Modelling the growth of *Shorea robusta* using growth ring measurements

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This paper presents distance-independent diameter growth models for Sal (*Shorea robusta* Gaertn. f.) in Kankali Community Forest, Chainpur VDC, Chitwan. As the basis for modelling, stem discs were cut 0.3 m above-ground for a sample of 80 trees that had recently been felled. Growth rings were measured along four radii and, except for the outer part of a few discs originating from old trees, individual growth rings could be distinguished without major difficulty. Supplementary data were gathered as a basis for preparing models relating [i] diameter under bark to diameter on bark and [ii] diameter 0.3 m above-ground to diameter 1.3 m above-ground. Based on these data, auxiliary models were developed and used to convert growth ring measurements into diameter increment at breast height. The mean diameter increment was 0.87 cm/year (n = 1514) and the standard deviation was 0.33 cm/year. The relationships between diameter increment and current diameter, stem age, growth in previous years, rainfall and temperature were modelled. Four different models were presented. Rainfall during the growth season, particularly the months of May-July, proved to influence growth considerably and suggests a scope for dendroclimatological studies in Sal. .

Key words: Climate change, community forestry, diameter growth models, effect of rainfall, growth ring measurements

With respect to its silvicultural characteristics, Sal (*Shorea robusta* Gaertn. f.) has been described as 'the most gregarious and aggressive' tree species of the forest (Troup, 1921). Sal is a multipurpose species that can be used for timber as well as fuel and fodder and it is, therefore, considered a particularly important and attractive tree species (Jackson, 1994). In Nepal natural Sal forests have been highly acknowledged for their economic potential (Rautiainen and Suoheimo, 1997). However, despite the economic potential of Sal, few academic studies have been conducted on the growth of this species in Nepal.

As only a few forest growth models have been developed in Nepal, the uncertainty of growth and yield estimates is often high. In order to safeguard against depletion of resources, community forests apply conservative estimates of productivity and allowable cut. A possible consequence of this is that forests are underutilised and provide less income to communities than could have been obtained with reliable information about annual increment. Hence, the potential value of preparing growth models to communities is likely to be high.

The impact of global climate change on forest growth remains uncertain, both because the exact changes with regard to temperature and rainfall patterns are unknown and because the responses of forest ecosystems to long-term changes are poorly understood. It has been argued that increasing CO_2 concentrations in the atmosphere might lead to carbon fertilization but examples of decelerating growth, e.g. Feeley *et al.* (2007) indicate that temperature and rainfall patterns are often crucial. Particularly for a semi-deciduous/semi-evergreen species like Sal, growing in a region with distinct wet and dry seasons, growth is likely to be limited mainly by rainfall. Future growth will remain uncertain but at least the observed effects of past climate on growth can provide a clue to what changes to expect in the short-medium term.

Annual growth rings are useful to determine the age and growth rate of trees, and tree ring analysis is widely used to study the effect of climate on growth (Xiangding and Xuzhi, 1991). The old belief that annual growth rings are not formed in most tropical trees has been proven wrong for many species and during the past decade, studies on growth rings in

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tropical trees have been increasingly successful (Brienen and Zuidema, 2006; Worbes, 2002). Although not always easy to distinguish, Sal usually produces one growth ring per year, thereby enabling growth ring measurements to be made (e.g. Rautiainen 1999; Vanclay 1994).

The objective of this study is to develop local distance-independent diameter growth models for individual trees based on growth ring measurements. These models are meant for application in forest management planning. An additional objective is to prepare models including effects of past climate on diameter growth, thereby providing a basis for assessing likely short-term effects of climate change on growth. Finally, the paper aims to act as a source of inspiration for further study into local growth models for Sal.

Materials and methods

Study site

The study was conducted in Kankali Community Forest which is located in Chitwan District, approximately 16 km north of Bharatpur. The altitudinal range is 300-900 m, the total forest area is 760 ha and the main tree species is Sal.

Data collection

For a random sample of 80 stumps, a stem disc was cut 0.3 m above-ground (stump height). The discs were planed and sanded to enhance the visibility of growth rings. The growth rings were marked with a pencil and the radius from pith to each ring was measured along four perpendicular lines from pith to bark using a ruler (accuracy 1 mm). For each year, the four measured radii were averaged. The age of a stem was assumed equal to the number of growth rings counted. For young trees, an attempt was made to verify the age estimate by interviewing residents. In almost all cases the age estimates tallied with one another.

Growth was measured under bark but diameter is normally measured on bark, and it was therefore necessary to prepare the basis for a model relating diameters on and under bark. This was done by measuring diameter on and under bark for the 80 discs also used for growth measurements. For an additional random sample of 24 stumps, diameter measurements were carried out in the field using a girth tape (accuracy 1 mm). For the sample as a whole (n = 104) the minimum and maximum diameters on bark were 11.1 cm and 108.2 cm, respectively. Due to the relative scarcity of large stumps the mean diameter on bark was as low as 30.8 cm.

Growth ring measurements were conducted at stump height. To allow the estimation of growth at breast height, it was necessary to prepare the basis for modelling the relationship between diameters 0.3 m and 1.3 m above-ground. Therefore, a random sample of 176 trees was selected in various parts of the forest, representing different stand densities, slopes and aspects. For these trees the stem diameter was measured at both 0.3 m and 1.3 m above-ground using a tape measure (accuracy 1 mm). The minimum and maximum diameters at breast height (DBH) were 3.0 cm and 46.8 cm and the mean DBH was 17.5 cm.

For the period 1998-2007 monthly precipitation, and minimum and maximum temperature observed at the meteorological station at Rampur (27° 37' N; 84° 25' E), approximately 25 km to the southwest of the Kankali forest were obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal (Figure 1). The mean annual rainfall recorded was 2298 mm (range 1736-2694 mm).

The overall diameter distribution of Sal in the Kankali forest was obtained from ComForM, a collaboration project between Institute of Forestry in Pokhara and Hetauda, Department of Forest Research and Survey, Forest and Landscape Denmark and several associated partners that had established permanent sample plots in the forest (Meilby *et al.*, 2006).

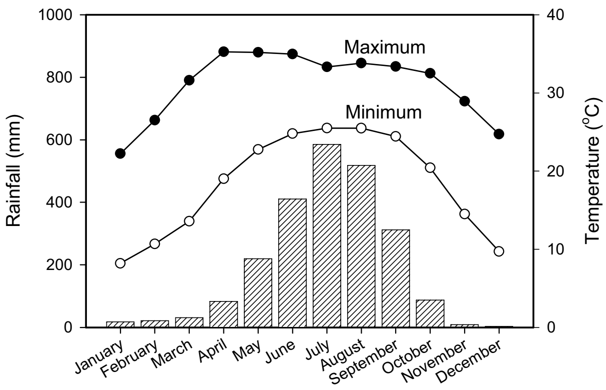

Fig 1 : Climate at Rampur approximately 25 km from Kankali (1998-2007): Mean monthly rainfall and mean monthly maximum and minimum temperatures. Data provided by the Department of Hydrology and Meteorology, Government of Nepal

Models

Auxiliary models

A total of 104 observations of stump diameter on bark and under bark were available for modelling. To describe the relationship between diameter under bark (d_{ub}) and diameter on bark (d_{ob}) the following regression models were tested:

$$d_{ob,i} = \alpha + \beta\, d_{ub,i} + \varepsilon_i \quad (1)$$

$$d_{ob,i} = \beta\, d_{ub,i}^{\gamma} + \varepsilon_i \quad (2)$$

$$d_{ob,i} = \alpha + \beta\, d_{ub,i}^{\gamma} + \varepsilon_i \quad (3)$$

where $i = 1\ldots104$, α, β, and γ are model parameters to be estimated, and the ε_is are random and normally distributed errors. Parameters were estimated using the NLIN procedure (non-linear model estimation) of the SAS v. 9.2 software package (Statistical Analysis System; SAS Institute, 2009a).

A total of 176 random trees were measured with regard to diameter at breast height and stump height (30 cm above-ground). The following model candidates were tested:

$$d_{1.3,i} = \alpha + \beta\, d_{0.3,i} + \varepsilon_i \quad (4)$$

$$d_{1.3,i} = \beta\, d_{0.3,i}^{\gamma} + \varepsilon_i \quad (5)$$

$$d_{1.3,i} = \alpha + \beta\, d_{0.3,i}^{\gamma} + \varepsilon_i \quad (6)$$

where $i = 1\ldots176$, $d_{1.3}$ and $d_{0.3}$ are stem diameters measured at breast height (1.3 m) and stump height (0.3 m), respectively, α, β, and γ are model parameters to be estimated, and the ε_is are random and normally distributed errors. Again parameters were estimated using the NLIN procedure.

Growth models

Based on the growth ring measurements, a total of 80 diameter growth series were available. These were used to parameterise a range of growth models where growth ($\Delta d_{i,t}$) in a given year (t) was described as a function of diameter ($d_{i,t}$) and disc age ($T_{i,t}$) before the growth season, diameter increment in the preceding growth season ($\Delta d_{i,t-1}$), rainfall (R_t), and minimum and maximum temperature. The models were developed from the two basic equations described by Zeide (1993): *increment* = $k \times size^{p} \times age^{q}$ and *increment* = $k \times size^{p} \times \exp(q \times age)$, where k, p and q are model parameters.

Model parameters were first estimated under the assumption that growth observations were independent. This was done using the NLIN procedure of the SAS software package. Next, models that performed particularly well were reformulated as mixed models including random, disc-specific effects. The parameters were estimated using the NLMIXED procedure (non-linear mixed model estimation) of the SAS v. 9.2 software package (SAS Institute, 2009b) and the following models were selected for further examination:

$$\Delta d_{i,t} = (\alpha + a_i)\, d_{i,t}^{\beta} \exp(-\gamma\, d_{i,t}) + \varepsilon_{i,t} \quad (7)$$

$$\Delta d_{i,t} = (\alpha + a_i)\, d_{i,t}^{\beta} \exp(-\gamma\, d_{i,t}) T_{i,t}^{-\delta} + \varepsilon_{i,t} \quad (8)$$

$$\Delta d_{i,t} = (\alpha + a_i)\, d_{i,t}^{\beta} \exp(-\gamma\, d_{i,t})\, \Delta d_{i,t-1}^{\phi} + \varepsilon_{i,t} \quad (9)$$

$$\Delta d_{i,t} = (\alpha + a_i)\, d_{i,t}^{\beta}\, T_{i,t}^{-\delta} \exp(\lambda\, R_t) + \varepsilon_{i,t} \quad (10)$$

where the a_is are random and normally distributed disc effects ($i = 1\ldots80$), $a_i \sim N(0, \sigma_a^2)$, the $\varepsilon_{i,t}$s are independently and normally distributed random errors, $\varepsilon_{i,t} \sim N(0, \sigma_\varepsilon^2)$, t is the year, and α, β, γ, δ, ϕ and λ are parameters to be estimated.

Results and discussion

Auxiliary models

The three models, (1)-(3), describing the relationship between diameter on and under bark all fitted the data very well with R^2 values of 0.998-0.999 (Table 1). Model (3) included three parameters and was thus the most flexible one. However, the power parameter, γ, could not be distinguished from 1 (Pr>|t| = 0.58) and, hence, there seemed to be no reason to prefer Model (3) over the linear Model (1), particularly as the Root Mean Squared Error (RMSE) of Model (1) was the lower one. Unfortunately, the dataset did not include stems with diameters of less than 8.4 cm under bark (11.1 cm on bark) and the estimated intercepts of Models (1) and (3) implied that the predicted diameter on bark of a stem with an under-bark diameter of 0 cm would be 2.5-2.7 cm. Since this is not in agreement with reality and since the model would be used to predict on-bark diameters for under-bark diameters considerably smaller than 8.4 cm, Model (2) was considered the best alternative.

Models (4)-(6) describing the relationship between on-bark diameter 0.3 m and 1.3 m above-ground all fitted the data very well with R^2 values of 0.992-0.993 (Table 1). In the three-parameter model (6), the intercept was not significantly different from zero

(Pr>|t| = 0.64) and the power parameter, γ, was statistically indistinguishable from 1 (Pr>|t| = 0.86). Therefore, Models (4) and (5) were preferred to Model (6). The linear Model (4) predicted a diameter of 0.25 cm at breast height for a diameter of 0 cm at stump height. Since this is not realistic, Model (5) was considered the most attractive alternative.

Diameter growth data

As a basis for modelling diameter growth at breast height, the original growth ring measurements 0.3 m above-ground were transformed using Models (2) and (5). Hence, denoting the average radius from pith to perimeter of a growth ring in year t by $\overline{r_t}$, the on-bark diameter at breast height (DBH) was estimated as:

$$d_{1.3,t} = \hat{\beta}_{(5)}\left[\hat{\beta}_{(2)}\left(2\overline{r}_t\right)^{\hat{\gamma}_{(2)}}\right]^{\hat{\gamma}_{(5)}}$$

where $\hat{\beta}_{(2)}$, $\hat{\beta}_{(5)}$, $\hat{\gamma}_{(2)}$ and $\hat{\gamma}_{(5)}$ are the estimated parameters of Models (2) and (5). Subsequently, annual diameter increment was estimated as $\Delta d_t = d_{1.3,t} - d_{1.3,t-1}$.

The majority of the sample trees were 10-20 cm DBH (84%) and 11-20 years of age (75%), and only 6.3% were larger than 50 cm DBH. Thus the composition of the sample clearly reflects that it is based on thinned trees. However, as all trees were once thinner than at the time of felling, the diameter increments and corresponding diameters before the growth season cover the diameter range up to 75 cm quite well (Figure 2). For the Kankali forest as a whole, ComForM estimated that as much as 81% of the Sal trees were less than 10 cm DBH and the estimated percentage of stems larger than 50 cm DBH was only 0.4%.

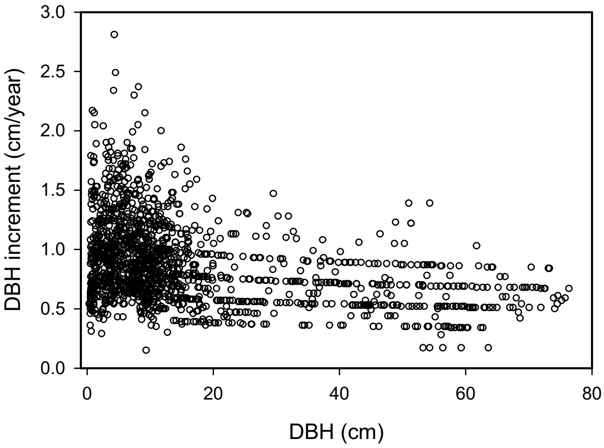

Fig. 2 : Diameter increment vs. diameter at breast height before the growth season

Effect of climate

Preliminary analysis showed that growth was only weakly correlated with whole-year climate variables. To identify the period of the year when weather had the greatest influence on growth, rainfall was totalled for periods of 3-6 months starting from March, April, May, June and July. Average maximum and minimum temperatures were calculated for the same periods. Coefficients of correlation between diameter increment and total rainfall, maximum and minimum temperature were estimated. It emerged that correlations between growth and minimum temperature generally were not significant at the 5% level. Therefore, they have not been included in Table 2.

Table 1 : Models describing the relationships between diameter on and under bark, (1)-(3), and between diameter at stump height and at breast height, (4)-(6). Standard errors are given in square brackets. Symbols: see text. Units of measurement: d_{ob}, d_{ub}, $d_{1.3}$, and $d_{0.3}$: cm

Model (structural part)		n	RMSE	Adj. R^2	Parameter estimates		
					Par. α	Par. β	Par. γ
(1)	$d_{ob} = \alpha + \beta d_{ub}$	104	0.753	0.999	2.735 [0.111]	1.061 [0.0031]	n.a.
(2)	$d_{ob} = \beta d_{ub}^{\gamma}$	104	0.891	0.998	n.a.	1.534 [0.0232]	0.9219 [0.0037]
(3)	$d_{ob} = \alpha + \beta d_{ub}^{\gamma}$	104	0.756	0.999	2.541 [0.367]	1.093 [0.0592]	0.9935 [0.0116]
(4)	$d_{1.3} = \alpha + \beta d_{0.3}$	176	0.751	0.992	0.2502 [0.123]	0.8499 [0.0054]	n.a.
(5)	$d_{1.3} = \beta d_{0.3}^{\gamma}$	176	0.751	0.993	n.a.	0.8953 [0.0185]	0.9879 [0.0061]
(6)	$d_{1.3} = \alpha + \beta d_{0.3}^{\gamma}$	176	0.753	0.993	0.1838 [0.398]	0.8625 [0.0725]	0.9965 [0.0198]

The correlation between rainfall and growth was generally positive as expected, and it appears that to obtain a high coefficient of correlation the period for which rainfall is calculated must include the months of May, June and July. Thus, the highest coefficients of correlation were observed for three- and four-month periods starting on the 1st of May, a five-month period starting on the 1st of April, and a six-month period starting on the 1st of March (Table 2).

Correlations between maximum temperature and growth were generally negative, reflecting the fact that maximum temperature and rainfall were negatively correlated. For example, the coefficient of correlation between total rainfall and maximum temperature for the three-month period May-July was -0.653 ($Pr>|r|=0.041$, n=10). The coefficients of correlation between growth and maximum temperature were generally lower in absolute terms than those calculated for growth and rainfall, and in the growth models it was therefore decided to include rainfall for the period May-July. The average total rainfall (1998-2007) for this period was 1215 mm with a minimum of 623 mm and a maximum of 1846 mm.

Growth models

Diameter increment was negatively correlated with age ($r = -0.385$, $Pr>|r| < 0.0001$), negatively correlated with diameter before the growth season ($r = -0.370$, $Pr>|r| < 0.0001$), positively correlated with diameter increment in the preceding growth season ($r = 0.404$, $Pr>|r| < 0.0001$), and positively correlated with rainfall in May-July ($r = 0.215$, $Pr>|r| < 0.0001$).

Parameter estimates of the four growth models, (7)-(10), are shown in Table 3. The final parameter estimates of the structural part of Models (7) and (8) differed little from those estimated using ordinary non-linear least squares (Sapkota, 2008). All parameters were significant at the 5% level or better, and except for the negative parameter estimate of β in Model (9) the signs of the estimated parameters were as expected. Thus, in agreement with the observed correlation patterns, growth generally decreased with increasing age, increased with increasing growth in the preceding growth season, and increased with increasing rainfall. Models (7) and (8) showed that growth initially increased, culminated, and finally decreased with increasing diameter.

The estimated variances of the random disc effects, $s^2(a)$, corresponding to standard deviations of about 0.1, were low compared with the estimated values of the fixed effects, α, which ranged from 0.97 to 1.12. The estimated variances of the error terms, $s^2(\varepsilon)$, were similar for all four models (0.073-0.083) but since only part of the data can be used for Models (9) and (10) direct comparison of the models must be based on a reduced dataset. For the 769 observations that can be used in all four models, the standard deviation of the prediction errors was observed to decrease from 0.32 cm for Model (7) to 0.31 cm for Model (8) and 0.30 cm for Models (9) and (10).

The annual diameter increment predicted by Model (7) peaked at a diameter of only 4 cm and reached a maximum value of about 1 cm/year. Beyond the

Table 2 : Coefficients of correlation† between diameter growth, Δd, and climate variables (rainfall and maximum temperature) calculated for periods of 3-6 months starting from the 1st of March to July

	Period length	First month of the period considered				
		March	April	May	June	July
Rainfall	3 months	0.131***	0.160***	0.215***	0.188***	0.089*
	4 months	0.167***	0.208***	0.211***	0.149***	0.060NS
	5 months	0.208***	0.214***	0.179***	0.127***	0.065NS
	6 months	0.207***	0.176***	0.161***	0.131***	0.063NS
Max. Temp.	3 months	-0.080*	-0.126***	-0.147***	-0.080*	-0.035NS
	4 months	-0.100**	-0.134***	-0.181***	-0.067NS	0.020NS
	5 months	-0.097*	-0.183***	-0.150***	-0.019NS	0.043NS
	6 months	-0.113**	-0.156***	-0.114**	0.003NS	0.091*

† Levels of significance: 'NS': not significant, '*': p<0.05, '**': p<0.01, '***', p<0.001

maximum, the predicted diameter increment decreased slowly and at a diameter of 70 cm it was still 0.5 cm/year (Figure 3). Model (8) including stem age indicated that, particularly for young stems, the expected growth deviated considerably between stems that had reached a given diameter within comparatively few years and those for which it had taken a longer time. As size and age increased, the difference between the diameter increments predicted by Models (7) and (8) tended to decrease.

The minimum observed rainfall in the three-month period May-July (1998-2007) was 623 mm and the maximum was 1846 mm. The diameter increment predicted by Model (10) for a rainfall of 500 and 2000 mm is shown in Figure 4. It appears that growth was strongly influenced by rainfall but, like for Model (8), it is also seen that the expected growth depended very much on the time that it had taken for a stem to reach a given diameter.

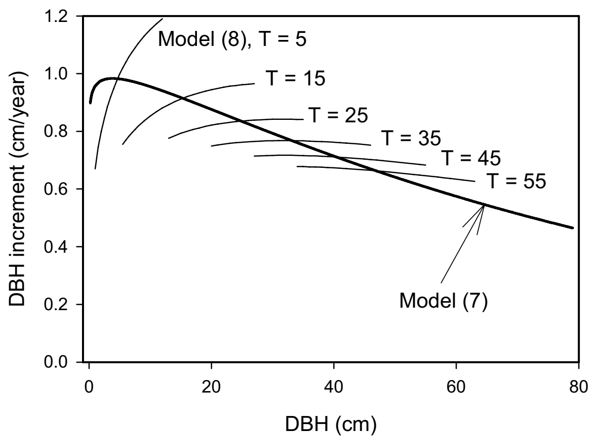

Fig. 3 : Diameter increment predicted by Models (7) and (8). For Model (8) growth predictions are shown at ages T = 5, 15, …, 55 years

Growth patterns

As expected, the diameter increment was strongly related to both diameter and age. But diameter and age were also strongly correlated and when variables such as diameter increment in the preceding year or rainfall during the growth season were included in a model, it therefore turned out that the decrease of growth after its culmination at diameters of 2-8 cm could either be modelled using diameter or age, but not both. The early culmination of growth may be related to the fact that in the Kankali forest most young stems presumably originated from root suckers.

All models include diameter at the beginning of the growth season. Therefore, the effects of stem age in Models (8) and (10) can be interpreted as effects of past growth success, reflecting differences between trees with regard to site conditions, competition and genetics. Similarly, in Model (9) the effect of diameter increment in the preceding growth season could be interpreted as an effect of past growth success in combination with weather conditions in the preceding year.

Growth and climate

The correlation between growth and climate variables describing average weather conditions within a year proved low. Higher correlations were obtained by considering the growth season only, estimating rainfall and average temperatures for periods of 3-6 months. Within the growth season, rainfall and maximum temperature were negatively correlated and while diameter growth was positively correlated with rainfall it was therefore negatively correlated with maximum

Table 3 : Diameter growth models. Approximate standard errors are given in square brackets. Symbols: see text. Units of measurement: d, Δd and Δd_{t-1} : centimetres, T: years from pith, R: metres of rainfall (total for the months of May, June and July)

			Estimates of fixed effects parameters							
	Model (structural part)	n	Par. α	Par. β	Par. γ	Par. δ	Par. ϕ	Par. λ	$s^2(a)$	$s^2(\varepsilon)$
(7)	$\Delta d = \alpha\, d^{\beta} \exp(-\gamma\, d)$	1514	0.9680 [0.023]	0.0454 [0.013]	0.0118 [0.001]	n.a.	n.a.	n.a.	0.0151 [0.003]	0.0785 [0.003]
(8)	$\Delta d = \alpha\, d^{\beta} \exp(-\gamma\, d) T^{-\delta}$	1514	1.0496 [0.031]	0.2688 [0.056]	0.0084 [0.001]	0.2739 [0.066]	n.a.	n.a.	0.0102 [0.003]	0.0793 [0.003]
(9)	$\Delta d = \alpha\, d^{\beta} \exp(-\gamma\, d)\, \Delta d_{t-1}^{\phi}$	1436	1.1094 [0.032]	-0.0469 [0.018]	0.0051 [0.001]	n.a.	0.2228 [0.026]	n.a.	0.0105 [0.003]	0.0729 [0.003]
(10)	$\Delta d = \alpha\, d^{\beta}\, T^{-\delta} \exp(\lambda\, R)$	781	1.1206 [0.070]	0.2842 [0.072]	n.a.	0.4575 [0.076]	n.a.	0.1767 [0.035]	0.0093 [0.004]	0.0830 [0.004]

temperature. Irrespective of the duration of the period considered, the correlation between growth and minimum temperature remained very low.

Model (10) included rainfall for a three-month period from May to July and showed a clear positive relationship between rainfall and growth. Based on this model it may appear that if the observed average rainfall of about 1200 mm (May-July) was to be halved in the future, it would lead to a reduction of growth of about 10%. Similarly, it appears that if rainfall was to be doubled, the expected diameter growth would increase by about 24%. Unfortunately the climate series only covers 10 years and, although there is no doubt that long-term changes of precipitation would have considerably greater effect on growth than those predicted by Model (10), the available data do not allow describing such long-term changes.

Limitations

The models describing relationships between diameter under and on bark and between diameter 0.3 m and 1.3 m above-ground were prepared on the basis of static data and are therefore implicitly based on the assumption that the pattern observed for a cross-section of trees at a given point in time was identical to the one that might be observed for an individual tree over time.

Stem discs were cut from the stump of trees felled in the latest thinning. For middle-aged and old trees only limited numbers of thinned trees were available, and it was difficult to get a felling permit. Therefore, only few middle-aged and old trees were included in the sample. Potentially, this may be a source of error. In addition, since the sample trees were all trees that had been removed in thinning, there is no guarantee that the observed growth is representative of trees in the Kankali forest in general. However, as trees selected for thinning appeared to include both healthy and weakened trees it is uncertain to what extent this might lead to bias.

It is important to note that since the growth models do not take stand conditions into account, growth predictions will only remain unbiased to the extent that the basal area of the forest remains roughly unchanged. However, since its establishment as a community forest, the Kankali forest has been in transition from a degraded to a more well-stocked state and the basal area can still be expected to increase somewhat in the coming years. Hence, the models reported here must be considered preliminary and in the long term models taking stand basal area into account are needed.

It may be argued that it would have been possible to account for stand conditions by measuring basal area of the forest within some neighbourhood around the sample trees. Unfortunately, since the development of the surrounding trees and the likely removal of such trees in the past would not be known with certainty, it would be impossible to provide reliable estimates of past basal area for a period of more than a few years.

As can be seen in Figures 2-4, particularly for Model (7), there is a clear indication that most trees in the area started as root suckers that did not have an initial establishment period characterised by slow growth. Instead most stems grew fast from the outset.

It is important to note that the low number of large discs in the sample implies that growth predictions for large-diameter trees are uncertain. Growth ring measurements were generally observed to become more difficult with increasing age and diameter and the large discs that were included in the sample were those for which growth rings could actually be observed. In a few cases it was necessary to discard discs because rings could not be distinguished properly. Since narrow rings are likely to be more difficult to distinguish than wider ones, the growth of the selected sample discs might be greater than average. Consequently, the growth predicted by the models at large diameters may be biased.

Conclusion

For Sal in Kankali Community Forest, growth ring measurements proved comparatively easy for young trees. For older, slow-growing trees it was more difficult to distinguish the growth rings. In addition, only few large trees were included in the sample. This may imply that model predictions are not true for large trees.

Sample trees were selected among trees that had been felled in thinning and if the thinned trees are not representative of the population with regard to growth, this may imply that growth predictions are biased.

Diameter growth was influenced considerably by rainfall during the growth season. But including rainfall in months outside the period from April to

August merely obscured the relationship between growth and rainfall.

The observed significant relationship between climate variables and diameter increment in combination with the feasibility of growth ring measurements indicates that there may be scope for dendroclimatological studies in Sal.

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