Research paper

Site Index Curve for Taiwania Plantations in the Liukuei Area

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【Summary】

An effective characterization of site quality is very important in forest management. Dominant height growth is calculated as a function of tree age and site, and, therefore, the evaluation of site quality is a prerequisite to computing the stand dominant height growth. Both anamorphic curves and polymorphic curves approaches were used to develop the site index model for Taiwania plantations in the Liukuei area, and their accuracy and precision were compared. Pairs of height-age observations were obtained through a stem analysis. The results indicated that based on simultaneously considering the accuracy and precision, i.e., the mean square error (MSE), the base-age-specific site index model developed by Payandeh and Wang (1994) and modified by this study was the best at estimating the site index value for all tree ages observed. In relative terms, the mean bias was < 3% for the chosen model in the validation dataset. While there is an advantage that the estimate and application of the base-age-invariant site index model was not affected by the base age used, this study showed a great large loss of accuracy and precision caused by base-age-invariant models, especially for those trees younger than 11 yr. Moreover, the accuracy of the site index model varied considerably depending on the choice predictor age in estimating the site index value at the base age. This study showed the tendency that for a predictor age, the closer to the base age it was, the higher the accuracy that was obtained.

Key words: base-age-specific site index model, base-age-invariant site index model, polymorphic height growth.

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研究報告

六龜地區台灣杉人工林地位指數模式之建立

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摘　要

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立地品等(site quality)之有效數量化是森林經營中至為重要之要務之一。由於林分之優勢樹高生長是為林齡和地位之函數，因此要計算林分優勢樹高之前必須先對立地之品等進行評量。本研究使用單形地位指數曲線(anamorphic site index curve)和多形地位指數曲線(polymorphic site index curve)兩種方式，以樹幹解析資料，使用不同之模式進行六龜地區台灣杉人工林地位指數曲線之建立，並進行配置模式間推估值正確性和精確性之比較。研究顯示在同時考慮正確性和精確性而言(mean square error, MSE)，所有模式中以Payandeh和Wang發表(1994)並經本研究調整後之模式，就所有觀測到各林齡之台灣杉人工林言之，其進行地位指數推估之成效最高，驗證資料顯示其相對偏差小於3%。基準年無關(base-age-invariant)之地位指數模式雖然具有模式配置不受到不同基準年影響之優點，但本研究發現和基準年相依(base-age-specific)之地位指數模式相比，前者之推估能力較後者為差，尤其是對林齡小於11年生之林分，其差異現象更為明顯。此外，地位指數之推估正確性會隨著推估地位指數時所有採用之起初林齡(predictor age)呈現相當大之變化。一般而言，研究結果顯示在推估地位指數時使用之起初林齡越接近基準年，則其推估會呈現更為精確之趨勢。

關鍵詞：基準年特定地位指數模式、基準年無關地位指數模式、多形高生長曲線。

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INTRODUCTION

Site quality, an innate productivity capability, is a primary factor affecting timber growth on forestlands. From the prospect of timber management, site quality can be defined as "the timber potential of a site for a particular species or forest type" (Clutter et al. 1983). Product size and values at various ages are largely controlled by the site quality and stand density. Therefore, the proper measurement and interpretation of site quality are important tasks for most forest managers.

A variety of quantitative tools can be used to estimate site quality including site index curves, growth intercepts, and soil-site evaluations (Carmean 1975, Carmean et al. 2006). Usually, 2 categories of methods measuring site quality are available (Clutter et al. 1983). With the direct method, site quality estimation based on stand dominant height data is most commonly used in North American (Payandeh 1974a, Spurr and Barnes 1980) and in Nigeria (Onyekwelu 2005).

Most height-based methods of site quality involve the use of site index curves. The site index is interpreted as the average height of the dominant or codominant trees (i.e., stand height) at a predetermined age. This age is called the index age or base age (Clutter et al. 1983), and is set at less than the rotation age, typically, at 25, 50 or 100 yr (Payandeh and Wang 1994).

Any set of site index curves is simply a family of stand dominant tree height development patterns with qualitative symbols or numbers corresponding to the curves for reference purposes (Clutter et al. 1983). Therefore, site index curves and dominant tree height growth functions are closely related to each other. Site indices are popular because they are relatively easy to measure, and dominant tree height growth is fairly independent of stand density, except at the extremes (Stansfield et al. 1991).

Site-index curves can be used to graphically estimate a site index merely by relating measured tree height and age values to the curves and then interpolating between curves for an estimation of the site index. This is a tedious operation and often produces inconsistencies in repeated readings for the same points on a set of curves (Payandeh 1974b). Therefore, due to the personal bias and judgment involved in the graphical estimation of a site index, a more-rapid and less-subjective estimation of the site index is attained by using a formulation to directly compute the site index, given age and height values (Carmean and Lenthall 1989).

Intensive management of (*Taiwania cryptomerioides* Hay) requires the ability to estimate site quality and the potential growth and yield that can be attained for fully stocked stands with different levels of site quality (Carmean 2007). Generally, accurate estimates of the site index depend on 2 conditions (i) the availability of suitable site trees that are dependable indicators of site quality, and (ii) availability of suitable site index curves or equations that accurately portray tree height growth patterns for the area where site quality is estimated (Carmean and Lenthall 1989).

An essential component of timber management on Taiwania plantations is the ability to accurately predict the growth and yield of Taiwania. Site quality, expressed by a site index or indirect variables such as habitat type, is an important predictor of timber growth. As future timber inventories and growth algorithms are developed for this resource, improved estimates of site quality are needed for efficient stratification and yield projections.

Only a few site index curves are available for Taiwania, despite the wide range and great economic importance of this tree in Taiwan. While a site index model on Taiwania plantations was developed by Liu (1996), the goodness of fit of this model has not yet been reported. Therefore, the purpose of this paper was to develop an accurate dominant-height growth model and site index curves for Taiwania plantations in the Liukuei area, using stem analysis method, and compare the estimation powers among different models.

MATERIALS AND METHODS

Only free-growing uninjured dominant and codominant trees are suitable for estimating the site index (Carmean and Lenthall 1989). Data for this study came from Taiwanian plantations in the Liukuei Experimental Forest of the Taiwan Forestry Research Institute (TFRI). Sample trees from Taiwania plantations in compartment 3, 10, 12, 14, 18, 20, and 24 were included in this study. Six to 12 well-formed, uninjured dominant and codominant trees representing a variety of tree ages and heights were selected for stem analysis in each compartment. Trees were sectioned at the stump, at 1.3 m, and at 2-m intervals up to the tip. The age at each height section was determined in the laboratory by counting the rings. From the stem analysis, a series of age-height pairs was derived for each tree. The site index of each tree was obtained by measuring the height at the base age (25 yr old). For site trees those were < 25 yr old, the tree height at 25 yr old was estimated using the Chapman-Richards growth model.

The precision of height growth and site-index curves can be determined using independently selected confirmation trees. Accordingly, 23 trees were randomly selected from the 67 trees to independently check the computed height growth and site-index curves. Data from the remaining 44 trees were used to compute the height-growth and site-index curves given in this study. These computations involved using paired height and age values from each tree at 1-yr intervals for computing the height growth and site-index curves.

The following notation is used hereafter:

H, tree height in (m) at age A;
A, tree age (yr);
A_0, base age (25 yr old);
S, site index in (m);
t_1 and t_2, ages (yr) at periods 1 and 2, respectively;
H_1 and H_2, heights (m) at t_1 and t_2, respectively;
Z, exp [b_1 (X - X_0)];
X, 1/age;
X_0, 1/base age;
Y, natural log of height (m);
Y_0, natural log of height at the base age;
L, 1/JP;
JP, joint point; and
b_i, estimated parameters.

Two types of modeling approaches to the site index models were used in this study. The associated mathematical formulation for each model is given below.

(I) Anamorphic curves approach

A site index family of curves called anamorphic curves means that for any 2 curves, the height of one at any age is a constant proportion of the height of the other at the same age (Clutter et al. 1983). Three methods are used to produce anamorphic site index curves.

1. Schumacher function (1939 cited by Clutter et al. 1983)

$H = K_i e^{\beta/A}$

Taking the logarithm of the tree height equation and some arrangements based on the definition of the site index, the resulting tree height growth and the associated site index are given as Eqs. 1a and 1b:

$$\mathrm{Ln}\,(H) = \mathrm{Ln}\,(S) + b_1\,(1/A - 1/A_0) \quad \text{and} \qquad (1a)$$

$$\mathrm{Ln}\,(S) = \mathrm{Ln}\,(H) - b_1\,(1/A - 1/A_0). \qquad (1b)$$

2. Chapman-Richards function (1961)

$H = b_1\,[1 - \exp(-b_2 A)]^{[(1 - b_3)^{-1}]}$

After holding the shape parameters b_2 and b_3 constant and varying the asymptote parameter, b_1, to comply with the site index definition, the tree height growth and site index are formulated as Eqs. 2a and 2b:

$$H = S\left[\frac{1 - \exp(-b_2 A)}{1 - \exp(-b_2 A_0)}\right]^{[(1 - b_3)^{-1}]} \quad \text{and} \qquad (2a)$$

$$S = H\left[\frac{1 - \exp(-b_2 A_0)}{1 - \exp(-b_2 A)}\right]^{[(1 - b_3)^{-1}]}. \qquad (2b)$$

3. Liu (1996)

The tree height growth and site index are formulated as Eqs. 3a and 3b:

$$H = S \times \left\{\frac{A_0}{A}\right\}^{b_1} \times \exp\,[b_2 (A_0 - A)] \quad \text{and} \qquad (3a)$$

$$S = H \times \left\{\frac{A_0}{A}\right\}^{b_1} \times \exp\,[b_2 (A_0 - A)]. \qquad (3b)$$

(II) Polymorphic disjointed curves approach

A polymorphic disjointed curves means that the proportionality relationship among curves does not hold, and the curves do not cross within the range of interest (Clutter et al. 1983). Generally, compared with anamorphic site index curves, polymorphic disjointed curves are quite flexible and more realistic because of the polymorphic patterns revealed in tree height growth under different levels of site quality (Carmean et al. 2001).

Polymorphic disjointed models used in this study are described below.

4. Payandeh and Wang (1994)

$H = b_1 S^{b_2}\,(1 - \exp(-b_3 A))^P$;
where $P = \mathrm{Ln}\,(S/b_1 S^{b_2}) / \mathrm{Ln}\,(1 - \exp(-b_3 A_0))$. (4a)

Equation 4a is derived from the extended Richards biological growth function developed by Ek (1971) and satisfies the condition of H = S at the index age.

It is impossible to solve the height growth equations for the site index in a closed form directly in terms of observed height and age, but an analogue suggested by Payandeh (1974a) provides a form in Eq. 4b for directly estimating the site index, given the age and height values:

$S = b_1 H^{b_2} (1 - \exp(-b_3 A_0))^P$;
where $P = \mathrm{Ln}(H / b_1 H^{b_2}) / \mathrm{Ln}(1 - \exp(-b_3 A))$. (4b)

Moreover, based on a constrained version of the Chapman-Richards function, Payandeh and Wang (1994) proposed a base-age invariant site index model as shown by Eq. 4c:

$H_2 = b_1 H_1^{b_2} (1 - \exp(-b_3 t_2))^P$;
where $P = \mathrm{Ln}(H_1 / b_1 H_1^{b_2}) / \mathrm{Ln}(1 - \exp(-b_3 t_2))$. (4c)

5. Yang et al. (1978)

$$H = b_1 S^{b_2} (1 - \exp(-b_3 A^{b4S^{b5}})) \quad (5)$$

As this equation does not satisfy the condition of the site index at the base age, Payandeh and Wang (1995) modified this equation as Eq. 5a to satisfy the site index requirement:

$$H = P(1 - \exp(-b_3 A^{b4S^{b5}})); \quad (5a)$$

where $P = S / (1 - \exp(-b_3 A_0^{b4S^{b5}}))$.

In the same manner, due to the lack of algebraic manipulation of Eq. 5a, the corresponding site index is listed as Eq. 5b:

$$S = P(1 - \exp(-b_3 A^{b4H^{b5}})); \quad (5b)$$

where $P = H / (1 - \exp(-b_3 A_0^{b4H^{b5}}))$.

6. Payandeh (1974b)

$$H = b_1 S^{b_2} (1 - \exp(-b_3 A))^{b_4 S^{b5}} \quad (6a)$$

$$S = b_1 H^{b_2} (1 - \exp(-b_3 A))^{b_4 H^{b5}} \quad (6b)$$

7. Rose et al. (2003)

$$H = b_1 S^{b_2} \left[1 - k^{\frac{A}{A_0}} \right]^{b_3 S^{b4}}; \quad (7a)$$

where $k = 1 - \left\{ \frac{S}{b_1 S^{b_2}} \right\}^{\frac{1}{b_3 S^{b4}}}$.

Its corresponding site index is

$$S = b_1 H^{b_2} \left[1 - k^{\frac{A}{A_0}} \right]^{b_3 S^{b4}}; \quad (7b)$$

where $k = 1 - \left\{ \frac{H}{b_1 H^{b_2}} \right\}^{\frac{1}{b_3 H^{b4}}}$.

8. Devan and Burkhart (1982)

A segmented polynomial differential system of equations was proposed by Devan and Burkhart (1982) to develop a site index model. With 1 joint point, the resulting site index model is described as Eq. 8:.

$Y = Y_0 Z + b_2 (Z - 1) + b_3 (X_0 Z - X) + b_4 (X_0^2 Z - X^2)$ for $X \leqq L$

$Y = Y_0 Z + b_5 (Z - 1) + b_6 (X_0 Z - X) + b_7 (X_0^2 Z - X^2)$ for $X > L$. (8)

The corresponding height growth model was implicitly obtained by the algorithm given by Devan and Burkhart (1982).

Goodness of fit tests were carried out to measure the model adequacy. The precision and accuracy of all site indices or height growth levels fitted were determined by the following statistical criteria in terms of heights (h) or site index (s) at different ages:

1) Average bias (m) $= \frac{1}{n} \sum (S_i - \hat{S}_i)$;

2) Average bias (%) $= \frac{1}{n} \sum ((S_i - \hat{S}_i) / S_i \times 100)$;

3) Average absolute bias (m) $= \frac{1}{n} \sum abs(S_i - \hat{S}_i)$;

4) Standard error of the estimate (SEE) (m) = $\sqrt{\sum (S_i - \hat{S}_i)^2 / (n - m - 1)}$; and

5) Mean squared error (MSE) = Bias^2 + Variance;

where $\hat{S}_i$ is predicted measurement at age A_i, S_i is the actual measurement at age A_i; m is the number of parameters in the model, and n is the number of points in a specified region of age, say 10~15, 16~20, 21~25 yr old.

RESULTS AND DISCUSSION

The base age used in this study was arbitrarily set to 25 yr old because most Taiwanian plantations in the Liukuei Experiment

Forest were still in a juvenile stage of < 35 yr in 2006. Since the sample trees used to estimate the site index are ranked as dominant or codominant trees in the crown class in the plantations, in the fitting model, the distribution effect of sample trees on the diameter at breast height (DBH) is not as critical as the case of estimating the taper along the bole (Wang et al. 2007). Due to the site index curves being interpreted as tree height growth over time, the ranges of ages and tree heights observed for sample trees is relevant to fitting the site index model in an even-aged plantation. The distributions of ages and tree heights of sample trees are shown in Table 1. For sample trees older than the base age (25 yr), their site index values can be observed through the stem analysis. For those trees younger than the base age, their site index value was estimated using the Chapman-Richards growth model. In this study, 21 sample trees were younger than the base age. The mean square error of the heights of these trees in the Chapman-Richards estimation ranged 0.2327~0.5953, with the average of 0.3714. The estimated parameter values and their standard errors of dominant height growth and site index for all models based on the fitting data are listed in Tables 2 and 3, respectively.

Two fundamental usages are involved in using site index models. They are (1) to estimate the site index from the height at any given age, and (2) to estimate the dominant height at any given age from the site index (Wang and Payandeh 1995). In this study, the former was done using the site index models, and the latter was done using the dominant height growth models.

While the site index curve and dominant tree height growth curve are closely related to each other, the goodness of fit in model fitting greatly differs between them. In this study, except for Devan and Burkhart (1982), all models were able to explicitly show both the site index and dominant tree height growth at the same time. It was found that the model estimation ability was higher for the dominant tree height growth for all models for both fitting data and validation data (Tables 4, 5). This finding may be used to explain why in many studies of site index models, the site index variable is put into the right hand side (RHS) of the equation, rather than into left hand side (LHS), and the resulting equation is called site index equation (Payandeh 1974a, Newnham 1988, Payandeh and Wang 1994). However in this study, the site index models are referred to as ones with the site index variable as the dependent variable, and

Table 1. Distribution of sample trees by age and height

Age (yr)	Height (m)							
	12~14	14~16	16~18	18~20	20~22	22~24	24~26	26~28
< 11								
11~15								
16~20	4	1	2	3	1			
21~25		4	3	6	5	2	1	
26~30		2	1	4	7	3	1	
31~35				2	3	3	2	1
36~40						2	1	1
> 40							1	1
Total	4	7	6	15	16	10	6	3

those models with site index variable as the independent variable are called dominant tree height growth models.

For those models for which site index and height growth can be algebraically exchanged with each other (Eqs.1a, 1b, 2a,

Table 2. Estimated coefficients and their standard errors (in parenthesis) of dominant height growth for all models based on fitting data

Model	Parameter				
equation	b_1	b_2	b_3	b_4	b_5
1a	-10.3148				
	(0.1048)				
2a		0.0647	1.3146		
	(0.00271)	(0.0337)			
3a	-1.1444	0.0238			
	(0.0208)	(000115)			
4a	2.6462	0.7704	0.0660		
	(0.1768)	(0.0196)	(0.000256)		
5a	0.0355	4.2657	-0.4683		
	(0.000897)	(0.6595)	(0.0500)		
6a	2.4802	0.8073	0.0606	5.2248	-0.4711
	(0.1980)	(0.0250)	(0.00271	(0.7616)	(0.0461)
7a	1.2025	1.0412	6.4271	-0.5450	
	(0.3655)	(0.1009)	(2.4106)	(0.1230)	

Table 3. Estimated coefficients and their standard errors (in parenthesis) of the site index for all models based on fitting data

Model	Parameter						
equation	b_1	b_2	b_3	b_4	b_5	b_6	b_7
1b	-5.6259						
	(0.0658)						
2b		0.0519	1.0983				
		(0.00438)	(0.0325)				
3b	1.0583	-0.0215					
	(0.0260)	(0.00193)					
4b	43.3419	-0.0935	0.0330				
	(2.3834)	(0.0122)	(0.00214)				
5b	21.8487	-1.8800	-0.2002				
	(1.6376)	(0.0223)	(0.00208)				
6b	7.91880	-0.5820	0.000205	-0.1189	0.4820		
	(1.5579)	(0.0556)	(0.000156)	(0.0141)	(0.0419)		
7b	0.1463	1.3894	-1.3012	0.3018			
	(0.0742)	(0.9345)	(0.0265)	(0.0115)			
8	1.05895	-4730.02	-4987.72	-2872.39	-71.1654	-57.2430	-61.7114
	(0.00843)	(4010.83)	(4245.22)	(2415.52)	(16.227)	(16.683)	(11.912)

Table 4. Comparison of bias and standard error of site index models for the validation data

Model equation	Bias			Standard error (m)	MSE (m^2)	Rank
	Average (m)	Percentage average (%)	Absolute average (m)			
1b	2.88	14.84	3.83	5.69	32.36	7
2b	0.59	3.15	2.61	4.35	18.90	5
3b	0.56	2.98	2.62	4.35	18.93	6
4b	-0.27	-2.13	1.28	1.78	3.17	1
5b	-0.30	-2.05	1.47	2.06	4.25	3
6b	-0.07	-1.21	1.46	1.94	3.75	2
7b	0.32	1.39	1.89	2.87	8.24	4
8	5.86	29.82	6.47	8.64	74.29	8

Table 5. Comparison of the bias and precision of dominant height growth models for the validation data

Model equation	Bias			Standard error (m)	MSE (m^2)	Rank
	Average (m)	Percentage average (%)	Absolute average (m)			
1a	0.18	4.40	1.12	1.55	2.41	7
2a	0.26	-4.77	1.02	1.44	2.06	3
3a	0.28	-6.18	1.04	1.46	2.14	5
4a	0.10	5.54	1.05	1.42	2.02	1
5a	0.14	-4.19	1.01	1.45	2.09	4
6a	-0.30	-2.89	1.06	1.49	2.22	6
7a	0.22	-5.34	1.03	1.43	2.05	2

P.S. For the Devan and Burkhart model (equation 8), because a huge inaccuracy was obtained for trees young than 5 yr old, it was excluded from the others in the comparisons.

and 2b), the initial attempt was made to fit the height growth model first to get the parameters, and then the resulting values were plugged into the site index model to estimate the site index at a given age and height. However, the validation results showed that a loss of accuracy and precision occurred compared to fitting the site index model directly. For example, in Model 2, the MSE increased from 18.9 to 22.81 if the former approach was used (Table 4). Therefore, for these models, an approach to fitting the site index was used, and their goodness of fit was compared with other models.

Comparisons of the site index among all models indicated that except for model Eqs. 1b and 8, a quite-small average bias in the site index was detected in both the fitting and the validation datasets (Table 4). However, the difference in the absolute average bias appeared to be greater for all models. In relative terms, the mean biases were < 4% for most equations in the validation dataset (Table 4). As judged by the accuracy and precision criteria considered simultaneously, model 4b was the best one at estimating the site index for both the fitting and validation datasets for all ages observed, followed by model 6b. A biased estimator with a small variance may be preferable to an unbiased estimator with a large variance, so the MSE was also used to evaluate the site index estimators (Coble and Wiant. 2000). The rank of models based on the MSE is listed in Table 4. The corresponding family of site index curves obtained by Eq. 4a for different site index values is plotted as Fig. 1. It is obvious that a polymorphic dominant height growth pattern was revealed for the different site qualities with slightly linear growth pattern on poor sites and a more-curved form on good quality sites.

The development of base-age-specific site index models requires that the site index be observed or estimated for sampled trees while fitting the models. However, the choice of the base age affects the parameters estimates for the height-age curve; therefore, the resulting equation will not be base-age invariant (Clutter et al. 1983, Stansfield et al. 1991). Utilization of the algebraic difference method will produce an equation that is base-age invariant. For example, Goelz and Burk (1992) employed a difference equation of the modified Chapman-Richards growth function to build up a base-age-invariant site index model. So did Payandeh and Wang (1994) in deriving a base-age-invariant site index model based on the constrained version of the Chapman-Richards function.

Most site index models used in this study are called base-age-specific models because of the occurrence of the site index value in fitting the models. Two base-age- invariant site index models developed by Goelz and Burk (1992) and Payandeh and Wang (1994) (i.e., Eq, 4c) mentioned above were also used in this study. While there is an advantage that the estimation and application of the base-age-invariant site index model is not affected by the base-age used (Bailey and Clutter 1974, Goelz and Burk 1992), this study showed a big loss of accuracy and precision caused by base-age- invariant models, especially for those trees younger than 11 yr. For instance, compared with the best model in the base-age-specific site index (i.e., Eq. 4b), the average absolute bias for trees younger than 11 yr in Eq. 4c was much bigger than that of

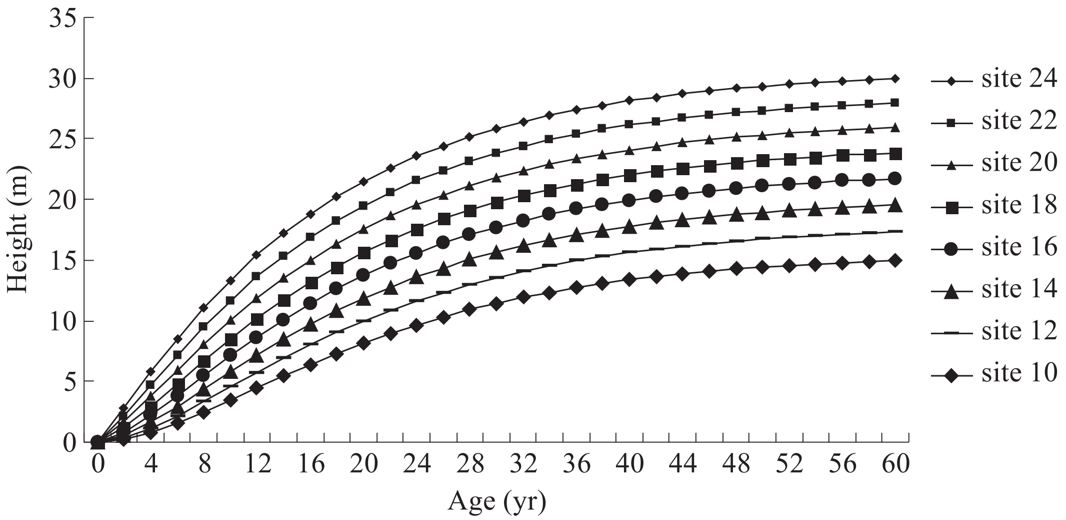

Fig. 1. Family site index curves at sites from 10 to 24 at an interval of 2 m obtained by equation 4a.

the same age class in Eq. 4b (11.96 vs. 1.89) in the validation dataset (Table 6). The difference in bias between these 2 models rapidly dropped with an increase in the tree age class. As the purpose of Eq. 4c is to predict tree height at a given year, as expected, a high inaccuracy was obtained when very young trees were used to estimate the site index. However, a much higher accuracy was gained by using trees aged closer to the base age. This finding is quite similar to that obtained by Payandeh and Wang (1994). The same situation was applied to the case of a base-age-invariant site index model in Goelz and Burk's (1992) study.

Eq. 4b was proposed by this study through a slight modification of Eq. 4c developed by Payandeh and Wang (1994). Instead of using H_2 as a dependent variable in Eq. 4c, in Eq. 4b the site index variable was used as a dependent variable. As the site index value needs to be determined in the fitting procedure, Eq. 4b is classified as a base-age-specific site index model.

The accuracy of a site index model varies considerably depending on the choice of predictor age in estimating the site index value at the base age. For all models, it produced quite-inaccurate estimates for young ages (i.e., < 15 yr). A strong and consistent trend of the accuracy was found : for a predictor age, the closer to the base age, the higher accuracy was obtained for all models (Tables 7, and 8). In other words, this study indicated that the choice of predictor age influenced the models' accuracy and precision. Therefore, the site index can not reliably be estimated with height measurements from very young trees. This finding is consistent with those demonstrated by other studies (Payandeh and Wang 1994, Wang and Payandeh 1995). A spindle-like pattern of a on residual plot of model 4b in the validation data is shown on Fig. 2.

The superiority of model 4b was also identified with regard to criteria of average absolute deviations and standard errors of estimates (Tables 6, and 9). To satisfy the condition of the site index at the base age, a constraint is often imposed on the height growth equation (Newnham 1988, Payandeh and Wang 1994). However, imposing the constraint usually adversely affects the accuracy of parameter estimation of the model (Wang and Payandeh 1994). This phenomenon was verified by this study as well. For example, imposition of a constraint in model 5 caused a loss of MSE from 1.63 in Eq. 5 to 2.09 in Eq. 5a in the validation dataset (Table 5).

The site index and dominant tree height growth are crucial to timber growth. In timber growth simulation studies, in practice, the site index of a stand given a specific age was

Table 6. Average absolute bias of the sit index (m) at different ages for all models for the validation data

Age (yr)	Sample	Model equation							
	size	1b	2b	3b	4b	5b	6b	7b	8
< 11	230	7.64	5.67	5.67	1.89	2.26	2.17	3.65	13.26
11~15	230	3.64	2.11	2.12	1.53	1.83	1.61	1.91	6.05
16~20	115	1.84	1.13	1.13	1.07	1.29	1.18	1.06	2.78
21~25	95	0.52	0.29	0.29	0.31	0.35	0.69	0.29	0.67
26~30	60	0.72	0.32	0.33	0.47	0.37	0.52	0.33	1.36
31~35	30	2.27	0.83	0.93	1.29	0.94	0.83	0.83	3.61
36~40	10	3.03	1.03	1.26	1.98	1.39	1.46	1.04	4.89

Table 7. Average biases of the site index (m) at different ages for all models for the validation data

Age (yr)	Sample size	Model equation 1b	2b	3b	4b	5b	6b	7b	8
< 11	230	5.99	2.43	2.40	-1.15	1.26	1.46	1.93	10.26
11~15	230	3.54	-0.49	-0.55	-0.48	-1.11	-0.68	0.31	6.05
16~20	115	1.69	-0.42	-0.41	-0.41	-0.98	-0.71	-0.12	2.78
21~25	95	0.47	-0.06	-0.05	-0.09	-0.27	-0.18	-0.03	0.51
26~30	60	-0.69	-0.15	-0.06	-0.06	0.20	0.20	-0.10	-1.36
31~35	30	-2.27	-0.63	-0.84	-0.72	0.42	0.76	-0.48	-3.61
36~40	10	-3.02	-0.60	-1.13	-0.78	1.17	1.46	-0.24	-4.89

Table 8. Average bias of site index in percentage (%) at different ages for all models for the validation data

Age (yr)	Sample size	Model equation 1b	2b	3b	4b	5b	6b	7b	8
< 11	230	31.11	12.97	12.85	-6.00	8.32	9.16	6.41	47.7
11~15	230	17.85	-2.76	-3.03	-3.53	-6.31	-4.41	2.14	25.62
16~20	115	8.52	-2.23	-2.19	-2.73	-5.31	-4.36	-0.81	13.97
21~25	95	2.36	-0.34	-0.27	-0.66	-1.45	-1.54	-0.17	2.48
26~30	60	-3.42	-0.51	-0.73	-0.06	1.14	0.66	-0.40	-6.97
31~35	30	-11.34	-3.13	-4.20	-3.53	2.13	3.75	-2.37	-18.06
36~40	10	-15.12	-3.27	-5.62	-3.73	5.91	7.28	-3.14	-24.46

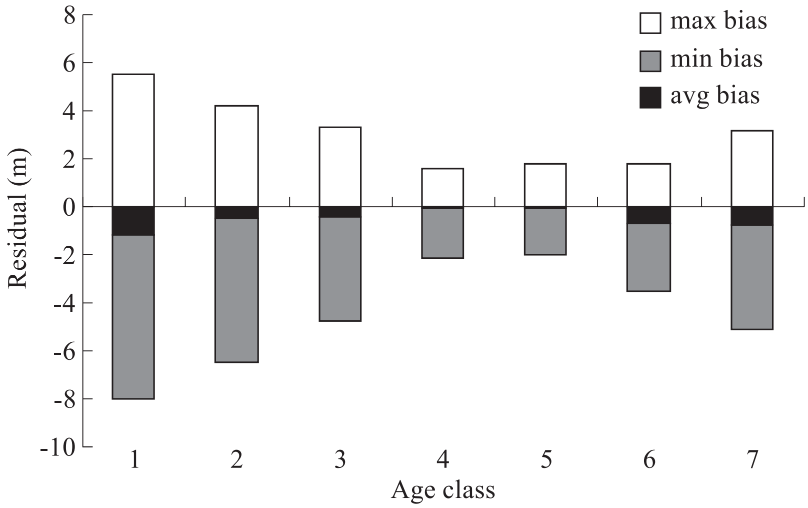

Fig. 2. Residual plots of the site index estimated by equation 4b when site indices were estimated based on the initial height at different predictor age classes. Among them age class 1 represents ages of < 11 yr; 2: 11~15 yr; 3: 16~20 yr; 4: 21~25 yr; 5: 26~30 yr; 6: 31~35 yr; and 7: 36~40 yr.

Table 9. Standard error of the estimate of the site index (m) at different ages for all models for the validation data

Age (yr)	Sample size	Model equation							
		1b	2b	3b	4b	5b	6b	7b	8
< 11	230	9.12	7.16	7.16	2.37	2.76	2.61	4.53	13.93
11~15	230	4.21	2.64	2.65	1.95	2.38	2.05	2.27	6.57
16~20	115	2.19	1.50	1.50	1.36	1.65	1.51	1.35	3.20
21~25	95	0.72	0.47	0.47	0.50	0.56	0.67	0.45	0.92
26~30	60	0.94	0.46	0.49	0.66	0.48	0.92	0.47	1.64
31~35	30	2.52	1.10	1.25	1.56	1.05	1.02	1.05	4.36
36~40	10	3.35	1.34	1.65	2.38	1.70	1.68	1.23	5.92

first estimated by measuring the average dominant and codominant tree heights (i.e., stand height), and the resulting height and age were plugged into an appropriate site index model to obtain the site index value. After getting the site index, the next step was to forecast the stand height growth over time; therefore, the choice of stand height growth models has to be addressed.

Given a site index value, the appropriateness of dominant tree height growth equations among all models was also evaluated in this study. It can be shown for all models, regardless of the site index, that the tree height growth curves starting from quite young ages converged toward each other to a point at the base age and then diverged afterwards; however, all of them except for model 3 showed an extended S shape. In this study the site quality was classified into four classes. They are poor sites with an index value of < 12, medium sites with an index value of 12~16, good sites with an index value of 16~22, and very good sites with an index value of > 22. The comparison of models was slightly different among alternative site qualities. For example, on poor sites, Eq. 5 (Yang) showed a rapid approach towards the asymptotic height (Fig. 3A). However, on good quality sites, the growth reflected by Eq. 5 was more aggressive such that it did not reach the asymptotic height until age 50 (Fig. 3C).

Model 3a (Liu) showed a decrease in height over time after reaching the highest point regardless of the site index values (Fig. 3). There was little difference among the others except for a big increment in Eq. 8 (Devan) for trees 4 yr old (Fig. 3C). For models 1a, 2a, and 3a, the resulting site index curves were an anamorphic form which is not capable of expressing polymorphic patterns of tree height growth with different site qualities. Based on the MSE criterion in Table 5, Eq. 4a was chosen for the preferred stand dominant height growth model. The superiority of Eq. 4a was more evident for good and very good site qualities (Fig. 3C, 3D).

Site-index estimates may be refined by including factors other than height and age. One such variable that is potentially important in refining estimates of site indices is habitat type. Habitat type is a basic unit in a land classification system based on the potential climax vegetation of a site (Alexander 1985), and it integrates environmental factors, such as temperature, moisture, and nutrients, that are important for plant growth (Daubenmire 1976, Stansfield et al. 1991, Nigh 1998).

Owing to the strong relationship of age to tree height revealed in pure even-aged

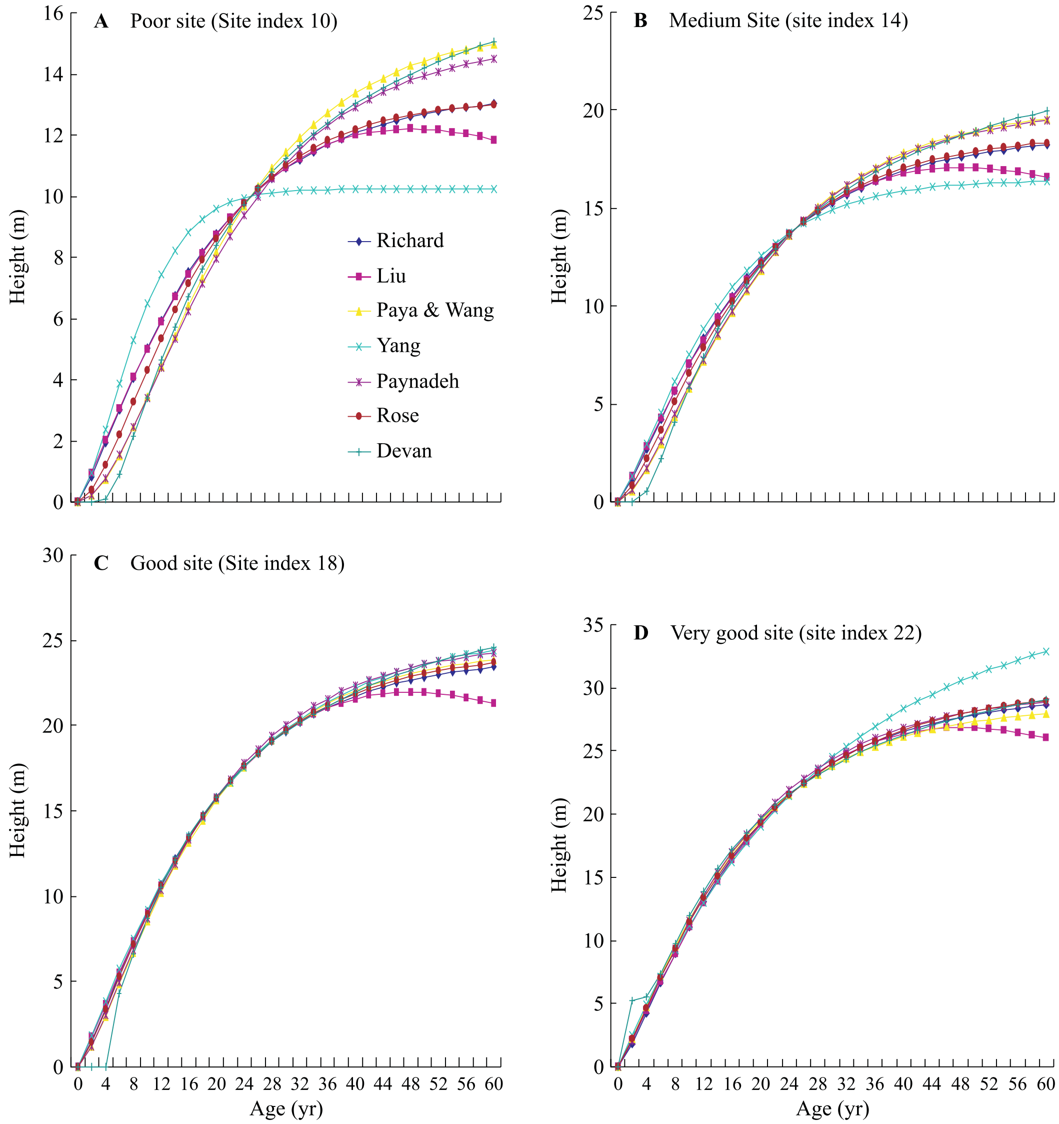

Fig. 3. Comparison of dominant height growth models on A: a poor site (site index 10); B: a medium site (site index 14); C: a good site (site index 18); and D: a very good site (site index 22). The legend is the same for all sites.

plantations, the site index is a convenient step toward the ultimate goal of predicting the production capability of forestlands in plantations (Carmean 1975). As the height at a particular age for a shade-tolerant species in uneven-aged stands often has little biological significance, a site index using diameter instead of age might be used to assess the site quality in the uneven-aged stands (Stout and Shumway 1982, Huang and Titus 1993, Wang et al. 2001).

CONCLUSIONS

Intensive management of Taiwania requires the ability to estimate site quality and the potential growth and yields that can be attained for fully stocked stands with different levels of site quality. Site quality is an important predictor of timber growth; therefore, an effective characterization of site quality is quite relevant to forest management. As future timber inventories and growth algorithms are developed for this resource, improved estimates of site quality are needed for efficient stratification and yield projections.

Armed with site quality and yield information, intensive management of Taiwania plantations can concentrate on the most productive forestlands that are capable of quickly producing large yields of valuable forest products.

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