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Original Research Paper

Study on Modelling of Site Quality Evaluation and Its Dynamic Update Technology for Plantation Forests

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ABSTRACT

Differential site index models were constructed using both the algebraic difference approach (ADA) and the generalized algebraic difference approach (GADA) in this study to evaluate the site quality of forest land without the site index table. Data related to China fir (*Cunninghamia lanceolata* (Lamb.) Hook.) were selected to fit the differential site index models and then the optimal model was chosen. The optimal model was determined using an accuracy test and residual analysis, and then the dynamic update technique of the optimal model was studied by MATLAB and .NET. The results showed that Richards' differential site index model ($SI = 19.171 \times (H_t/19.171)^{ln(1-exp(-0.067\times20))/ln(1-exp(-0.067\,At))}$) had the best prediction performance. The ADA and GADA could be used to evaluate site quality without the site index table and the differential site index model could provide prompt dynamic updates.

INTRODUCTION

Plantation forest management plays an important role in maintaining balance in terrestrial ecosystem and developing forest economy. Humans expect to be able to improve tree growth and increase the efficiency of resource management in plantation forests. Therefore, for working forests, land managers must have a clear understanding of the level of site quality or stand productivity to assist them in improving tree growth and increasing the efficiency of resource management. The evaluation of site quality involves both non-forest land and forest land (Wu et al. 2007). With an analysis based primarily on the concepts of suitable trees and suitable sites, different silvicultural species and cultivation models were used to analyse various site conditions on non-forest land. The evaluation of forest land is an important issue that includes the determination of the level of productivity of certain species. This provides a basis for determining how to best manage forest stands. When evaluating forest land, the assessment of site quality should probably include the determination of site class and site index.

The models of site evaluation are core and key to evaluating site quality. Scholars from around the world have developed various models. Some scholars have documented how tree growth was affected by environmental (Houghton 1994) and climatic factors (Bailey et al. 1978, Monserud et al. 2006) such as altitude, phosphorus content of soil (Corona et al. 2005) and other soil nutrients, and soil moisture (Seynave et al. 2005). Since tree growth is sensitive to the productivity of the forest lands, stand height is the best indicator of site quality based on the findings of other scholars (Meng 1996). Therefore, environmental factors have not been listed as indicators. The stand age-height was selected as the variable in the evaluation model. Three construction techniques, the guide curve method (Garcia Abejon & Tella Ferreiro 1986), the parameter prediction method (Barrio Anta & Dieguez-Aranda 2005) and the algebraic difference approach (ADA), were used for modelling the growth of the dominant trees. The guide curve method directly uses the prototype of the theoretical growth equation to model tree height during different periods by proportional control (Von Gadow & Hui 2001) and the static model was fitted and obtained by this method. All or parts of the parameters for the theoretical equation are expressed as the site index function in the parameter prediction method. It is difficult to directly estimate the site index by clearly defined formulas (McDill & Amateis 1992).

The ADA is used for evaluating site quality (Bailey & Clutter 1974) and has played an essential role in the simulation technique used to determine the site index. The ADA takes advantage of the characteristic that the equation parameters do not change with every point-in-time. Through given variables of the initial stand, one of the three parameters is restrained and three parameters are compressed into two parameters (Elfving & Kiviste 1997). The dynamic equation is derived by the ADA, and it has been applied successfully in various models based on these characteristics. The ADA has been used to predict the height of dominant trees in a slash pine plantation (Lappi & Bailey 1988). Using statistical analysis, the results showed that the prediction errors are in the range of the standard error. Thus, use of the ADA can reliably predict the height of dominant trees (Lappi & Bailey 1988). Cao et al. (1997) forecasted the dominant tree height for direct-seeded loblolly and longleaf pine stands in Louisiana, USA, using ADA and found that the short-term prediction outcome was quite satisfactory. The generalized algebraic difference approach (GADA) has been proposed as a method that can be used to obtain a polymorphic variable asymptote equation (Cieszewski & Bailey 2000). Subsequently, the GADA was used for predicting the dominant height of trees based on 285 managed and thinned permanent plots of natural longleaf pine (*Pinus palustris* Mill.) in the East Gulf Coast region of the United States (Lauer & Kush 2010). The basal area growth system for single-species, even-aged maritime pine (*Pinus pinaster* Ait.) stands in Galicia, Spain, was developed from 212 plots. The results showed that the data were best described by a dynamic equation from Korf growth function using the GADA (Anta et al. 2006). The GADA was used for exploring a dynamic site-dependent height-age model for maritime pine (Nunes et al. 2011).

In this study, without the site index table, the site evaluation model was established using ADA and GADA to evaluate site quality of a plantation forest. Then, model dynamic update technology was studied. The construction evaluation model was updated promptly as new data accumulated. More accurate decision support was provided for evaluating site quality in forest resources management and decision making.

MATERIALS AND METHODS

Data Collection and Processing

In this study, plot data were collected from the forest management inventory of Fujian Province. The canopy density of stands was > 0.5. The survey factor data were selected to comply with the following basic principles: The data from China's fir forests covered different afforestation times and sites with various site conditions across all of Fujian Province; the stand management techniques were consistent across the study area; the stands had experienced relatively little human disturbance, and little more than thinning of the canopy. Threefold standard deviation was used to eliminate aberrant data, and then data from 5,070 sample plots of China fir were chosen for use in fitting the model by random sampling (the annual year data were uniformly distributed as much as possible). Twenty percent of all data, or data from 1,268 randomly selected plots, were chosen as a validation data set to test the model.

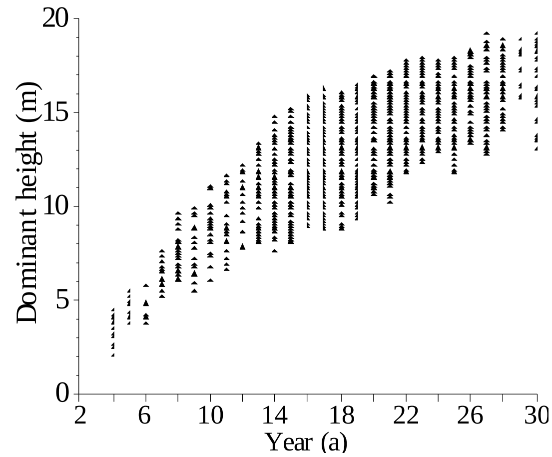

Fig. 1: Correlation between stand age and dominant tree height.

The primary survey factors were compartment, subplot, stand age, dominant tree species, tree species composition, average stand height, forest management techniques previously used and afforestation time from 1976 to 2006. The environmental variables were landform, elevation, slope, slope direction, slope position, soil type and humus thickness.

The height of the dominant trees was selected during the construction of the site index model. Since dominant tree height data had not been recorded during the forest resources inventory of Fujian Province, the height of the dominant trees was calculated using the formula $H_{dominant} = 0.233 + (0.828 \times H_{average})$ (Li & Lin 1979). To test the applicability of the average tree height for the dominant trees, a correlation coefficient was calculated to measure the relationship between dominate tree height and stand age. This correlation coefficient met the statistical requirements (Fig. 1, correlation coefficient = 0.83). Thus, the average tree height for the dominant trees was calculated by the above formula and the corresponding age was used to fit and validate the site quality model.

Site Index Model

Algebraic difference approach: The difference equation was derived as follows: (i) a theoretical growth equation was chosen as the fundamental (basic) equation; (ii) a parameter of the equation was set, which was related to an unobservable site variable; (iii) the initial value was measured and then substituted into the fundamental equation to obtain an original equation; and (iv) free parameter values were solved from the original equation and then were substituted into the fundamental equation. A difference equation was obtained using the derivation method. When the difference equation method was used for deriving the differential site index model, the differential site index model of Richards was derived by GADA; other differential site index models were derived by ADA (Table 1).

For example, when the initial tree measurement data were (A_1, H_1) and re-measurement data were (A_2, H_2), the difference equation was deduced with the logarithmic curve as follows:

The point of the initial measurement data in the curve was:

$H_1 = a \lg A_1 - b$; that is, $b = a\ lg\ A_1 - H_1$ ...(1)

The point of the re-measurement data in the curve was:

$H_2 = a \lg A_2 - b$; that is, $b = a\ lg\ A_2 - H_2$ ...(2)

H_2 has been calculated using eq. (1), (2) and b, which is the free parameter calculated as follows:

$H_2 = H_1 - a\ (lg\ A_1 - lg\ A_2)$ ...(3)

When $H_2 = SI$, $H_1 = H_t$, $A_2 = T$, and $A_1 = A_t$, then eq. (4) was calculated using eq. (3) as follows:

$SI = H_t - a\ (lg\ A_t - lg\ T)$ ...(4)

where SI is the site index, T is the standard age, A_t is the age determined for dominant trees, and H_t is average height of dominant trees when age is A_t; a, b and c are parameters.

Determination of the standard age: After the maximum average increment of tree height was calculated, the standard age was determined. The standard age should be taken as an integer multiple of 10 or 5 instead of the age of some null array. The standard age of China fir was 20 years, which was calculated using existing data in this study and was the same as that reported for China fir by the Ministry of Forestry in 1990 (Ministry of Forestry 1990).

Fitting and evaluation for the site index model: The statistical indicators were calculated to determine whether the corresponding model met the accuracy requirements. In this study, the following statistical tests were carried out to compare the fitting effect on the accuracy of the site index model for China fir: determination coefficient (R^2, eq. (5)) and residual sum of squares (RSS, eq. (6)), and then the testing statistics used were root mean squared error (RMSE, eq. (7)), mean absolute error (MAE, eq. (8)), F test, Chi-square test (eq. (9)) and residual analysis.

$$R^2 = 1 - \frac{\sum_{i=1}^{m}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{m}(y_i - \overline{y}_i)^2} \quad ...(5)$$

$$RSS = \sum_{i=1}^{m}(y_i - \hat{y}_i)^2 \quad ...(6)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad ...(7)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - \hat{y}_i\right| \quad ...(8)$$

$$c^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i - \overline{y}_i)^2}{s_0^2} \quad ...(9)$$

Where y_i represents the observed value of the tree height for the i^{th} dominant trees; $\hat{y}_i$ is the true predicted value of i^{th} observed value by the fitted equation, which was fitted with remaining observations without the use of the i^{th} observation; m is the number of trees for fitting the model; n is the number of trees for testing the model, $\overline{y}_i$ is the mean value for the observed tree height; and s_0^2 is the standard deviation for the observed tree height.

The F test method was as follows: The ages were plugged into the differential site index models (Table 1). A simple linear regression equation (eq.10) was set up. The accuracy of this equation can be analysed by the Sig and b values; that is, when $Sig < 0.05$ and b is close to 1, the model fitting effect was nearly perfect.

$$y_i = a + b\,\hat{y}_i \,. \quad ...(10)$$

The Chi-square test was listed as follows: c^2 was calculated by eq. (9) and then the criterion could be determined by the P value; that is, when $P > 0.05$, the model had a good applicability; otherwise, when $P < 0.05$, the model did not have good applicability.

$$P(c^2 < c^2_{1-a/2}) = P(c^2 > c^2_{1-a/2}) = a / 2 \quad ...(11)$$

The residual analysis is listed as follows: When the standardized residuals of the observation value are lower than –2 or higher than +2, they would be identified as outliers. The residual was allowed to range from –2 to +2 (Feng 2004). The residual analysis was accomplished by residual plot. The sample point (age, $y_i - \hat{y}_i$) was depicted in the right angle coordinate system, where the horizontal axis was reflected by age (or diameter class) and longitudinal axis by $y_i - \hat{y}_i$.

Dynamic Update Design of the Model

Implementation methods of dynamic update of the model: The fitting accuracy of the established site index evaluation model relied on the accuracy and amount of the field measurement data that were used to fit the model. The site index evaluation models were stored in the model library

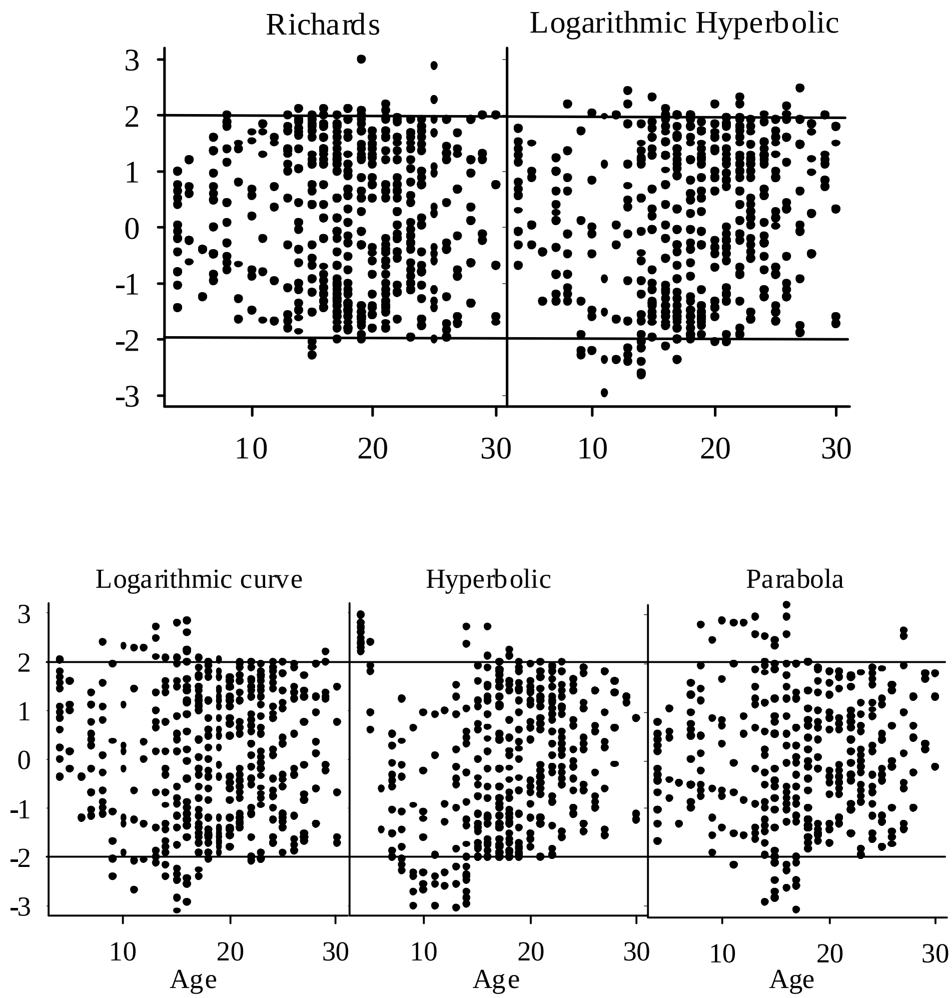

Fig. 2: Residual of the five differential site index models.

and used newly collected field measurement data to promptly update the model. Through invoking the program related to model fitting, when the data used to fit the model were modified, the model was automatically refitted and the model parameters were modified in the model library. That is, dynamic update model technology was implemented.

During the process, the data from the update implementation method containing the age and dominant tree height of a particular species were read from the fitting data table, and then the MATLAB control was invoked to fit the fundamental evaluation models from the evaluation model alternative table. The parameter and determination coefficient of every model were obtained. The model with the maximum determination coefficient was chosen. The differential site index evaluation model was updated. The model and model parameters were stored in the evaluation model table to replace the original site quality evaluation model of the corresponding tree species.

Database design: Tables for standard age, fitting data, the evaluation model alternative and the evaluation model were designed in the database. The standard age table contained the tree species and standard age data. The fitting data table contained the age and the average height of the dominant trees; these data were used to fit the model. The optional table for the evaluation model contained the number, foundation model, model parameter, and determination coefficient. The evaluation model tabled contained the number of the site index evaluation model, tree species and differential site index model. In all the tables, the relationship structure is displayed as follows:

The standard age table (tree species and standard age), primary key: tree species.

Table 1: Differential site index models (*SI*) of China fir.

Model name	Fundamental equation	Differential site index model
Richards	$H=a(1-exp(-bA))^c$	$SI=19.171\times(H_t/19.171)^{ln(1-exp(-0.067\times20))/ln(1-exp(-0.067At))}$
Logarithmic hyperbolic	$lg(H)=a-b/A$	$SI=H_t\times10^{-3.392\,(1/20ÿ1/At)}$
Logarithmic curve	$H=algA-b$	$SI=H_t-15.691\,(lgA_t-lg20)$
Hyperbolic	$H=a-b/A$	$SI=H_t+68.939\,(1/A_t-1/20)$
Parabola	$H=a+bA-cA^2$	$SI=H_t-0.934(A_t-20)+0.014(A_t^2-20^2)$

Table 2: Fitting and error test for five differential site index models.

Differential site index model	Fitting		Error test	
	R^2	*RSS*	*RMSE*	*MAE*
$SI=19.171\times(H_t/19.171)^{ln(1-exp(-0.067\times20))/ln(1-exp(-0.067At))}$	0.806	3418.87	1.122	1.125
$SI=H_t\times10^{-3.392\,(1/20ÿ1/At)}$	0.730	3499.47	1.757	1.450
$SI=H_t-15.691\,(lgA_t-lg20)$	0.727	3616.54	1.728	1.437
$SI=H_t+68.939\,(1/A_t-1/20)$	0.650	6497.15	1.949	1.613
$SI=H_t-0.934(A_t-20)+0.014(A_t^2-20^2)$	0.729	4507.15	1.924	1.421

Table 3: *F*-test and Chi-square test for five differential site index models.

Differential site index model	*F* test				Chi-square test
	a	*b*	*F*	*Sig*	*P*
$SI=19.171\times(H_t/19.171)^{ln(1-exp(-0.067\times20))/ln(1-exp(-0.067At))}$	0.185	0.978	2938.396	0.0001	0.464
$SI=H_t\times10^{-3.392\,(1/20ÿ1/At)}$	-0.726	1.062	2804.048	0.0001	0.795
$SI=H_t-15.691\,(lgA_t-lg20)$	3.256	0.749	2919.822	0.0001	0.471
$SI=H_t+68.939\,(1/A_t-1/20)$	0.115	0.982	2064.153	0.0001	0.469
$SI=H_t-0.934(A_t-20)+0.014(A_t^2-20^2)$	-0.012	1.005	2001.005	0.0001	0.671

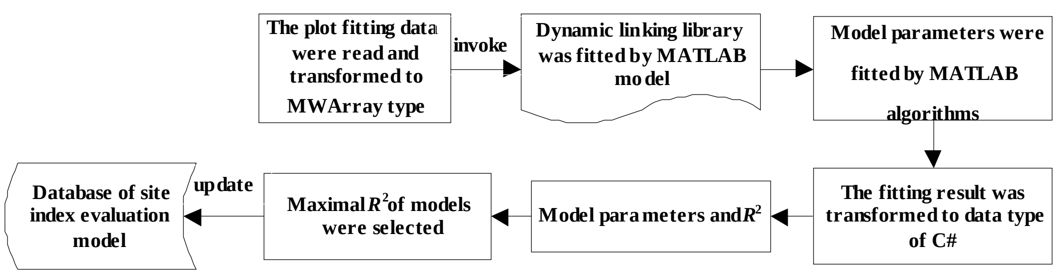

Fig. 3: Implementation method of the model automatic update.

The fitting data table (tree species, age and average height of dominant trees), primary key: {tree species, age}.

The evaluation model alternative table (number, fundamental model, parameter 1, parameter 2, parameter 3 and R^2), primary key: number.

The evaluation model table (number, tree species and differential site index model), primary key: {number, tree species}.

RESULTS

The Site Quality Evaluation Model of China Fir

The parameters were first assigned an initial value to determine parameter values in fitting the non-linear models. The parameters from five fundamental models were solved and the different site index models were obtained based on the ADA and GADA (Table 1). The results showed that the most suitable fitting model for China fir was the Richards' differential site index model, where the R^2 is maximum and RSS is minimum (Table 2).

RMSE and MAE were smallest for the error test of differential site index model for Richards in five models (Table 2). The Chi-square test showed that $P > 0.05$ for the five models; therefore, all of these models passed the test (Table 3). The results of the F test for five models showed $Sig < 0.0001$, so it was concluded that the five models had a good fitting effect. The b ($b = 0.978$) is much closer to 1 for the differential site index model of Richards (Table 3).

The most of residuals fell between –2 and +2 for the five differential site index models. However, the residual distribution of Richards is the highest concentrations (Fig. 2), which showed that the differential site index model of Richards was optimal and met the statistical requirements.

Finally, $SI = 19.171 \times (H_t/19.171)^{ln(1-exp(-0.067\times 20))/ln(1-exp(-0.067\,At))}$ was selected as the optimal site quality evaluation model for China fir in five models by the ADA and GADA in the study area.

Implementation of the Algorithms

The computer program which automatically updated the site index evaluation model used .NET and the MATLAB algorithms (Phan 2004). The specific implementing method as follows:

1. The .m file, which was created in MATLAB, was used for fitting and calculating the model, and then the codes of the fitting model were written using MATLAB's M language in this file.
2. The .NET component was generated using the MATLAB DeployTool and then was added and referenced to Webform in Visual Studio software; i.e., the required dynamic linking library was fitted by the MATLAB model and was referenced to realize automatic updating of the site index evaluation model library in .NET.
3. The fitting data in the sample plot database were read by C# code and then the age and height of the dominant tree for a particular species were read by Sql statements. Later, the data were saved using Sql DataAdapter and then the age (a) and dominant height (h) variables were assigned. The data type of variables a and h were converted into the data type needed for MATLAB.
4. The required dynamic linking library and the data that were converted into the data which the variables a and h were converted into were fitted by invoking the MATLAB model.
5. The data of fitting results were transformed into C# language data types to update the parameters and R^2 of the equations that had been derived from the evaluation model alternative table. The site index evaluation model of the maximum determination coefficient was chosen and then stored in the model evaluation table to replace the original site index evaluation model for the corresponding tree species. At this point, the dynamic update for the model was complete.

DISCUSSION AND CONCLUSION

A good mathematical model should have excellent prediction performance and provide the best fitting results and smallest fitting residual, with few parameters and a biological explanation to ensure that it reflects the regulation of trees growth in height. The model should also have the advantage of a relatively simple mathematical form, be easy to apply and easy to popularize once it is produced. Based on the goodness-of-fit statistics, Richards' functions showed better fitting results than other functions for China fir. The Richards' model itself is based on multiple biologically significant parameters, so it has shown excellent agreement with measured forest growth when applied to a plantation forest (Buda & Wang 2006). These results are consistent with those previously reported (Hui et al. 2010, Luo & Jiang 1990) for China fir. In summary, the Richards' differential site index model ($SI = 19.171 \times (H_t/19.171)^{ln(1-exp(-0.067\times 20))/ln(1-exp(-0.067\,At))}$) has the best prediction performance in this study. Therefore, the GADA is more suitable as the polymorphic site index model and is also fits for the site index evaluation of other tree species on condition that there is no site index table.

A considerable amount of data was needed to construct the model used in this study. However, few data were available for fitting the model in practice. When determining the number of samples used in the modelling, the design of the sampling plan was carried out to meet the desired model accuracy and save time and funds spent on sample selection. In the design of the sampling plan, determining the number of the sample units was a primary problem because the sampling accuracy was directly affected by the number of sample units. The design of the simple random sampling units should mainly consider the following factors: The overall variation in the sample population, survey accuracy requirements (the error range allowed) and the precision of the sampling techniques. The formula of sample n for simple random sampling is as follows:

$$C = y_{max} - y_{min} / 6\bar{y} \quad ...(12)$$

$$n = (u_a C/E)^2 \quad ...(13)$$

where C is overall variation coefficient, y_{max} is the maximal value in the overall unit, y_{min} is the minimal value in the overall unit, $\bar{y}$ is the mean value in the overall unit, t is the reliability index, general reliability is 95% (i.e. $u_a = 1.96$; E is relative error limit), and estimation accuracy is generally not less than 95% ($E = 0.05$) (Zhang 2006).

The precision of the average height for the dominant trees was important for the accuracy of the model, so we studied the dynamic update technology to ensure that the model parameters were promptly updated in this study. Dynamic updating technology is significant because it could rapid and accurate fitting and correcting of parameters. Additionally, the error test of models should be considered in dynamically updated technology to get high precise model; more and more models will be added to the model library to replenish and perfect the models that are stored in the model library for use in future research.

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