BASAL AREA GROWTH OF EVEN-AGED *AZADIRACHTA INDICA* STANDS IN GUJARAT STATE, INDIA

V. P. Tewari

Arid Forest Research Institute, P. O. Krishi Mandi, New Pali Road, Jodhpur 342005, India
E-mail: vptewari@yahoo.com

&

K. von Gadow

Institut für Waldinventur und Waldwachstum, Büsgenweg 5, D-370077 Göttingen, Germany

Received August 2003

TEWARI, V. P. & VON GADOW, K. 2005. Basal area growth of even-aged *Azadirachta indica* stands in Gujarat State, India. *Azadirachta indica* (neem) is one of the most important multipurpose tree species for not only the rural but also the urban people of India. The tree is found in tropical dry areas up to an altitude of 1200 m and it can thrive on a wide variety of soil and climatic conditions. Almost all parts of the tree have one or more uses. Based on a comprehensive data set, this paper compares seven different stand level models for predicting basal area growth of even-aged stands of neem, located in Gujarat State, India. The models tested in this paper belong to the path invariant algebraic difference form of a non-linear model. The models can be used to predict basal area growth as a function of stand variables such as initial basal area, age or dominant height and stem number ha^{-1} and are crucial for evaluating different silvicultural treatment options. The performance of the models for basal area was evaluated using different quantitative criteria. The Schumacher and Souter models showed the best performance. A worked example of the effect of low and high thinning on basal area development is also given as appendix.

Key words: Neem – stand variables – basal area model – path invariant difference form equations – thinning

TEWARI, V. P. & VON GADOW, K. 2005. Pertumbuhan luas pangkal dirian sebaya *Azadiracta indica* di Gujarat, India. *Azadirachta indica* (neem) merupakan satu daripada spesies pokok serba guna yang paling penting bagi penduduk bandar dan luar bandar India. Pokok ini tumbuh di kawasan tropika yang kering sehingga altitud 1200 m dan dapat hidup dalam pelbagai keadaan tanih serta iklim. Hampir seluruh bahagian pokok mempunyai satu kegunaan atau lebih. Berdasarkan set data yang komprehensif, kertas kerja ini membandingkan tujuh model aras dirian yang berbeza untuk meramal pertumbuhan luas pangkal dirian neem sebaya yang terletak di Gujarat, India. Model-model yang diuji dalam kertas kerja ini tergolong dalam bentuk bezaan algebra tak berubah laluan bagi model tak linear. Model-model ini dapat diguna untuk meramal pertumbuhan luas pangkal sebagai fungsi pemboleh ubah dirian, umpamanya luas pangkal awal, usia atau ketinggian dominan dan bilangan batang sehektar. Model-model ini juga adalah penting untuk menilai pilihan rawatan silvikultur yang berbeza. Prestasi model untuk luas pangkal dinilai menggunakan kriteria kuantitatif yang berbeza. Model Schumacher dan model Souter menunjukkan prestasi terbaik. Contoh terkerja bagi kesan penjarangan rendah dan tinggi terhadap perkembangan luas pangkal turut diberi dalam lampiran.

Introduction

Neem (*Azadirachta indica*) is one of the most useful and important multipurpose tree species for the rural and urban people of India. The tree is found in tropical dry areas up to an altitude of 1200 m and it can thrive on a wide variety of soil and climatic conditions. Almost all parts of the tree have one or more uses (Kishan & Tewari 1999). The wood is valued for household furniture, carts, yokes, boards and panels and agricultural implements. Small branches and twigs provide fuelwood. Small twigs are also used as toothbrushes. The leaves are valued as fodder for cattle and goats and are also used for making compost. Neem leaves have several important medicinal properties and are used as insect repellent and in the control of nematodes. The pulp of the ripe fruit is used as tonic, purgative, emollient and anthelmintic. Azadirachtin, saponin and nimbin are some of the major active components isolated from neem. The seed kernel is used as an insecticide and has been found to be an effective repellent against a great variety of insects. The kernel also yields oil, commercially known as *margosa* oil, which is used to produce soap and toothpaste. The bark of the tree is used for various medicinal purposes, primarily as an anti-protozoal, anti-allergic, anti-dermatitic and anti-fungal. Anti-spermicidal properties have also been identified in neem.

Neem is mainly found as an avenue tree, solitary shade tree or in small patches forming shelter around homesteads. Information about its growth is very scarce. Dominant height growth, volume yield and site index equations have been developed by Tewari and Kishan (2002), but no information is yet available on the basal area growth for this species which is crucial for evaluating different silvicultural treatment options.

The stand basal area is an important density measure, which simultaneously takes into account the average tree size and the number of trees per unit area. Basal area is used to analyse the relationship between stand density and tree growth. Moreover, in combination with the number of trees, basal area can be used to define the type and weight of thinning (Staupendahl 1999, von Gadow & Hui 1999). Models of stand basal area growth have been developed using a differential equation or the path invariant algebraic difference form of a non-linear equation. The latter approach, proposed by Clutter *et al.* (1983), is especially effective.

The models presented here have not been developed from data from thinned stands. However, because of the need to predict growth after thinning, a worked example on the effect of low and high thinning on basal area development is also included as an appendix.

Materials and methods

Data

Some village woodlot plantations of neem were raised under a social forestry programme and also as block plantations in Gandhi Nagar and Palanpur Forest Divisions of Gujarat State, India. The social forestry programme was started in India in the 1980s with the financial assistance from the World Bank. Under this programme the Forest Departments of various states in India took up large-scale plantations of different species as woodlot plantations, plantations on marginal and wastelands and along roadsides to cater to the needs of rural people. The average rainfall of the area is 928 mm. The temperature varies between 48 and 25 °C in the summer and between 27 and 12 °C in the winter. The soils of the region are gravelly loams to clayey loams. A total of six sample plots were laid out, five in the Gandhi Nagar and one in Palanpur Forest Divisions, covering a fairly good range of ages and densities. Each plot represented the growing conditions in the stand and contained about 30 to 84 trees. General information about the plots is given in Table 1.

The measurements in the plots started in 1994 and annual re-measurements were continued for five seasons until 1999, except for plot 6, which had four measurements giving a total of 29 observations for the analysis. The plot data included records of age (A), dominant height (H), number of trees ha^{-1} (N), basal area ha^{-1} (BA) and quadratic mean diameter (D_g). The summary statistics of the data sets are given in Table 2.

Figure 1 shows the development of dominant height and basal area over stand age for the six plots. Figure 1(a) shows that plot 6 was located at the poorest site while plots 1–5 were on relatively good sites. At the start of the study in 1994, numbers of trees ha^{-1} were almost the same in plot 1 and plot 4 (758 and 800 respectively) but Figure 1(b) exhibits a decrease in the basal area of plot 1. This was due to the high mortality rate in plot 1 during the course of study and the number of trees reduced to 568 while in plot 4 there was little mortality and number of trees ha^{-1} at the end of the study period was 782.

Table 1 Details of the six plots enumerated in 1994

Plot	Area (ha)	Planting year	[1]Spacing (m)	Tree/plot	[2]Tree ha^{-1}
1	0.06	1977	4 × 3	48	758
2	0.07	1971	4 × 4	30	422
3	0.07	1974	5 × 3	32	474
4	0.06	1979	3 × 3	45	800
5	0.03	1990	2 × 1.5	84	3043
6	0.04	1982	3 × 3	42	1028

[1]Spacing at the time of planting; [2]at the time of first measurement in 1994

Table 2 Summary statistics for the data sets from the plots

Attribute	Minimum	Maximum	Mean	Standard deviation
Age (years)	4.00	28.30	18.20	6.55
Dominant height (m)	5.41	14.87	10.75	3.10
Stems ha^{-1}	380	3043	1032	886.42
Quadratic mean diameter (cm)	4.71	21.37	14.14	5.19
Basal area ($m^2 ha^{-1}$)	4.34	16.86	11.45	3.13

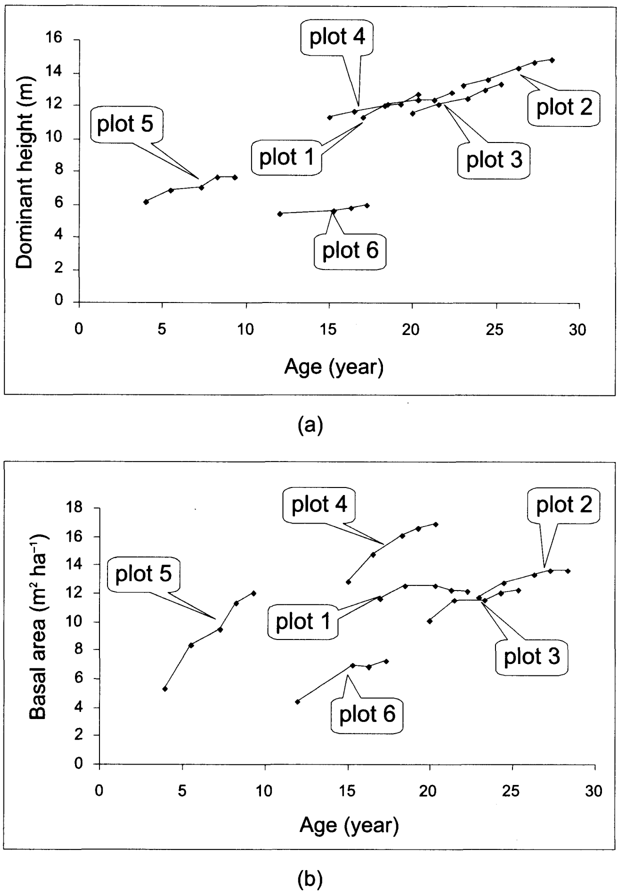


Figure 1 Graphic representation of the data: (a) height development; (b) basal area development

The development of number of trees ha^{-1} over period of time and the relationship between quadratic mean diameter of the trees and stem ha^{-1} is presented in Figure 2. There was no thinning done in the plots and decrease in stem numbers ha^{-1} shown in Figure 2(a) was because of mortality. The solid line in

Figure 2(b) represents the limiting line which indicates the maximum stems ha^{-1} the plots can have at a given quadratic mean diameter at maximum basal area.

Growth models

In the analysis of basal area growth, the path invariant algebraic difference form of several growth functions was applied. After screening the literature, seven such models were selected.

Pienaar and Shiver (1986) developed a growth function, which makes it possible to forecast basal area growth as a function of age, height and stem number:

$$\ln(BA_2) = \ln(BA_1) + \alpha * \left(\frac{1}{A_2} - \frac{1}{A_1}\right) + \beta * (\ln N_2 - \ln N_1) + \gamma * (\ln H_2 - \ln H_1) + \delta * \left(\frac{\ln H_2}{A_2} - \frac{\ln H_1}{A_1}\right) \quad (1)$$

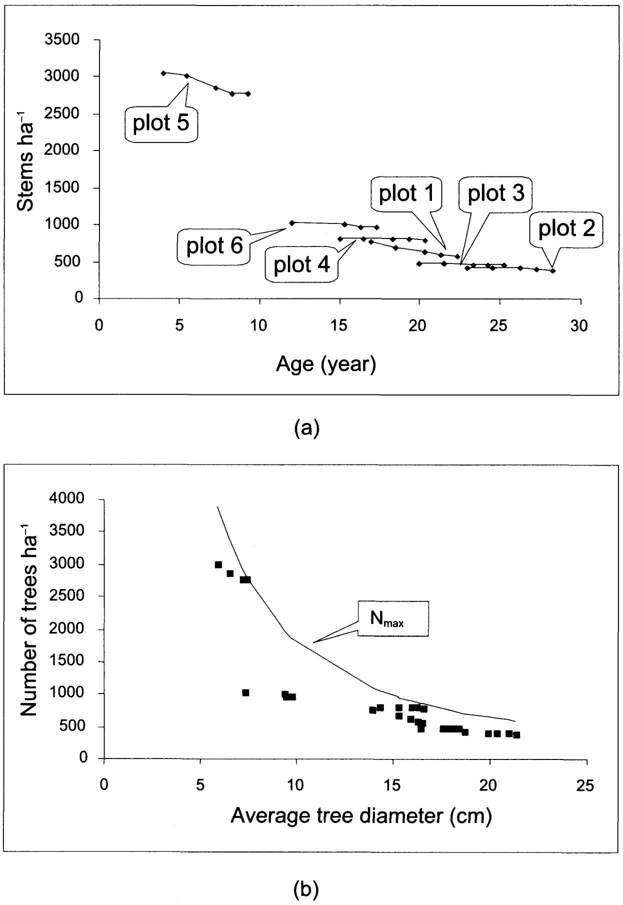


Figure 2 Graphic representation of the data: (a) stem number development; (b) relationship between stems ha^{-1} and average tree diameter. N_{max} = maximum stems ha^{-1} at maximum basal area

where

BA_1 and BA_2	= basal area at ages A_1 and A_2
H_1 and H_2	= top height at ages A_1 and A_2
N_1 and N_2	= number of stems at ages A_1 and A_2
α, β, γ and δ	= model parameters

Forss *et al.* (1996) modified equation (1) as follows:

$$\ln (BA_2) = \ln (BA_1) + \alpha * \left(\frac{1}{A_2} - \frac{1}{A_1} \right) + \beta * (\ln N_2 - \ln N_1) + \gamma * (\ln H_2 - \ln H_1) \tag{2}$$

If there is no or low mortality, which may be a consequence of heavy or closely spaced thinning events, we can approximate that there will be no change in number of stems ha^{-1} at age A_1 and age A_2 and $N_1 = N_2$. In this case equation (2) can be simplified to yield equation (3):

$$\ln (BA_2) = \ln BA_1 + \alpha * \left(\frac{1}{A_2} - \frac{1}{A_1} \right) + \beta * (\ln H_2 - \ln H_1) \tag{3}$$

Hui and von Gadow (1993) developed the following equation for projecting a known basal area for stands of *Cunninghamia lanceolata* of varying density:

$$BA_2 = BA_1 * N_2^{1-\alpha * H_2^{\beta}} * N_1^{\alpha * H_1^{\beta - 1}} * \left(\frac{H_2}{H_1} \right)^{\gamma} \tag{4}$$

Applying the condition when $N_1 = N_2$, this equation can be simplified as:

$$BA_2 = BA_1 * \left(\frac{H_2}{H_1} \right)^{\gamma} \tag{5}$$

Schumacher (1939) proposed following age dependent basal area model, which was later used by Schumacher and Colle (1960), Clutter (1963) and Sullivan and Clutter (1972):

$$\ln (BA_2) = \alpha + (\ln BA_1 - \alpha) * \left(\frac{A_1}{A_2} \right) \tag{6}$$

Souter (1986) presented another model based on the Schumacher model, which can be given as:

$$\ln (BA_2) = \left(\frac{A_1}{A_2} \right) * \ln BA_1 + \alpha * \left(1 - \frac{A_1}{A_2} \right) + \beta * \left(\ln N_2 - \left(\frac{A_1}{A_2} \right) * \ln N_1 \right) \tag{7}$$

The parameters of models 1–7 were estimated with the help of the statistical software package STATISTICA using non-linear regression techniques.

The seven models were then fitted to the 29 annual measurements in the six plots using ordinary least squares (OLS) method. For fitting, we used interval data of successive measurements and converted equations 1–3 and 6 and 7 by taking the exponential of both sides to make their statistics comparable with those of equations 4 and 5.

Model evaluation

The quantitative evaluation of models is a very important part of growth modelling. The mean residual (MRES), a measure of average model bias, describes the directional magnitude, i.e. the size of expected under- or overestimates. Indices of model precision are root mean square error (RMSE), model efficiency (MEF) and variance ratio (VR). The criteria, their formula and ideal values are shown in Table 3.

RMSE was based on the residual sum of squares, which gave more weight to the larger discrepancies. MEF index was analogous to R^2 and provided a relative measure of performance. VR measured the estimated variance as a proportion of the observed one. MRES and RMSE were expressed as relative values, which was more informative when components with different measurement units were compared.

Results and discussion

The parameter estimates and summary statistics are shown in Table 4. The fit statistics given in Table 4 showed that models 6 and 7 produced high values for the coefficient of determination and low values for the sum of squared residuals (SSE), which indicated the precision of the model compared with the rest of the models tested. Thus these two functions performed best in comparison with other functions.

The superiority of any model cannot be established only on the basis of fit statistics. Therefore, all models were validated using quantitative evaluation based on the statistical criteria given in Table 3 to test their predictive abilities. The values of these criteria obtained for different models are presented in Table 5.

The values in Table 5 showed that equation 7 had minimum bias followed by equation 6. The rest of the models had larger bias and slightly underestimated the

Table 3 Criteria for evaluating model performance

Criterion	Formula	Ideal value
Mean residual (MRES)	$\frac{\sum (y_i - \hat{y}_i)}{n}$	0
Root mean square error (RMSE)	$\sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n-1-p}}$	0
Model efficiency (MEF)	$\frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2}$	0
Variance ratio (VR)	$\frac{\sum (\hat{y}_i - \bar{\hat{y}}_i)^2}{\sum (y_i - \bar{y})^2}$	1
Coefficient of determination (R^2)	$1-\frac{SSE}{TSS}$	1

Note: y = observed values; $\hat{y}$ = predicted values; $y-\hat{y}$ = residuals; p = number of model parameters. SSE = sum of squared residuals, TSS = total sum of squares

Table 4 Estimated parameters and summary statistics obtained for the basal area models

Model	α	β	γ	δ	R^2	MSE
1	- 3.9525	0.6103	1.3175	- 0.3154	0.949	0.49655
2	- 4.4876	0.5987	1.3055		0.949	0.47056
3	- 4.4901	0.9644			0.942	0.51033
4	0.9954	- 0.7232	0.6581		0.925	0.68427
5			1.7616		0.901	0.82149
6	3.1680				0.956	0.36357
7	3.2987	- 0.0185			0.956	0.38129

MSE = mean squared errors

Table 5 The estimated values for the statistical criteria considered for testing the predictive abilities of the models

Model	MRES	RMSE	MEF	VR
1	0.09005	0.70466	0.05122	1.14193
2	0.09330	0.68597	0.05124	1.13845
3	0.04076	0.71437	0.05849	1.13779
4	0.09895	0.82721	0.07451	1.30237
5	0.13089	0.90636	0.09886	1.34188
6	0.00758	0.60297	0.04375	0.95034
7	0.00015	0.61749	0.04370	0.95536

prediction. Equation 7 was virtually bias free as the value of MRES for this model was only 0.000015. Also, equations 6 and 7 produced minimum RMSE and higher precision than the other models used. Models are statistically sound in prediction if they give values for MEF and VR close to 0 and 1 respectively. In this analysis only models 6 and 7 met this condition. The rest showed greater deviation from the ideal values. Models 4 and 5 produced the largest values for all criteria. Overall, the statistical criteria used for model evaluation clearly reflected the superiority of models 6 and 7 for their predictive abilities over the other models studied. These models were successfully applied for basal area prediction in Norway spruce and similar results were obtained by Gurjanov *et al.* (2000).

An important step in evaluating fitted equations is to perform a graphical analysis of residuals searching for dependencies or patterns, which indicate systematic discrepancies. The examination of residual plots is recommended because by just comparing the RMSE does not reveal if the models are unbiased over the entire range of data. Therefore, residuals obtained by fitting equations 6 and 7 were plotted over predicted basal area values. Plots of observed versus predicted values were also generated (Figure 3). The figure indicated that both equations provided

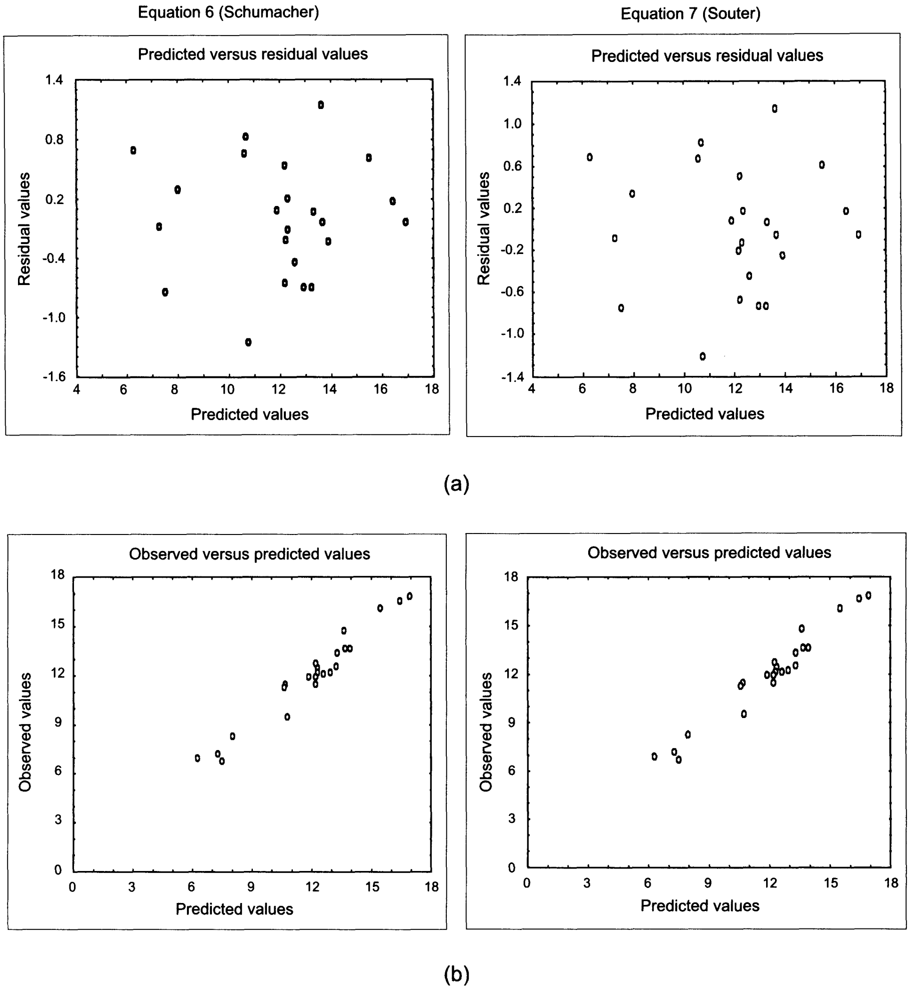


Figure 3 (a) Plot of residuals vs. predicted values; (b) plot of observed vs. predicted values using models Schumacher (6) and Souter (7)

almost identical predictions of basal area growth. However, the residual plots showed that the range of residuals was slightly higher for equation 6 (1.15–1.26) than for equation 7 (1.14–1.22).

Equations 3, 5 and 6 were more suited for modelling basal area growth when no mortality or change in number of stems ha^{-1} was observed in plantations, i.e. $N_1 = N_2$. If there is mortality or appreciable change in stem number ha^{-1} over a period of time, equations 1, 2, 4 and 7 can be considered. Even under the condition $N_1 = N_2$, these equations can be applied after simplification. There are some limitations to the modelling approach presented in this paper. The data used were not from the thinned stands. However, a worked example, using the model presented here has been incorporated to show the effect of thinning on basal area growth (Appendix). The observed decrease in the stem numbers in the plots was due to natural mortality. The model may be less accurate when used to predict neem basal area growth when natural mortality is significant (in dense stands and over long projection intervals).

The limited range of conditions under which neem plantations were selected for the study might have some effect on the potential utility of the models developed when applied to a wider range of conditions. Also, planting spacing is confounded with age since the older plantations have the widest spacings.

References

Clutter, J. L. 1963. Compatible growth and yield models for loblolly pine. *Forest Science* 9: 354–371.

Clutter, J. L., Fortson, J. C., Pienaar, L. V., Brister, G. H. & Baily, R. L. 1983. *Timber Management–A Quantitative Approach.* John Wiley and Sons, Chichester.

Forss, E., von Gadow, K. & Saborowski, J. 1996: Growth models for unthinned *Acacia mangium* plantations in South Kalimantan, Indonesia. *Journal of Tropical Forest Science* 8(4): 449–462.

Gurjanov, M., Orios, S. S. & Schröder, J. 2000. Grundflächenmodelle für gleichaltrige Fichtenreinbestände. *Forstwissenschaftliches Centralblatt* 117: 187–198.

Hui, G. Y. & von Gadow, K. 1993. Zur Modellierung der Bestandesgrundflächenentwicklung-dargestellt am Beispiel der Baumart *Cunninghamia lanceolata. Allgemeine Forst-und Jagd-Zeitung* 164: 144–149.

Kishan, K. V. S. & Tewari, V. P. 1999. Aboveground biomass tables for *Azadirachta indica* A. Juss. *International Forestry Review* 1: 109–111.

Pienaar, L. V. & Shiver, B. M. 1986. Basal area prediction and projection equations for pine plantations. *Forest Science* 32: 626–633.

Schumacher, F. X. 1939. A new growth curve and its applications to timber-yield studies. *Journal of Forestry* 37: 819–820.

Schumacher, F. X. & Colle, T. S. 1960. *Growth and Yield of Natural Stands of the Southern Pines.* T. S. Coile Inc., Durham.

Souter, R. A. 1986. Dynamic stand structure in thinned stands of naturally regenerated loblolly pine in the Georgia Piedmont. Ph.D. thesis, University of Georgia, Athens.

Staupendahl, K. 1999. *Modelling Thinnings Based on the Ratio of Relative Removal Rates.* Report on Growth and Yield Modelling of Tree Plantations in South and East Africa for University of Joensuu.

Sullivan, A. D. & Clutter, J. L. 1972. A simultaneous growth and yield model for loblolly pine. *Forest Science* 18: 76–86.

Tewari, V. P. & Kishan, K. V. S. 2002. Development of top height model and site index curves for *Azadirachta indica* A.Juss. *Forest Ecology and Management* 165: 67–73.

von Gadow, K. & Hui, G. Y. 1999. *Modelling Forest Development.* Kluwer Academic Publishers, Dordrecht.

Appendix

A worked example is presented here to show the effects of low and high thinning on basal area development. The example was based on the data of plot 5 described in this paper. Some stand variables for the plot observed at the start of inventory in 1994 are given below:

Variable	Value
Age (years)	4
Quadratic mean diameter (cm)	4.71
Stand basal area (m^2 ha^{-1})	5.31
Dominant height (m)	6.11
Stems ha^{-1}	3043

In a managed forest, thinnings usually have a far greater effect on forest development than natural growth. Thus the development of a managed forest is not only determined by natural tree growth, but also by the weight and type of the prescribed thinning. A quantitative description of thinning is an essential prerequisite for forecasting future stand development. We have considered two types of thinning, low thinning and high thinning, at every five years with the first thinning at the age of five years. Here five thinnings are shown as an example between four and 28 years of age. The thinning weight is expressed as relative stem number removed and defined as:

thinning weight, $rN = \dfrac{N_{removed}}{N_{total}}$

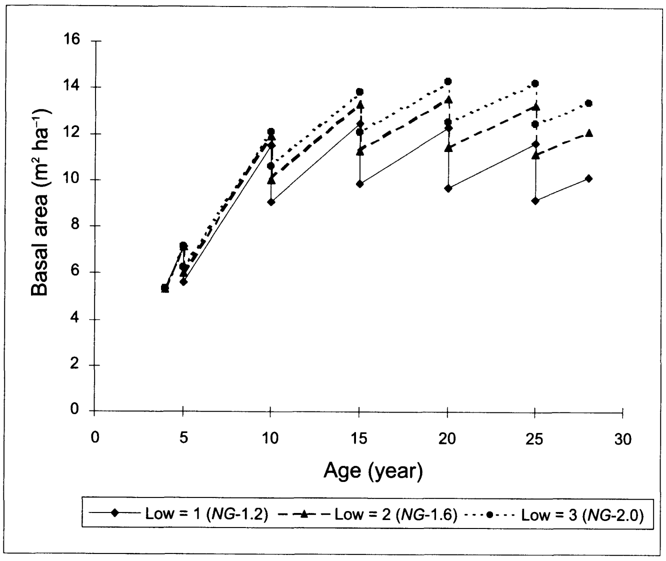
In both cases (low as well as high thinning), 25% of the stem number was removed at each thinning. The thinning type (NG) is given as:

$$NG = \frac{N_{removed}}{N_{total}} \bigg/ \frac{G_{removed}}{G_{total}} = \frac{rN}{rG}$$

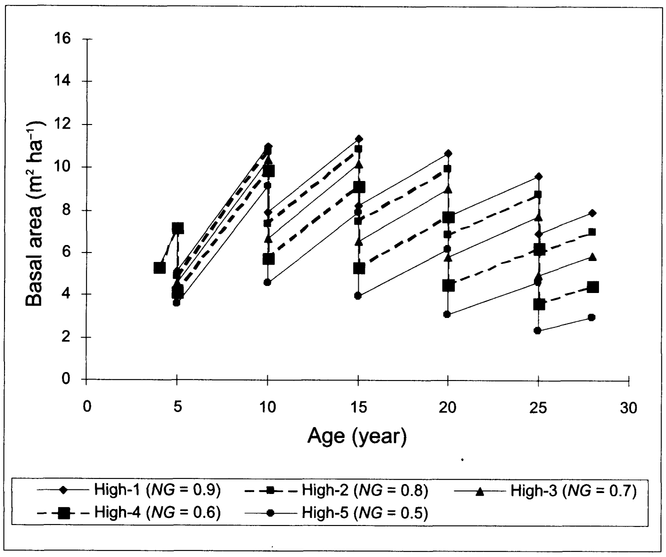
where
N = stem number and
G = basal area ha^{-1}

$NG > 1$ indicates a low thinning and $NG < 1$, a high thinning; $NG = 1$ corresponds to a row or random thinning. In our worked example, we evaluated low thinnings with NG values of 1.2, 1.6 and 2 and high thinnings with NG values of 0.9, 0.8, 0.7, 0.6 and 0.5. Since rN has been fixed as 0.25, we can calculate rG values for each NG value in the low and high thinnings.

For estimating basal area in the stand at every stage, we used the Souter model (equation 7). The basal area development is presented in Figure 4. Figure 4(a) shows the highest basal area values for the Low-3 option with $NG = 2.0$. However, when considering the cumulative yield at the time of final harvest at the age of 28



(a)



(b)

Figure 4 Basal area development: (a) low thinning; (b) high thinning years (the yield available in the stand at this age plus the thinning yields), the Low-1 option showed the highest total yield because the larger-size trees were removed during the thinnings (the number of removed trees being equal).

Similarly, looking at the high thinnings, Figure 4(b) shows higher basal area levels in High-1 (with $NG = 0.9$), but the total yield of this option was relatively low due to the fact that smaller trees were removed, unlike in the other High-options. The cumulative yield at the time of final harvest at the age of 28 years was highest in the High-4 option. In the case of High-5 ($NG = 0.5$), it was slightly less as 50% of basal area was removed at each thinning. The total thinning yield was higher than in the rest of the options but the available stand volume at the final age was very low.