A diameter class growth model for assessing the sustainability of silvicultural prescriptions in natural tropical forests

ANDREW F. HOWARD

Faculty of Forestry, University of British Columbia, 2357 Main Mall, Vancouver, B.C., Canada V6T 1Z4

JUVENAL VALERIO

Department of Forest Engineering, Institute of Technology of Costa Rica, Apdo. 159, Cartago, Costa Rica

SUMMARY

In spite of the general lack of growth and yield data from managed natural tropical forests, foresters must attempt to quantify the effects of proposed silvicultural prescriptions to assess sustainability. A generalized diameter class growth model was developed for this purpose. Data from the literature were used to derive the required accounting equations. The model was encoded into a spreadsheet programme and used in an illustrative study of a community forest under management in the Osa Peninsula of Costa Rica. A prescription devised by the second author was shown to produce a sustainable yield of approximately 26 m^3/ha every 15 years from a small forest on the Osa. While both the total volume and basal area per hectare stabilized after seven cutting cycles, the diameter distribution was still in flux. Practising foresters should find the modelling approach demonstrated here useful in the design of conservative management practices while awaiting improved data on the growth and yield of managed tropical forests.

RÉSUMÉ

Malgré un manque général de données de production et de croissance dans les forêts tropicales aménagées, les forestiers doivent tenter d'évaluer les effets de certaines prescriptions silviculturales sur une gestion équilibrée de l'environnement. Pour ce propos, un modèle standard de la croissance des classes de diamètre a été mis au point. Les données bibliographiques ont été utilisées pour établir les équations nécessaires et le modèle, codifié sur un tableur, a été utilisé dans une étude sur une forêt communautaire de la Péninsule Osa au Costa Rica. La méthodologie suivie par le deuxième auteur a permis une production durable d'environ 26 m^3/ha tous les 15 ans à Osa. Alors que le volume total ainsi que la surface terrière par hectare se sont stabilisés après 7 cycles de coupe la répartition des diamètres dans le tableau des classes de diamètre variait encore. Bien que la précision des résultats sur la croissance et la production demandent à être améliorés, les forestiers devraient trouver cette modélisation utile pour la conception de pratiques d'aménagement durable de la forêt tropicale.

RESUMEN

A pesar de la falta general de datos sobre el crecimiento y productividad de bosques tropicales, naturales, administrados, los ingenieros de montes deben tratar de cuantificar los efectos de las prescripciónes silviculturales propuestos para evaluar sostenabilidad. Un modelo generalizado de crecimiento del diámetro fue desarrollado con esta intención. Se usó datos de la literatura para sacar les ecuaciónes de contabilidad requeridas. El modelo fue cifrado en el programa de una hoja electrónica y usado en un estudio ilustrativo de un bosque comunal bajo administración en la Península Osa de Costa Rica. Una prescripción inventada por el segundo autor produjo un rendimiento sostenible de aproximademente 26 m^3/ha cada 15 años en un bosque pequeño en la Osa. Mientras el volúmen total y el área basal habían stabilizado después de siete ciclos de corte, la distribución de diámetro estaba continuamente cambiando. Para los ingenieros de monte el método aquí demostrado les será útil en el diseño de prácticas de administración conservadores mientras estàn esperando datos mejorados sobre el crecimiento y la productividad de bosques tropicales administrados.

INTRODUCTION

The assessment of the sustainability of forest management practices in natural tropical forests designed for production of multiple products is a particularly vexing problem due to the lack of product growth and yield data from both managed and unmanaged stands. Nowadays, polycyclic silvicultural systems based on partial cuttings are almost always applied to these forests in which case sustainability depends on a stable level of reserve growing stock in each component stand. In spite of the fact that growth and yield data required for accurate modelling of stand dynamics for these forests is generally lacking, managers must attempt to quantify the effects of proposed silvicultural prescriptions to assess sustainability. This modelling exercise will, at least, lead to improved understanding of stand, and ultimately forest, dynamics which is essential for the design of conservative practices that must be applied until additional data on growth and yield are available.

The objectives of this paper are two-fold. First, the basic principles of diameter class models are reviewed with the goal of informing potential users about this simple, but useful technique, and to serve as background for the rest of the paper. Second, a generalized diameter class growth model developed for use in a project investigating the long-term sustained yield of managed natural tropical forests is presented. The model was encoded into a spreadsheet programme and used in an illustrative study of a community forest under management in the Osa Peninsula of Costa Rica.

A REVIEW OF THE PRINCIPLES OF DIAMETER CLASS GROWTH MODELS

Diameter class growth models, also known as stand projection models, differ from whole-stand models because the development of each diameter class in a stand is modelled separately (Davis and Johnson 1987). This method is a logical choice for use in the design of management of tropical forests because individual treatments for stands usually include the specification of either harvest, killing, or retention of numbers and species of trees in various diameter classes. This technique also provides the data required for a detailed analysis of stand structure which is an important consideration in the management of non-timber resources. Computer-based quantitative design of silvicultural prescriptions is meant to augment, not replace, the qualitative aspects of design and is particularly helpful in the specification of marking guides when partial cutting is employed. Stand projection and simulation modelling have previously been proposed as a means for exploring management options in tropical forests (Neil 1981, Synnott 1980, Canonizado 1978, Nor 1978).

Davis and Johnson (1987) reviewed the basic concepts of diameter class growth models. The method involves accounting for changes in the number of trees in each diameter class with time, usually per unit area of forest. This requires the quantification of at least four components:

1. Upgrowth - the number of trees moving out (up) of each class due to growth;
2. Ingrowth - the number of trees moving into each class, including the smallest class, due to growth;
3. Mortality - the number of trees dying in each class per unit of time usually expressed as an annual percentage;
4. Cut - the number of trees removed or killed in either commercial or non-commercial silvicultural activities.

In the tropics, and perhaps elsewhere, it is also important to account for the number of trees killed unintentionally during commercial harvesting operations. These trees are either completely destroyed or severely damaged, representing incipient additional mortality, as a result of the felling and extraction processes. Some amount of logging damage is unavoidable, although through improved harvesting practices it can be reduced. These five components are shown in equation (1) which demonstrates the accounting procedures.

$$N_{i,p+1} = N_{ip} + I_i - U_i - M_i - C_i - D_i \qquad (1)$$

where,

$N_{i,p+1}$ = the number of trees in class i at the end of the growth period,
N_{ip} = the number of trees in class i at the beginning of the growth period,
I_i = the number of trees growing into class i in the period,
U_i = the number of trees growing out of class i in the period,
M_i = the number of trees which die in class i in the period,
C_i = the number of trees which are cut in class i in the period,
D_i = the number of trees destroyed or severely damaged during commercial harvesting operations in class i during the period of growth.

The use of the generalized model shown in equation (1) depends on the development of accounting equations for each of the five components, preferably from empirical observations in forests similar to the target forests. A desirable feature of these individual models is that they should incorporate the effect of changes in the intensity of proposed silvicultural treatments on the variable of interest (U_i, I_i, etc.).

A DIAMETER CLASS MODEL FOR THE TROPICS

A diameter class model was developed for use in a study of long-term sustained yield of timber for a managed community forest on the Osa Peninsula in Costa Rica. The forest is part of the BOSCOSA project in the Fundacion Neotropica, San Jose, Costa Rica. In this project, land owners are being organized into cooperatives with the goal of improving the management of both agricultural and forest lands, and hence providing stable employment for members through sustainable management.

Model Structure

The model was developed by deriving accounting equations for each of the five components shown in equation (1). Upgrowth and ingrowth for all species in all but the four smallest diameter classes is estimated using an annual diameter growth model. The model was derived from data published by Jonkers (1987) and de Graaf (1986), on the growth of natural tropical forests in Surinam in response to variable intensities of treatment and is shown in equation (2).

This prescription was simulated for a single stand of mature, fully stocked mixed species in the Osa Peninsula. The restriction that at least 20 m³/ha per harvest must be obtained during the maintenance period was imposed to insure all operations would be commercially viable. To achieve this level of harvest (net growth) the cutting cycle for the maintenance phase was varied until sufficient volume accumulated. For this stand the resulting cutting cycle was 15 years. A mortality rate of 1.75% was used and held constant throughout the simulation. This rate is within the range observed by Jonkers (1987) and also by Lieberman *et al.* (1985). Summary statistics including the equations for volume per tree and initial diameter distribution fitted to the original inventory data are shown in Table 1.

RESULTS AND DISCUSSION

Summary statistics for the first period of growth (10 years) after the initial entry are shown in Table 2. This treatment removed approximately one third of the total commercial volume greater than 50 cm DBH which amounted to just over 41 m³/ha. This level of cut resulted in a 15.9% and 22.3% reduction in basal area and total volume respectively. Damage from harvesting operations led to a loss of 16.6 m³ which represents 9.0% of the total volume and more than 40% of the volume harvested. After growth the net reduction in growing stock (standing volume) was 24.3%. Annual mortality averaged 2.04 m³ or 1.11% of the total volume. Annual net growth amounted to only 1.29 m³/ha.

TABLE 2. *Summary Statistics for the First Growth Period*

	Basal Area		Volume	
	m²/ha	%	m³/ha	%
Totals				
Harvest	4.2	15.9	41.1	22.3
Damage	3.2	12.1	16.6	9.0
Mortality	3.1	11.7	20.4	11.1
Growth	4.5	16.8	33.4	18.1
Stock	-6.0	-22.8	-44.8	-24.3
Per Annum				
Mortality	0.31	1.17	2.04	1.11
Growth	0.45	1.68	3.34	1.81
Net Growth	0.14	0.52	1.29	0.70

The second and third treatments in the conversion stage produced reduced levels of damage and mortality due to the lower numbers of large trees (> 60 cm DBH) in the stand. Otherwise these cuttings yielded similar results to the original entry. Standing volume, basal area, and number of trees were 54.3, 58.4, and 76.0% of the original stand conditions, respectively, after the third cut in the conversion phase.

Summary statistics after the first treatment of the maintenance phase and fourth period of growth are shown in Table 3.

TABLE 3. *Summary Statistics for the Fourth Growth Period*

	Basal Area		Volume	
	m²/ha	%	m³/ha	%
Totals				
Harvest	42.9	19.9	26.2	29.4
Damage	1.3	8.9	5.7	6.4
Mortality	2.4	16.6	13.3	14.9
Growth	6.3	43.5	40.3	45.2
Stock	-0.3	-1.9	-4.9	-5.5
Per Annum				
Mortality	0.16	1.10	0.89	0.90
Growth	0.42	2.90	2.69	3.02
Net Growth	0.26	1.79	1.80	2.11

This treatment removed 26.2m³/ha which represented almost 30% of the total standing volume. Approximately 1 m³/ha was lost to damage for every 4.6 m³/ha harvested. After growth residual growing stock continued to decline by 5.5%. Annual mortality declined to 0.90% of the total standing volume. The dramatic effect of volumetric losses to mortality in bigger classes was reduced because there were fewer large trees to begin with. Net annual growth increased to 1.8 m³/ha/yr, a 40% rise over the rate observed after the initial cut of the conversion phase. This improvement was due exclusively to the reduced losses to mortality as gross growth declined.

Summary statistics after the fourth treatment in the maintenance phase and seven periods of growth are shown in Table 4.

TABLE 4. *Summary Statistics for the Seventh Growth Period*

	Basal Area		Volume	
	m²/ha	%	m³/ha	%
Totals				
Harvest	2.9	20.0	26.2	32.0
Damage	1.3	9.3	5.2	6.4
Mortality	2.3	16.5	11.7	14.3
Growth	6.5	45.6	42.6	52.1
Stock	-0.0	-0.2	-0.5	-0.6
Per Annum				
Mortality	0.16	1.10	0.78	0.87
Growth	0.43	3.04	2.84	3.48
Net Growth	0.28	1.94	2.06	2.60

The volume removed was 26.2 m³/ha, the same as that taken in the first treatment of the second phase. Losses to damage from harvesting were also similar. This treatment resulted in a slight decline in growing stock as measured by volume, but essentially no change with respect to basal area. This indicates that the growing stock is not being depleted, but is still undergoing some changes in diameter distribution. Annual mortality declined slightly compared to period 4, and net growth increased to 2.06 m³ ha/yr.

Comparisons of the numbers of trees in each diameter class between periods show that the diameter distribution had not fully stabilized (see Figure 1). After six periods the number of trees is relatively constant up to approximately 19 cm DBH but continues to increase in classes 20 to 39 cm. Decreases are shown in the larger classes. After seven periods the distribution appears to have stabilized for trees 29 cm DBH and smaller. Increases are seen in the number of trees between 30 and 47 cm DBH, while decreases continued in the larger classes.

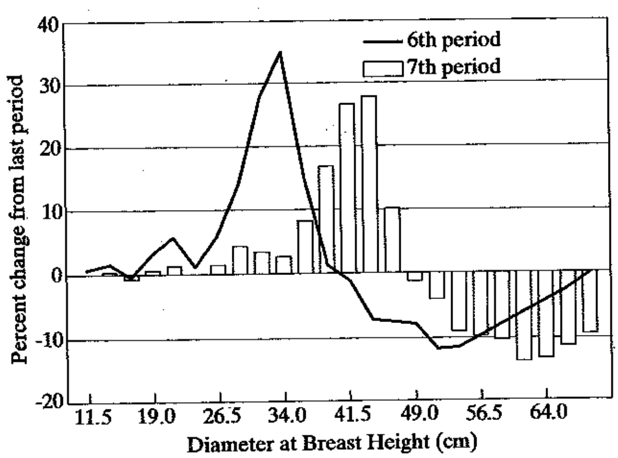

FIGURE 1. *Change in Diameter Distribution Between Periods*

It appears that the prescription tried on the case study stand does lead to a sustainable yield of timber. However, after seven periods of growth it is not clear if the diameter distribution will stabilize. The shift of growing stock from larger to smaller classes is continuing after the seventh period. This suggests that ultimately larger numbers of trees may have to be cut in the smaller classes to compensate for lower total volume in trees 60 cm and larger. This consequence would actually provide greater opportunity to eliminate smaller trees with reduced potential for volume and value growth in each treatment. It is also likely that it would lead to a stabilization of the diameter distribution.

One feature of the spreadsheet model which could prove extremely useful is that cutting cycles can be determined for individual stands. This process must be completed by trial and error; however, the task did not prove to be especially onerous in this study. The silvicultural prescription was applied to twelve other stands on the Osa Peninsula for which inventory data were available, giving a total of thirteen. Mortality rates for the stands were varied between 1.95 and 1.55% according to qualitative observations made in the field using results reported in the literature (Lieberman *et al.* 1985) as a guide. The cutting cycle (growth period) was varied for each stand until a sustained, net volume of approximately 20 m³/ha could be harvested. Summary statistics for all thirteen stands are shown in Table 5.

TABLE 5. *Summary statistics for Stand Projections of thirteen Stands on the Osa Peninsula*

	Original				Cutting	Net
Stand	m³/ha	m²/ha	#trees/ha	Mortality Rate (%)	Cycle (yrs)	Growth* m³/ha/yr)
A	96	20	323	1.95	20	1.09
B	184	26	283	1.75	15	2.06
C	122	22	263	1.95	20	1.27
D	154	25	237	1.75	15	1.52
G	148	27	308	1.75	15	1.66
H	167	35	695	1.75	15	1.43
I	126	23	443	1.75	20	1.37
J	126	28	482	1.55	15	1.39
K	129	29	434	1.55	20	1.28
L	142	27	396	1.75	20	1.27
M	136	27	437	1.55	15	1.51
N	177	33	501	1.75	15	1.72
P	181	25	484	1.75	15	2.12

*Net growth in period 7.

The derived cutting cycles varied from a low of 15 years to a high of 20 years. Logically, stands which were originally well-stocked (for example stands B, H, and P) and apparently on better sites had shorter cutting cycles. These sites are able to carry more and taller trees per hectare than the poorer stands. In the model, the same rate of diameter growth occurs on more trees; consequently, it takes less time to accumulate the same net volume available for harvesting. Simulated net growth for the stands varied from 1.09 to 2.12 m³/ha/yr which is consistent with results reported in the literature for natural tropical forests (Maitre 1991, de Graaf 1986, Johnson 1976, Synnott and Kemp 1976, Dawkins 1959).

Foresters must consider differences in cutting cycles for stands of varying quality both when designing stand-specific prescriptions and when planning overall forest production. Failure to consider variable cutting cycles will lead to improper and perhaps destructive prescriptions for individual stands, and an uneven flow of timber from forests as a whole. If a constant supply of timber is a requirement of management, premature cutting in stands may be needed to meet supply demands, ultimately leading to depletion of the forest. Forest management planning for forests managed using polycyclic systems is a complex problem particularly when cutting cycles vary among management units. Use of a model such as the one presented here is a means for obtaining the data required for scheduling the flow of timber for a forest composed of highly variable stands.

CONCLUSIONS

The diameter class model presented here was shown to be a useful quantitative tool for assisting in the assessment of the sustainability of a specific silvicultural prescription. The model provides sufficient detail for examining the dynamics of individual diameter classes which permits a more comprehensive assessment of sustainability and stability. It also provides the means for determining appropriate cutting cycles for individual stands subject to yield restrictions which is an important part of both stand-specific and forest wide management. Practising foresters should find the modelling approach useful in the design of conservative management practices while awaiting improved data on the growth and yield of managed tropical forests.

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APPENDIX A. *Data Used to Derive the Diameter Growth Equation*

DBH (cm)	% Bart	Mean Annual Growth (cm)
7.5	6.7	.19
15	6.7	.30
25	6.7	.45
35	6.7	.40
45	6.7	.46
7.5	43.3	.29
15	43.3	.56
25	43.3	.47
35	43.3	.79
45	43.3	.53
7.5	76.7	.45
15	76.7	.95
25	76.7	.87
35	76.7	.57
45	76.7	.34
17.5	10.4	.28
22.5	10.4	.25
27.5	10.4	.29
32.5	10.4	.35
42.5	10.4	.35
47.5	10.4	.33
17.5	17.1	.38
22.5	17.1	.28
27.5	17.1	.45
32.5	17.1	.51
37.5	17.1	.51
42.5	17.1	.57
47.5	17.1	.46
52.5	17.1	.45
57.5	17.1	.46
67.5	17.1	.25