}[1 - \exp(-0.066A)]^P$; ....(2)

where S, A_0, H_d, and A are described above, and $P = \ln(S/2.6462S^{0.7704}) / \ln[1 - \exp(-0.066A_0)]$.

Compatibility and numeric equivalence among stand-level attributes

Empirical equations developed by Beck and Della-Bianca (1972) were used to predict the basal area and volume at some projected age when the site index, initial age, and basal area are given. The associated equation is listed as equation (3):

$\ln(Y_2) = b_0 + b_1(S^{-1}) + b_2(A_2^{-1}) + b_3(A_1/A_2)\ln(B_1) + b_4(1 - A_1/A_2) + b_5(S)(1 - A_1/A_2)$; ....(3)

where Y_2 is the stand volume ($m^3\ ha^{-1}$) at some projected age A_2, S is the site index, B_1 is the present basal area ($m^2\ ha^{-1}$), and A_1 is the present age (yr).

When $A_2 = A_1 = A$ and $B_2 = B_1 = B$, equation (1) reduces to the general yield model as equation (4):

$\ln(Y) = b_0 + b_1(S^{-1}) + b_2(A^{-1}) + b_3\ln(B)$...(4)

To obtain the numeric equivalence between basal area and volume, a procedure following Knoebel et al. (1986) was used to yield a basal area projection model in equation (5):

$\ln(B_2) = (A_1/A_2)\ln(B_1) + (b_4/b_3)(1 - A_1/A_2) + (b_5/b_3)(S)(1 - A_1/A_2)$.............................(5)

In this analysis, equation (3) was fitted by ordinary least squares to each of the growth periods, and the resulting regression coefficients were plugged into equation (5) to obtain a basal area projected model. *F*-tests were performed to check the significance of the independent variables and determine if separate coefficients were needed for each period. From these tests, we determined that 2 sets of coefficients were needed – one for growth periods with no thinning and another for growth periods after 1 thinning.

The tree density function in stumps was fitted with equation (6) for 2 sets of observations as mentioned above:

$\ln N = b_0 + b_1(A^{-1}) + b_2 S + b_3(B^{-1})$...........(6)

Based on a stem analysis of data from taper and site index studies (Wang et al. 2007, 2008), the individual tree total volume was estimated by equation (7):

$V = 0.0000729\ D^{1.65635}\ H^{1.11574}$;....................(7)

where V is the tree volume (m^3), D is the diameter at breast height (cm), and H is the tree height (m).

The relationship of individual tree height growth to the stand dominant height growth was estimated using equation (8):

$\ln(H_d/H) = b_0 + [b_1 + b_2\ln(B) + b_3(A^{-1}) + b_4 S](D^{-1} - Dmax^{-1})$;...................................(8)

where H_d is the average dominant tree height in stand (m), H is the individual tree height (m), D is the diameter at breast height (cm), and Dmax is the maximum DBH in stand (cm).

Since the independent estimates of average diameter ($\overline{d}$), and average squared diameter ($\overline{d^2}$) often produce negative variances on the diameter (Knoebel et al. 1986), a procedure discussed by Frazier (1981) was used to predict the logarithm of the variance of the diameter as equation (9):

$$\ln(\overline{d^2} - \overline{d}^2) = b_0 + b_1 \ln(B) + b_2 \ln(H_d) + b_3 \frac{A \times N}{10000};\ \ldots\ldots (9)$$

where $\overline{d^2}$ is the average squared tree diameter of the stand (cm^2), $\overline{d}^2$ is the squared average of the tree diameter of the stand (cm^2), H_d is the average dominant tree height of the stand (m), B is the basal area (m^2 ha^{-1}), A is the stand age (yr), and N is the number of trees ha^{-1}.

To derive the stand attributes by DBH classes in the stand table, the minimal DBH in the stand must be determined. The minimal DBH can be predicted using equation (10):

$$\ln \mathrm{Dmin} = b_0 + b_1 [B/(0.00007853975 \times N)]^{1/2} + b_2 N^{-1/2} + b_3 (A \times H_d)^{-1};\ \ldots\ldots (10)$$

where Dmin is the minimal DBH (cm), B is the basal area (m^2 ha^{-1}), N is the number of trees ha^{-1}, A is the stand age (yr), and H_d is the average dominant tree height in stand (m).

In this study, 2 options of thinning practice were provided. One is the traditional way (i.e., thinning from below) in basal area, the other is thinned with the basal area removal ratio allocated for each diameter class. A removal function defined that the amount of basal area removed in each diameter class was based on the ratio of the square of the midpoint diameter of the class to the average squared diameter of the stand as used in equation (11):

$$P_i = \exp\left[b_1 \left(d_i^2 \big/ \overline{d^2}\right)^{b_2}\right];\ \ldots\ldots (11)$$

where P_i is the proportion of basal area removed from diameter class i, d_i is the midpoint diameter of class i, $\overline{d^2}$ is the average squared diameter of the stand, and b_1 and b_2 are parameters to be estimated.

After fitting the different attributes into all relevant equations, integration was performed, and computer programs based on Knoebel et al. (1986) were coded to create Taiwania plantation stand growth and yield simulator to simulate the growth response under alternative silvicultural strategies and different site qualities. An overall flowchart diagram of the TCSIM simulator is shown in Fig. 1.

RESULTS AND DISCUSSION

In order to ensure that the growth and yield model will produce logical and consistent results, it is essential to check if the specified values of stand attributes at the beginning of the projection period are within the interval of data used in the fitting process.

Values far beyond the range of data may yield illogical and inconsistent results due to inappropriate extrapolations (Knoebel et al. 1986). Table 1 shows the ranges of stand attributes on plots fitted in this study. In the TCSIM simulator, an allowance of 10% in maximum and minimum values of each attribute was arbitrarily given to allow flexibility in the stand simulation. Any value specified beyond this allowance was considered an extreme value and had to be specified again for the simulator operation.

Due to great variations among plots in geographic conditions and management regimes, the tree density (e.g., number of trees per hectare) for each observation was quite variable (Table 1). Therefore, the tree density prediction equation was fitted with a little lower R^2 for both unthinned and thinned stands (Table 2). In other words, given an age, site index, and stocking in basal area, only a moderate proportion of the variation in tree density among plots could be explained by the model. The same situation in fitting

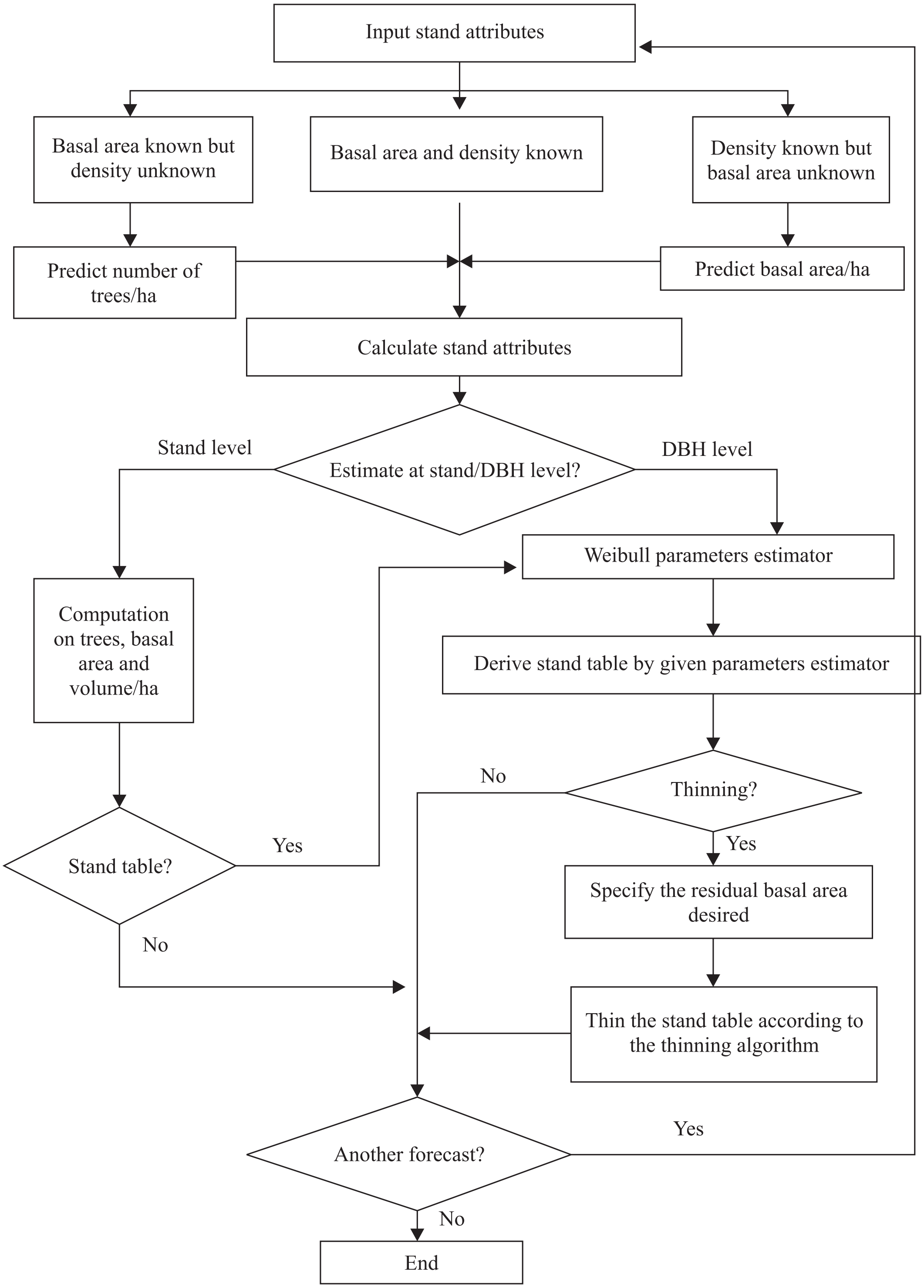

Fig. 1. Flowchart diagram of the Taiwania plantation growth and yield simulation program (TCSIM).

Table 1. Range of stand attributes used in fitting the growth and yield model

Attribute	Range	Maximum	Minimum	Mean ± SD
Age (yr)	47	55	8	25 ± 2
Stems ha^{-1}	2614	3000	386	1824 ± 220
DBH (cm)	27.8	39.5	11.7	20.9 ± 3.1
Basal area (m^2 ha^{-1})	69.9	84.2	14.3	52.4 ± 7.8
Volume (m^3 ha^{-1})	501.8	580.6	78.8	351 ± 64

DBH, diameters at breast height.

Table 2. Coefficient estimates and fitting statistics for tree density projections (equation 6) on unthinned and thinned stands

Unthinned stands				Thinned stands			
Parameter	Coefficient	*t*-value	Pr > *t*	Parameter	Coefficient	*t*-value	Pr > *t*
b_0	7.90735	49.45	0.0001	b_0	7.03681	49.11	0.0001
b_1	17.5543	12.62	0.0001	b_1	13.83722	6.12	0.0001
b_2	-0.06924	-5.82	0.0001	b_2	-0.02513	-2.26	0.0061
b_3	-24.61614	-12.91	0.0001	b_3	-19.72501	-5.72	0.0001
R^2	0.68			R^2	0.62		

the tree density was found in Knoebel et al.'s study (1986).

Coefficients of compatible and numeric equivalent equations for predicting the basal area per hectare and total volume are listed in Table 3 for total volume projection. R^2 values in Table 3 show that 92% of the variation in the total volume among plots in unthinned stands and 84% of the variation in thinned stands were explained by the models. In the basal area projection, to meet the numerical equivalence requirement, all coefficients were directly derived from those obtained in Table 3. As the stand height growth (average of dominant and codominant trees) depends largely on the site quality, with little relevance to thinning treatments, in this study, stand height growth in both data sets were projected using the stand height growth predicting model developed by Wang et al. (2008).

In the stand-level survey, stand height growth can be assessed through the stand

Table 3. Coefficient estimates and fitting statistics for volume yield projections (equation 3) on unthinned and thinned stands

Unthinned stands				Thinned stands			
Parameter	Coefficient	*t*-value	Pr > *t*	Parameter	Coefficient	*t*-value	Pr > *t*
b_0	3.23751	12.38	0.0001	b_0	3.52467	4.01	0.001
b_1	-12.42523	-3.93	0.0004	b_1	-5.25341	-2.01	0.04
b_2	-9.33265	-10.62	0.0001	b_2	-8.44988	-3.32	0.001
b_3	0.98536	25.12	0.0001	b_3	0.77087	4.05	0.0001
b_4	3.83785	5.80	0.0001	b_4	3.6539	2.39	0.02
b_5	0.02780	0.60	0.5472	b_5	0.34088	5.51	0.0001
R^2	0.92			R^2	0.84		

height growth model. However, the height growth of individual trees depends on their own size, the site quality, the stocking density, etc; therefore, it may reveal a different pattern of growth (Knoebel et al. 1986). As no detectable difference was found between the 2 datasets, pooled data were used to estimate the association of individual tree height growth with the stand dominant height growth (Table 4).

Table 5 shows the fitting of Eq. 9 for the pooled dataset. Given a value of $\overline{d^2}$ obtained from the estimate of basal area and an estimate of ln ($\overline{d^2}$ - $\bar{d}^2$), the quadratic mean diameter of the stand was determined algebraically.

Forest resource managers would have a more-useful production prediction tool if the growth components were considered with respect to various size classes rather than for the entire stand. In this paper, stand tables were generated using a parameter recovery procedure to estimate the parameters of the stand DBH structure function. In TCSIM, the predicted average diameter and basal area per hectare obtained from the whole stand-level projection were used through the moment-based 3-parameter Weibull system with a constant parameter ‘a’ approach to obtain estimates of the Weibull function. Given the parameter estimates, the number of trees by diameter class was obtained by multiplying the total number of trees per hectare predicted in the whole stand-level projection by the proportion of the total number of trees in a given diameter class determined by the 3-parameter Weibull density function. The basal area and total volume by diameter class were obtained by numerically integrating the Weibull probability density function over the range of diameters in each class. For the detailed procedure, refer to Knoebel et al. (1986).

Table 4. Coefficient estimates and fitting statistics for the individual trees height prediction equation (equation 8) using pooled data

Parameter	Coefficient	*t*-value	Pr > *t*
b_0	-0.10269	15.95	0.0001
b_1	2.39228	1.56	0.12
b_2	1.48842	13.14	0.0001
b_3	-16.68036	-4.67	0.0001
b_4	0.67827	9.11	0.0001
R^2	0.85		

Table 5. Coefficient estimates and fitting statistics for predicting the 1st and 2nd noncentral moments of the diameter distribution (equation 9) using pooled data

Parameter	Coefficient	*t*-value	Pr > *t*
b_0	-12.1688	-2.33	0.0419
b_1	-1.1331	-1.57	0.1471
b_2	7.26095	2.4153	0.0369
b_3	0.30307	1.94	0.0818
R^2	0.87		

In the 3-parameter Weibull function, the position parameter, “a”, is considered the smallest possible diameter in the stand, and is often approximated by Dmin, the minimum observed diameter in the sample plot. However, it will be positively biased since Dmin is always greater than or equal to the true smallest diameter in the stand. Thus, the value of parameter “a” should most likely be located between 0 and Dmin. Frazier (1981) previously found that the Weibull distribution could be estimated reasonably well from “a” equals to 0.5×Dim; therefore, an estimate of parameter “a” of 0.5 Dmin was used by Knobel et al. (1986) and in this study. The fitting result of Dmin is shown in Table 6.

To project the parameters of the diameter distribution function, both parameter prediction methods and parameter recovery methods are used worldwide. In the former, the parameters are directly predicted from stand

Table 6. Coefficient estimates and fitting statistics for predicting the minimum diameter at breast height (equation 10) using pooled data

Parameter	Coefficient	*t*-value	Pr > *t*
b_0	1.4066	12.41	0.0001
b_1	0.01597	2.28	0.024
b_2	34.58749	6.95	0.0001
b_3	-27.11849	-2.63	0.0093
R^2	0.82		

variables (e.g., age, site, and density) using regression techniques, and then the number of trees and yield per unit area are calculated for each diameter class. The drawback of this approach is that regression models for predicting the parameters usually account for only a small percentage of the variation, i.e., low R^2 values (Cao et al. 1982). On the contrary, in the parameter recovery method, compatible whole-stand and diameter distribution estimates of specific stand attributes are obtained, and therefore, this method was selected by many studies (Matney and Sullivan 1982, Cao and Burkhart 1984, Hyink and Moser 1983).

Several desirable properties which should be sought during the derivation of growth and yield model are the analytical compatibility of equations between growth and yield, invariance of the projection length and numeric equivalency between alternative applications of the equations, and compatibility of stand tables with the whole-stand values (Knoebel et al. 1986). In TCSIM, while the compatibility was based on the basal area, a difference in volume obtained between whole stand-level prediction and the stand table was found because the former stand volume was obtained through site, age, and basal area; however, the latter, stand total volume from table was obtained by summarizing volumes of trees in different diameter classes. This study shows that the difference between the 2 at the initial age will drastically decrease through the prediction of the future status of the stand (Tables 9, 11).

With the traditional thinning from below, a left-truncated diameter distribution was obtained due to the overall heavy thinning of the lower-diameter classes. The basal area removal function in this study (Table 7) provides a way to remove the allocated basal area from each diameter class, thus increasing monetary profits from the thinned wood.

To be able to use the model to evaluate possible stand growth due to changes in age, site, and silvicultural treatments, validation of the fitted model adequacy was necessary. The mean absolute residual value in the percent deviation from observed values was used to measure the accuracy of the goodness-of-fit for various stand components. Differences in relative agreement were found among stand attributes. Among them, the bias value of DBH was smallest indicating the high degree of reliability of the DBH prediction; however, due to the variation involved in tree height predictions, the goodness-of-fit of the volume prediction was not as good as that of DBH (Table 8). Moreover, due to the positive and negative bias that occurred among attributes, overall, no remarkable system bias was found in the validation dataset.

It was noted that due to the lack of plots thinned more than once, predictions in TCSIM can be applied to stands thinned once only.

Table 7. Coefficient estimates and fitting statistics for the basal removal function (equation 11) using thinned data

Parameter	Coefficient	*t*-value	Pr > *t*
b_1	-1.1187	14.82	0.0001
b_2	1.9935	11.35	0.0001
R^2	0.72		

Table 8. Bias representing the absolute residual value between the observed and predicted stand attributes in percentage for 30 selected observations

Attribute	Absolute bias (%)*		
	Average	Minimum	Maximum
Number of stems ha^{-1}	5.8	1.5	17.0
Basal area (m^2 ha^{-1})	12.9	2.2	27.4
Volume (m^3 ha^{-1})	15.1	3.5	30.1
DBH (cm)	4.6	1.6	24.2
Dominant height (m)	11.0	1.3	22.9
Min DBH (cm)	25.4	5.6	46.0
Max DBH (cm)	7.3	1.7	17.0

* Absolute bias (%) = abs [(observed value – predicted value)] / observed value × 100.

Computer software

The code in Visual FORTRAN for TCSIM was based on a model developed by Knoebel et al. (1986) and modified by the senior author to fit the Taiwania plot data on site index and major attributes of growth and yield functions. Overall, 1 main program with 11 subroutines and functions was included in TCSIM. The computer program is illustrated in a simplified flowchart diagram presented in Fig. 1. The descriptions of the steps and procedures outlined in the flowchart are given here.

The input data required by the program included (a) the age at the beginning of projection period, (b) the age at the end of projection period (equal to age at beginning of projection period if no projection in the future is desired), (c) the site index (m) at a base age of 25 yr, (d) either the number of trees per hectare or the basal area per hectare or both at the beginning of the projection period must be known, with the case that given 1 attribute, the other can be predicted from the age, site index, and the known attribute from the equations, and (e) the number of previous thinnings.

Both batch and interactive modes are offered in TCSIM to yield whole stand-level or diameter distribution-level estimates. The interactive mode is preferred for the case of evaluating the effects of thinning strategies on the growth and stand structure because of the prompt response obtained. When the number of projections is large, the batch mode is desired.

More than 1 thinning can be handled by the Knoebel model; however, due to the lack of data on plots with more than 1 thinning at the experimental site, only effects of 1 thinning treatment can currently be assessed by TCSIM developed in this study.

To illustrate the implementation and output of TCSIM, the following case is provided.

A 14-yr-old plantation with a stand density of 2100 stems and a basal area of 52 m^2 ha^{-1} at a site index of 14 m with thinning operation to 40 m^2 ha^{-1} using the basal area removal function thinning algorithm was used to predict the stand table at 44 yr old.

When using TCSIM, users must provide data on the initial age, predicted age, site index, and at least 1 value of either stand density or basal area or both values. Given the specified age and site, TCSIM will compute related stand attributes and derive the stand table by the parameter recovery method (Table 9). Given the residual basal area and thinning algorithm, the stand attributes, amount removed, and stand table after thinning are

Table 9. Predicted stand values and stand tables at an initial age of 14 yr

Whole-stand growth and yield estimates

Initial age = 14 yr
Predicted age = 14 yr
Initial basal area = 52.0 m^2 ha^{-1}
Predicted basal area = 52.0 m^2 ha^{-1}
Predicted number of trees = 2100 ha^{-1}
Site index (base age 25 yr) = 14 m
Thinning in the past = 0
Predicted volume = 264.2 m^3 ha^{-1}
Initial number of stems = 2100 ha^{-1}

Predicted stand/stock table

DBH (cm)	Trees (ha^{-1})	Basal area (m^2 ha^{-1})	Height (m)	Volume (m^3 ha^{-1})
5	0.7	0.0	7	0
7	10.5	0.0	7	0
9	45.3	0.3	7	1
11	117.7	1.1	8	4
13	226.8	3.1	8	12
15	346.3	6.2	8	23
17	423.3	9.6	8	36
19	406.8	11.5	9	42
21	296.3	10.2	9	37
23	155.9	6.4	9	23
25	55.9	2.7	9	10
27	12.8	0.7	9	3
29	1.8	0.1	9	0
Total	2100.0	52.0	---	192

Stand table summary:

Input summary	Projection summary
Age = 14 yr	Age = 14 yr
Site index (base age 25 yr) = 14 m	Number of trees = 2100 ha^{-1}
Basal area = 52.0 m^2/ha^{-1}	Basal area = 52.0 m^2 ha^{-1}
Number of trees = 2100/ha^{-1}	Volume = 193 m^3 ha^{-1}
Previous thinning = 0	Minimum diameter = 5.0 cm
	Mean diameter = 17.8 cm
	Maximum diameter = 29.0 cm
	Mean tree height of dominant trees = 8 m

shown in Table 10. The final whole stand attributes and stand table at the predicted age (44 yr) are shown in Table 11. Therefore, comparisons among alternative thinning intensities and the thinning algorithm are provided as well. Moreover, this study showed that the identical results obtained using with a long projection length or cutting it into several short lengths and simulating them separately indicated the invariance of the projection length in TCSIM.

CONCLUSIONS

TCSIM was designed from the whole-stand growth viewpoint. In TCSIM, factors

Table 10. Predicted stand values and stand table at the initial age of 14 yr after thinning

Predicted stand/stock table after thinning				
DBH (cm)	Trees (ha^{-1})	Basal area (m^2 ha^{-1})	Height (m)	Volume (m^3 ha^{-1})
5	0.0	0.0	0	0
7	0.0	0.0	0	0
9	0.4	0.0	7	0
11	10.2	0.1	8	0
13	41.6	0.6	8	2
15	106.0	1.9	8	7
17	249.6	5.7	8	21
19	406.8	11.5	9	42
21	296.3	10.2	9	37
23	155.9	6.4	9	23
25	55.9	2.7	9	10
27	12.8	0.7	9	3
29	1.8	0.1	9	0
Total	1337.3	40.0	---	146

Stand table summary after thinning:

Age = 14 yr	Site index (m at base age 25 yr) = 14 m
Minimum DBH = 9.0 cm	Mean DBH = 19.5 cm
Maximum DBH = 29.0 cm	Mean tree height of dominant trees = 8 m
Basal area = 40.0 m^2 ha^{-1}	Volume = 146 m^3 ha^{-1}
Number of trees prior to thinning = 2100 ha^{-1}	Number of trees removed = 763 ha^{-1}
Basal area prior to thinning = 52 m^2 ha^{-1}	Basal area removed = 12 m^2 ha^{-1}
Volume prior to thinning = 192 m^3 ha^{-1}	Volume removed = 46 m^3 ha^{-1}

affecting stand growth such as age, site, density, and management activities are integrated and programmed into the software. Preliminary trails with TCSIM produced reasonable values in simulating growth and yield of Taiwania plantations. Through the aid of TCSIM, dynamic changes for a given stand can be effectively evaluated. Moreover, TCSIM can be used for timber production, and also for carbon stock and flow estimations.

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LITERATURE CITED

Beck DE, Della-Bianca L. 1972. Growth and yield of thinned yellow-poplar. USDA Forest Service Research Paper SE-101. 20 p.

Bennett FA. 1970. Variable-density yield tables for managed stands of natural slash pine. USDA Forest Service Research Note SE-141. 7 p.

Biging GS. 1985. Improved estimate of site index curves using varying parameters model. For Sci 31:248-59.

Buckman RE. 1962. Growth and yield of red pine in Minnesota. US Department Agriculture Technical Bulletin 1272. 50 p.

Burkhart HE, Sprinz PT. 1984. Compatible

Table 11. Predicted stand values and stand table at a predicted age of 44 yr

Whole stand growth and yield estimates

Initial age = 14 yr
Predicted age = 44 yr
Initial basal area = 40.0 m^2 ha^{-1}
Predicted basal area = 65.7 m^2 ha^{-1}
Predicted number of trees = 924 ha^{-1}

Site index (base age 25 yr) = 14 m
Thinning in past = 1
Predicted volume = 463.1 m^3 ha^{-1}
Initial number of stems = 1337 ha^{-1}

Predicted stand/stock table

DBH (cm)	Trees (ha^{-1})	Basal area (m^2 ha^{-1})	Height (m)	Volume (m^3 ha^{-1})
15	0.3	0.0	16	0
17	2.3	0.1	17	0
19	8.5	0.2	17	2
21	22.4	0.8	17	6
23	47.4	2.0	18	16
25	84.6	4.2	18	33
27	129.0	7.4	19	58
29	166.1	11.0	19	85
31	175.6	13.3	19	102
33	146.2	12.5	19	95
35	90.5	8.7	20	66
37	38.8	4.1	20	31
39	10.6	1.3	20	9
41	1.8	0.2	20	2
Total	924.3	65.7	---	505

Stand table summary

Input summary
Age = 14 yr
Site index (base age 25 yr) = 14 m
Basal area = 40.0 m^2 ha^{-1}
Number of trees = 1337 ha^{-1}
Previous thinning = 1

Projection summary
Age = 44 yr
Number of trees = 924 ha^{-1}
Basal area = 65.7 m^2 ha^{-1}
Volume = 505 m^3 ha^{-1}
Minimum diameter = 15.0 cm
Mean diameter = 30.1 cm
Maximum diameter = 41.0 cm

cubic volume and basal area projection equations for thinnned old-field loblolly pine plantations. For Sci 30:86-93.

Cao QV, Burkhart HE. 1984. A segmented distribution approach for modeling diameter frequency data. For Sci 30:129-37.

Cao QV, Burkhart HE, Lemin Jr. RC. 1982. Diameter distribution and yields of thinned loblolly pine plantations. Publication no. FWS-1-82. School of Forestry and Wildlife Resources, Virginia Polytechnic Institute and State University.

Chen LC, Hunag GM, Chang TY, Horng FW. 1996. The effect of planting density on the growth of Taiwan-fir plantation at Liukuei area. Taiwan J For Sci 11(1):1-11. [in Chinese with English summary].

Chen LC, Huang GM, Lin JS, Chiou CR. 1997. Growing stock and growth estimation of Taiwania plantations in the Liukuei Area. Taiwan J For Sci 12(3):319-27. [in Chinese with English summary].

Clutter JL. 1963. Compatible growth and yield models for loblolly pine. For Sci 9:354-71.

Clutter JL, Fortson JC, Pienaar LV, Brister GH, Bailey RL. 1983. Timber management: a quantitative approach. John Wiley & Sons. 333 p.

Daniels RF, Burkhart HE. 1975. Simulation of individual trees growth and stand development in managed loblolly pine plantations. Division of Forestry and Wildlife Resources, Virginia Polytechnic Institute and State Univ. FWS-5-75. 69 p.

Davis LS, Johnson KN. 1987. Forest management. 3rd ed. McGraw-Hill Inc. p 95-166.

Davis LS, Johnson KN, Bettinger PS, Howard TE. 2001. Forest management: to sustain ecological, economic, and social values. 4th ed. McGraw-Hill Inc. p 182-256.

Frazier JR. 1981. Compatible whole-stand and diameter distribution model for loblolly pine stands. [Unpublished Ph D. dissertation]. Division of Forestry and Wildlife Resources, Virginia Polytechnic Institute and State Univ. 125 p.

Hann D, Ritchie MW. 1988. Height growth rate of Douglas-fir: comparison of model form. For Sci 34:165-75.

Hann D, Wang CH. 1990. Mortality equations for individual trees in the mixed conifer zone of southwest Oregon. Oregon State Univ. Corvallis Research Bulletin 67. 17 p.

Hung LP. 1974. Growth of Taiwania plantation established by test of planting on different forest districts in Taiwan. Taipei, Taiwan. Bulletin of Taiwan Forest Institute no. 236. 27 p. [in Chinese with English summary].

Hyink DM, Moser JW. 1983. A generalized framework for projecting forest yield and stand structure using diameter distribution. For Sci 29:85-95.

Knoebel BR, Burkhart HE, Beck DE. 1986. A growth and yield model for thinned stands of yellow-poplar. Forest Science Monograph. 27 p.

Lin CS, Horng FW. 1991. The growth of *Taiwania cryptomerioides* at Lu-Kuei area. Taiwan Forest Research Institute New Series 6(3):229-48. [in Chinese with English summary].

Lin WC. 1975. Spacing study on Taiwania plantations. Q J Chin For 8(4):18-27. [in Chinese with English summary].

Liu CM, Chung HH. 1993. Nonlinear yield models for Taiwania plantations. Q J Chin For 26(2):39-49. [in Chinese with English summary].

Liu SC, Lin KC, Tang JL. 1984. Growth and wood properties of planted Taiwania cryptomerioies at Lu-Kuei. Taipei, Taiwan. Taiwan Forestry Research Bulletin no. 408. p 25. [in Chinese with English summary].

Matney TG, Sullivan AD. 1982. Compatible stand and stock tables for thinned and unthinned loblolly pine stands. For Sci 28:161-71.

McCarthy EF. 1933. Yellow-poplar characteristics growth, and management. US Department Agriculture Technical Bulletin 356. 57 p.

Munro DD. 1974. Forest growth models – a prognosis. In Growth models for tree and stand simulation. Stockholm: Royal College of Forestry Research Notes no. 30.

Pauwels D, Lejeune P, Rondeux J. 2007. A decision support system to simulate and compare silvicultural scenarios for pure even-aged larch stands. Ann For Sci 64:345-53.

Smith NJ, Hann DW. 1984. A new analytical model based on the – 3/2 power rule of self-thinning. Can J For Res 14:605-9.

Stage AR. 1973. Prognosis model for stand development. USDA Forest Service Research Paper INT-137.

Sullivan AD, Clutter JL. 1972. A simultaneous growth and yield model for loblolly pine. For Sci 18:76-86.

Wang DH, Hsieh HC, Tang SC. 2007. Taper modeling on Taiwania plantation trees in the Liukuei area. Taiwan J For Sci 22(3):339-53.

Wang DH, Tang SC, Hsieh HC, Chung CH. 2008. Site index curve for Taiwania plantations in the Liukuei area. Taiwan J For Sci 23(4): 335-49.

Zhang LJ, Moore JA, Newberry JD. 1993. Disaggregating stand volume growth to individual trees. For Sci 39(2):295-309.

Zhang SH, Burkhart HE, Amateis RL. 1996. Modeling individual tree growth for juvenile loblolly pine plantations. For Ecol Manag 89: 157-72.