SITE INDEX CURVES FOR SITE QUALITY ASSESSMENT OF *NAUCLEA DIDERRICHII* MONOCULTURE PLANTATIONS IN OMO FOREST RESERVE, NIGERIA

J. C. Onyekwelu

Department of Forestry and Wood Technology, Federal University of Technology, P. M. B. 704, Akure, Nigeria. E-mail: onyekwelujc@yahoo.co.uk

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ONYEKWELU, J. C. 2005. Site index curves for site quality assessment of *Nauclea diderrichii* monoculture plantations in Omo Forest Reserve, Nigeria. Timber production potential of a site is measured by site index, which is defined as the dominant height of a stand at a base age. A site index equation for site quality determination in *Nauclea diderrichii* (Opepe) stands in Omo Forest Reserve, Nigeria was developed using a base age of 30 years. Dominant height data were collected from 30 temporary sample plots of 25 × 25 m in plantations of five to 30 years. Linear and non-linear models widely used in site index studies in forestry were fitted to dominant height-age data. Adjusted coefficient of determination (R^2_{Adj}), root mean square error (RMSE) and residual plots were used in choosing the 'best model'. The best model was $H_d = 36.29\ (1 - \exp(-0.027\ Age))^{0.542}$. The proportional or guide curve method was adopted in constructing the sites curves, with the chosen model as the average guide curve. Based on this curve, the plantation was divided into five site quality classes, A to E, with class A representing the best site while class E, the poorest. Result showed that a 30-year-old Opepe plantation in the study area attained average dominant height of about 30, 26 and 22 m on site quality classes A, C and E respectively. The site index curve was used as a guide to recommend the time of first and subsequent thinning operations in Opepe plantations as well as suitable sites for future plantations.

Key words: Site quality – timber production – *N. diderrichii* – Opepe – index age – guide curve method

ONYEKWELU, J. C. 2005. Lengkung indeks tapak untuk menilai kualiti tapak ladang monokultur *Nauclea diderrichii* di Hutan Simpan Omo, Nigeria. Potensi penghasilan balak bagi sesuatu tapak dikira melalui indeks tapak, iaitu ketinggian dominan dirian pada usia dasar. Persamaan indeks tapak bagi penentuan kualiti tapak dirian *Nauclea diderrichii* (Opepe) di Hutan Simpan Omo, Nigeria dibangunkan menggunakan usia dasar 30 tahun. Data ketinggian dominan dikumpul daripada 30 plot sampel sementara bersaiz 25 m × 25 m di ladang yang berusia antara lima hingga 30 tahun. Model linear dan tak linear yang sering digunakan dalam bidang perhutanan untuk kajian indeks tapak dipadankan kepada data ketinggian dominan dan usia. Pekali penentu tersuai (R^2_{Adj}), ralat punca min kuasa dua (RMSE) dan plot baki diguna untuk menentukan 'model terbaik'. Model terbaik ialah $H_d = 36.29\ (1 - \exp(-0.027\ Age))^{0.542}$. Kaedah berkadar atau kaedah lengkung pandu digunakan untuk membina lengkung tapak dengan mengambil model yang terpilih sebagai lengkung pandu purata. Berdasarkan lengkung ini ladang dibahagikan kepada lima kelas kualiti, iaitu A hingga E. Kelas A mewakili tapak terbaik sementara kelas E yang paling teruk. Keputusan menunjukkan bahawa ladang Opepe berusia 30 tahun di kawasan kajian mencapai ketinggian dominan purata 30 m, 26 m dan 22 m masing-masing bagi kelas kualiti A, C dan E. Lengkung indeks tapak diguna sebagai panduan untuk mengesyorkan masa penjarangan pertama dan yang seterusnya bagi ladang Opepe serta tapak yang sesuai bagi ladang pada masa depan.

Introduction

Site quality assessment is the evaluation of innate productive capacity of an area of forest land for one or more tree species. Site quality assessment is very important in forest management because a site could support one species excellently while supporting another species poorly. The oldest, commonest and most widely used technique for evaluating site quality or productivity of even-aged stands is site index.

Site index is defined as the average total height of dominant and co-dominant trees (i.e. site trees) at a specified reference or base age, which is commonly selected to lie close to the rotation age (Clutter *et al.* 1983). It is little affected by varying densities and species composition, relatively stable under varying thinning intensities and is strongly correlated with volume. The principal uses of site index systems are: (1) to estimate height at any give age from site index, (2) to estimate site index from height at any given age, (3) to stratify forest land into productive classes, (4) to provide entry to yield tables, and (5) as predictive variable in growth and yield models (Wang & Payandeh 1995). However, the most common objective of site index is to determine the height development pattern that the stand is expected to follow throughout rotation (Clutter *et al.* 1983).

Site index equations are essential elements of quantitative tools in forest management (Teshome & Petty 2000). It can be evaluated mathematically or graphically. The mathematical approach is preferred because the graphical method involves an element of subjectivity, coupled with the difficulty in performing statistical tests on the goodness of fit of the curve. Most of the mathematical techniques used to fit site index curves could be viewed as special cases of three general equation development methods, namely, the guide curve, difference equation and parameter prediction methods (Clutter *et al.* 1983). Among the various techniques for developing site index curves, the proportional or guide curve method has become popular in recent times for even-aged single species plantations (Nanang & Nunifum 1999). The predominant use of the guide curve method for even-aged plantations has been attributed to the general lack of remeasured permanent plot data for forest plantation, coupled with the fact that most plantation species in the tropics do not show annual or seasonal growth rings (Clutter *et al.* 1983, Nanang & Nunifum 1999).

Early work on forest plantations in Nigeria started in early 20th century and was dominated by indigenous tree species. Among the indigenous species (e.g. *Terminalia ivorensis, Nauclea diderrichii, Triplochiton scleroxylon, Cedrela odorata, Entandrophragma* sp. and *Mansonia* sp.) that have been successfully raised in plantations in Nigeria, *N. diderrichii* (Opepe) is the most dominant. The aim of establishing Opepe plantations is to provide construction timber and transmission poles. Large-scale establishment of Opepe plantations suffered neglect between early 1970s and 1990 because attention was shifted to the establishment of faster growing exotic species (e.g. *Gmelina arborea* and *Tectona grandis*). Consequently, research in Opepe, including site quality assessment, has not been the subject of much study. However, there has been a renewed interest in establishing Opepe stands in some industrial plantation sites in south-western Nigeria (Onyekwelu 2001). This study was aimed at generating site index curves for site quality assessment of Opepe plantations in Omo Forest Reserve, Nigeria. It is hoped that the site index curves that will result from this study will be used to manage current and future Opepe plantations.

Material and methods

Study area

Site index was estimated for unthinned even-aged Opepe stands in Omo Forest Reserve, Nigeria, situated between latitudes 6° 35' and 7° 05' N and longitudes 4° 05' and 4° 40' E. Two seasons are distinguished, namely, rainy and dry seasons. The dry season begins in December and ends in February while the rainy season spans from March to November. Annual rainfall ranges from 1750 to 2200 mm while mean annual temperature and average daily relative humidity are 26.5 °C and 80% respectively. Average elevation is 123 m above sea level. Soils were formed from crystalline rocks of undifferentiated basement complex of the pre-Cambrian series. They are predominantly ferruginous tropical soils, typical of the variety found in rain forest regions of south-western Nigeria. The soil is comprised of well-drained, mature, red, stony and gravely soils in the upper parts of the sequence. Texture of the topsoil is loamy and sandy and subsoil consists of clay with gravel at 30–60 cm depth.

Data collection

The age classes of the 10 randomly selected plantations spanned from the youngest to the oldest stand, i.e. five to 30 years. Each selected stand (age class) was divided into one-hectare blocks, of which three blocks were randomly selected. A 25 × 25 m temporary sample plot was laid at the centre of each block. Measurements taken on all trees within each plot were diameter at breast height (dbh) and total height. The number of trees was also taken. The total height of the six largest trees per plot served as the dominant trees (this represented the 100 largest trees per ha). Stand age was obtained from plantation records.

Development of site index equations

Site index for Opepe plantations in Nigeria has not been the subject of much study; thus, the first consideration was choosing the appropriate base age. After due consideration of the rotation age and the age of culmination of mean annual increment as recommended by various researchers (e.g. Curtis *et al.* 1974, Trousdell *et al.* 1974, Teshome & Petty 2000), 30 years was adopted as the appropriate base age for the determination of site index of Opepe plantations in this study. Among the various techniques for developing site index equations, the proportional or guide curve method was adopted for this study because the data were obtained from temporary sample plots, thus permitting only the use of this method (Clutter *et al.* 1983, Nanang & Nunifum 1999). Various linear and non-linear equations commonly used for site index studies in forestry were selected from forestry literature (Carmean 1972, Clutter *et al.* 1983, Malende & Temu 1990, Akindele 1991, Onyekwelu & Fuwape 1998, Teshome & Petty 2000, Onyekwelu 2003) and adopted in this study. The linear equations were

$$H_d = a_0 + a_1\,(\text{Age}) + a_2\,(\text{age})^2 + e_i \quad (1)$$

$$H_d = a_3 + a_4\,(\text{Age}) + a_5\,(1/\text{Age}) + e_i \quad (2)$$

$$H_d = a_6 + a_7 \ln(\text{Age}) + e_i \quad (3)$$

and the non-linear equations were

$$H_d = a_8\,(1\text{-exp}\,(-a_9\,\text{Age}))^{a_{10}} + e_i \quad (4)$$

$$H_d = a_{11}\,(\text{exp}\,(-a_{12}\,\text{Age}^{a_{13}})) + e_i \quad (5)$$

where

H_d = total height of dominant trees,

$a_0 - a_{13}$ = regression coefficients

The equations were compared and the most appropriate chosen. There were a number of criteria for selecting the 'best model'. However, since the dependent variables in equations (1) to (5) were similary transformed, the adjusted coefficient of determination (R^2_{Adj}) and the root mean square error (RMSE) were considered appropriate criteria for selecting the best model, in which case the model with the highest R^2_{Adj} and the lowest RMSE was chosen. Visual examination of the residuals was also used in assessing the models. Using the predicted height growth trend described by the chosen model (guide curve), anamorphic site index curves were fitted to pass through five different site index classes of A to E (i.e. the stands were stratified into five site quality classes), with site quality decreasing from site A to E. This was accomplished by holding the shape parameters constant and varying the asymptote parameter as necessary to achieve the required dominant height when plantation age (A) equals base age (A_0), which is 30 years in this study. This approach has been used in previous studies (Clutter *et al.* 1983, Teshome & Petty 2000).

Results

Summaries of the growth characteristics of the 180 site index sample trees (dominant trees) are presented in Table 1. Mean total height ranged from 11.6 m at five years to 26.3 m at 30 years. In all stands sampled, maximum height of dominant trees was 29.2 m. Development of dominant height became even from the age of 24 years.

The parameters and statistics of the linear and non-linear regression models (1 to 5) generated in this study are presented in Table 2. The initial observation was that all the models had very high R^2_{Adj} and low RMSE. All parameters included in models (1) to (5) were significant, indicating that none of the models was overparameterised. The residuals exhibited a normal and random distribution, with no clear systematic trend (Figure 1). A comparison of the three linear models (1 to 3) revealed that they performed similarly, having almost equal R^2_{Adj} and RMSE (Table 2). This was also true of the non-linear models (4) and (5). While model (2) performed best among the linear models, model (4) was best between the non-linear ones. A comparison of models (2) and (4) revealed model (4) to be the best, having the highest R^2_{Adj} and lowest RMSE of 0.9293 and 1.6062 respectively (Table 2). The residuals of models (2) and (4) were similarly distributed (Figure 1). Thus, equation (4) was selected for the construction of the site index curves for Opepe plantations in the study area. The predicted curve from model (4) was within the observed variation of the dominant height-age data (Figure 2). The site index curves showed that a 30-year-old Opepe plantation in the study area attained average dominant height of about 30, 26 and 22 m on site classes A, C and E respectively (Figure 3).

Table 1 Summary statistics for the site index sample trees (dominant trees)

Age (years)	No. of plots	No. of trees per plot	Dbh (cm)			Total height (m)		
			Min	Max.	Mean*	Min	Max.	Mean*
5	3	6	10.2	14.5	12.0 ± 0.31	9.5	12.9	11.6 ± 0.23
6	3	6	14.2	17.8	15.4 ± 0.23	9.7	14.9	12.3 ± 0.34
7	3	6	15.9	21.7	18.2 ± 0.40	13.2	16.9	15.1 ± 0.21
9	3	6	21.5	26.8	23.4 ± 0.37	14.0	19.5	16.2 ± 0.37
15	3	6	24.2	35.6	29.5 ± 0.86	16.2	23.4	19.9 ± 0.48
19	3	6	28.0	38.0	32.8 ± 0.76	18.2	26.6	21.4 ± 0.44
24	3	6	29.4	43.8	35.0 ± 0.83	21.0	28.0	25.0 ± 0.43
26	3	6	30.8	42.4	37.0 ± 0.71	21.0	27.1	25.6 ± 0.38
28	3	6	33.4	47.5	37.7 ± 0.97	23.5	28.5	25.6 ± 0.36
30	3	6	35.5	52.2	41.5 ± 0.98	23.8	29.2	26.3 ± 0.34

* Mean ± standard error

Table 2 Estimated parameters and statistics for models (1) to(5) fitted to temporary plot data for *Nauclea diderrichii* plantations

Equation	Coefficient	Estimated parameter	Adjusted R^2	RMSE
(1)	a_0	7.14	0.9176	1.6242
	a_1	1.07		
	a_2	-0.0145		
(2)	a_3	17.78	0.9209	1.6078
	a_4	0.36		
	a_5	-37.55		
(3)	a_6	-1.92	0.9190	1.6149
	a_7	8.28		
(4)	a_8	36.29	0.9293	1.6062
	a_9	0.027		
	a_{10}	0.542		
(5)	a_{11}	0.016	0.9167	1.6401
	a_{12}	6.02		
	a_{13}	-0.062		

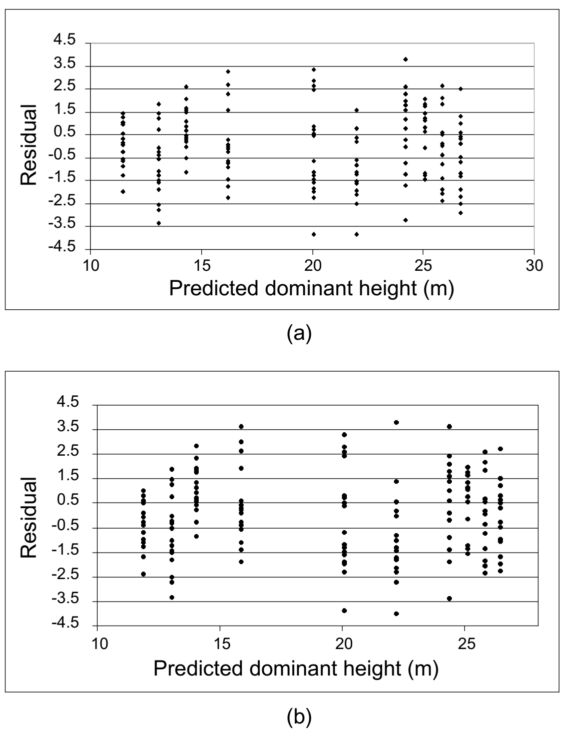

Figure 1 Residual plot for (a) the best linear (equation 2) and (b) non-linear (equation 4) equations

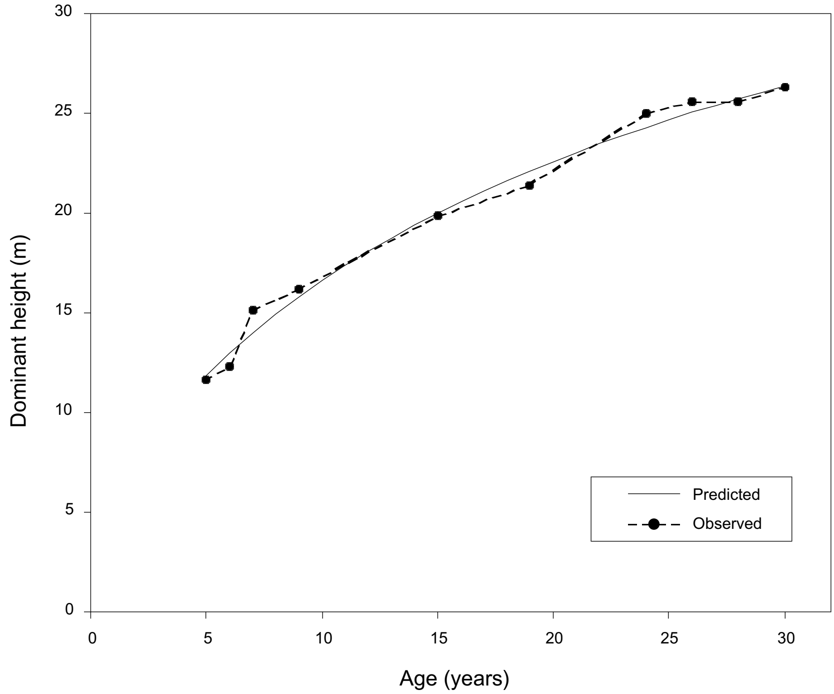

Figure 2 Comparison of observed dominant height-age data and predicted curve from model (4)

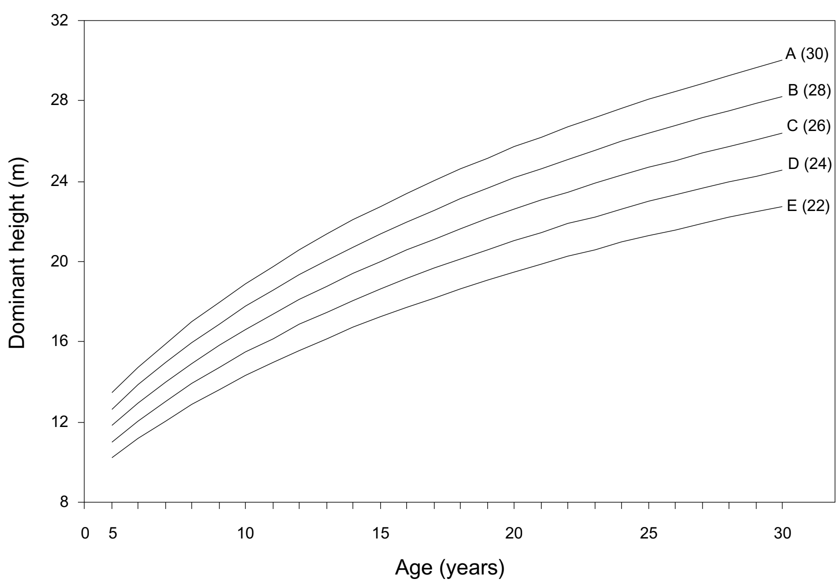

Figure 3 Site index curves for *Nauclea diderrichii* plantations constructed using model (4). A–E are the site classes.

Discussion

The absence of permanent plots and the inability of Opepe to show annual growth rings, necessitated the use of temporary plot data of different ages covering major part of the rotation of the species for this study, as has been the practice. This data limitation permitted only the use of guide curve method in developing the site index equations. It was, therefore, assumed that the distribution of plots with respect to site quality was identical across all ages (Alder 1980). Failure of this assumption would lead to the fitted guide curve being biased away from the true average height growth trend (Walters *et al.* 1989). It is evident from Figure 2 that the assumption was not violated, as the fitted guide curve did not appear to be biased away from the true average height growth trend of the species under investigation. The guide curve method was used to generate anamorphic site index curves. These curves are a family of parallel lines with constant slope but varying intercepts, achieved by holding the shape parameters constant and varying the asymptote parameter to obtain the required dominant height value when stand age (A) equals the index age (A_0), which is 30 years in this study (Clutter *et al.*, 1983, Teshome & Petty 2000). For any two curves in anamorphic curve family, the height of one at any age is a constant proportion of the height of the other at the same age. Unlike the anamorphic curves, polymorphic site index curves, which is another type of site index curve family, do not exhibit proportionality in relationship (Clutter *et al.* 1983). Temporary plot data cannot be used to generate polymorphic curves; only remeasurement or stem analysis data are used.

Non-linear regression models are widely used in site index studies in forestry. The difficulty associated with obtaining solutions to the parameters of non-linear models, which limited its use in site index studies in the past, has been overcome with the advent of electronic computers. There exist a myriad of statistical software with which the parameters of non-linear models can be estimated with ease and within a very short time. Non-linear models, unlike linear ones, provide justification for extrapolation beyond the range of conditions represented by a given set of data (Pienaar & Turnbull 1973). This and coupled with the fact that non-linear models performed better than linear ones, justified the adoption of a non-linear model in developing site index curves for Opepe in this study area.

The base age of 30 years used for the development of site index curves in the present study is appropriate judging from the fact that base age is usually chosen to approximate rotation age (Curtis *et al.* 1974, Onyekwelu & Fuwape 1998, Teshome & Petty 2000). In addition, base age should be selected such that the period of rapid growth is completed, i.e. mean annual increment (MAI) is culminated (Trousdell *et al.* 1974). The rotation age for timber in Opepe plantations is between 30 and 40 years depending on site quality (Dupuy & Mille 1993, FORMECU 1999, Onyekwelu *et al.* 2003). The period of rapid growth in Opepe plantations in the study area was completed between 23 and 30 years (Onyekwelu 2001).

Figure 3 presents the site index curves developed for Opepe plantations in Omo Forest Reserve. Areas of good site quality are also areas where height growth is high (Clutter *et al.* 1983). The best site quality class for Opepe was site class A, while the average and the poorest site quality classes were C and E respectively. This implies that a stand with height development pattern similar to curve A in Figure 3 is growing on a better site and has higher volume production than a stand with height development pattern similar to curve B. This is because good sites produce volume more rapidly compared with poor sites. The site index curves presented in Figure 3 indicated the height development patterns of dominant trees in Opepe plantations. A stand with a mean dominant height of about 15 m at age 10 years is expected to follow the height development pattern exhibited by class D while a stand with a mean dominant height of about 18 m at age of 10 years is expected to follow the height development pattern exhibited by class B. However, there could be a shift in site index such that the development pattern exhibited by a dominant tree at younger age is not followed throughout rotation. This shift could be occasioned by climatic fluctuation, measurement error, damage to dominant height by diseases and fire as well as removal of dominant trees through thinning (Teshome & Petty 2000). Whether the site index curves generated in this study would be followed throughout rotation can be validated with data from permanent plots. This entails establishing permanent sample plots in the study area, from which data would be collected over a period of time, and used to validate the site index curve. To serve as a good validation tool, the data collected from the permanent plots must fall within the age range of the data used in this study (five to 30 years). Alternatively, some selected sample plots could be measured for dominant height over a period of time and the data can then be used to validate whether dominant height develops as indicated by the site index curve.

Large-scale plantations of Opepe are being planned in the study area as evidenced by the renewed interest in establishing its plantations. Opepe accounted for about 40% of the 462 ha indigenous species (e.g. *N. diderrichii, T. ivorensis, C. odorata, T. scleroxylon* and *Mansonia* sp.) trial plots established by the African Development Bank (ADB) Forestry IIB project (1989 to 1996) in Omo Forest Reserve (Onyekwelu 2001). It is expected that the results of these trials will pave the way for large-scale plantations of the species. Consequently, a good knowledge of its growth and yield is necessary for the formulation of sound forest management plans, especially silvicultural decision-making processes such as time of first and subsequent thinnings. The site index curve developed in this study will be useful in identifying suitable sites for large-scale establishment of Opepe plantations and to quantify its growth and yield on various site conditions. The results of this study revealed that the best sites for future Opepe plantations in Omo Forest Reserve were site classes A, B and C due to their above average and average dominant height development (Figure 3). As much as possible, site classes D and E should be not be used for Opepe plantation establishment since height development of the species within these sites was poor.

The site index curve will also serve as guide in making thinning decisions for the plantations of the species. Among the various methods used to determine the time of first and subsequent thinnings, the dominant height approach is preferred because it reflects site effect more than the other methods (e.g. age, basal area and volume methods). Consequently, some researchers have adopted the dominant height approach to determine the time of first and subsequent thinnings for various tree species. For example, in a *Cupressus lusitanica* plantation in Ethiopia, the first thinning was recommended to be carried out at the attainment of dominant height of 11 m for site classes 27, 21 and 12 at ages five, seven and 13 years respectively (Teshome and Petty 2000). Also, the thinning schedules developed for Opepe plantations by Dupuy and Mille (1993) and Onyekwelu (2001) indicated that first, second and third thinnings, should be administered at the attainment of average dominant heights of 13, 17 and 22 m respectively. Applying these dominant height recommendations to various site index classes in the study area indicated that first thinning at the dominant height of 13 m should be conducted at ages five, six and nine years at site index classes A, C and E respectively while second thinning at dominant height of 17 m should be administered at ages eight, 10–11 and 15–16 years at site classes A, C and E respectively.

Conclusions

From the foregoing, it can be concluded that the base age of 30 years is suitable for site index studies of *N. diderrichii* plantations in Omo Forest Reserve. Non-linear models performed better than linear ones and were adopted in generating the site index curves. The curves generated in this study showed the height development pattern that the stands are expected to follow throughout rotation. They can be used to quantify the production potential of various sites as well as to identify suitable sites for large-scale Opepe plantations. Site index curves are also useful for the formulation of sound forest management plans, especially silvicultural decision-making processes such as time of first and subsequent thinning operations of current and future stands. The site index model constructed is expected to give satisfactory estimates for the production potential of various sites planted with Opepe. However, before applying the model beyond the study area, the model must be validated with data from permanent sample plots.

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