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SIMPLE METHODS FOR CALCULATING MINIMUM DIAMETER AND SUSTAINABLE YIELD IN MIXED TROPICAL FOREST

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Methods are described for calculating optimum felling diameter for timber production and the sustainable yield with non-equilibrium diameter distributions on the basis of tree growth and mortality data from permanent sample plots.

Optimum diameter is calculated by calculating the cumulative age and volume of the survivors from a regenerating cohort, to derive a mean annual increment per 100 seedlings (MAI%). The maximum MAI% represents an optimum felling diameter for timber production. For three species in Ghana (*Guarea cedrata, Khaya ivorensis, Triplochiton scleroxylon)* this optimum appears to be about 60 cm diameter. Sustained yield is calculated by an iterative method using a spreadsheet package. Inventory data are organized by classes whose width is the time of passage through one felling cycle. The survival to maturity is calculated for each class. A fraction of each class may be retained and accrued to later cycles. The iterative calculation from trial values of sustainable yield derives suitable retention values for each class. The method is simple to operate in practice and requires only basic or assumed growth data.

INTRODUCTION

There is increasing interest in the use of complex simulation models to plan and manage tropical mixed forest. A range of techniques are reviewed by Vanclay (1992). However, often the data available, and the actual possibilities of enforcing control of management in the forest, do not justify the use of complex methods. The classical methods for calculation of yields and control of felling, developed for selection forests in Europe, remain applicable as a basis for deriving management regimes (e.g. Knuchel, 1953; Jack, 1960). These methods certainly have limitations, in that they ignore the interaction of stand density and growth, and the propensity for increases in felling damage and associated mortality with heavier logging (Tang, 1976). Nonetheless, simple methods have an important role in reviving positive stand management practices in the selection forests of the tropics. They form a bridge between the situation in which there is no effective management or control of logging, and one in which sophisticated analyses based on simulation models and linear programming are used to regulate felling (e.g. Usher, 1966; Buongiorno & Michie, 1980; Buongiorno & Lu, 1990). The introduction of control procedures and log accounting should not have to await the completion of such sophisticated research, but can be introduced effectively on the basis of some straight-forward analyses of permanent sample plot data or presumed growth and mortality rates.

This paper describes some methods that can be applied given a knowledge of average tree growth and mortality rates to estimate the optimum minimum felling diameter for maximum production, and to estimate sustainable levels of felling over several cycles given irregular and non-equilibrium diameter distributions. The techniques are exemplified using permanent sample plot data from Ghana.

GROWTH AND MORTALITY RATES FROM PERMANENT SAMPLE PLOT DATA

Between 1970 and 1981 some 855 permanent sample plots were established in Ghana's selection-managed tropical high forests, according to the procedures described by Baidoe (1968). Of these, 651 plots were remeasured after approximately 5 years, and 396 plots measured again 10 years after establishment. The plots were 1-ha units, 100 x 100 m, subdivided into twenty five 20 x 20 m quadrats. On each quadrat, 2 trees were selected for permanent marking and measurement. Diameter at breast height or above buttress, crown illumination according to Dawkin's classification (Dawkins, 1958; Alder & Synnott, 1992), and a count of competing basal area were recorded for each tree.

A sub-set of this data, comprising 295 plots, was analyzed by the author between 1989 and 1990 as part of a study for the Ghana Forestry Department and UK Overseas Development Administration to develop a management model for the tropical high forest in Ghana (Alder, 1990). In that report, it was noted that the competing basal area showed no significant correlation with tree increment, whereas there were highly significant relationships with tree diameter and crown illumination.

For the present paper, the data are summarised in the format shown in Table 1. The species codes shown are according to the following list:

Code	Species	Code	Species
ANT	*Antiaris toxicaria*	KI	*Khaya ivorensis*
EA	*Entandophragma angolense*	MAN	*Mansonia altissima*
EC	*Entandophragma cylindricum*	NES	*Nesogordonia papaverifera*
EU	*Entandophragma utile*	P	*Piptadeniastrum africanum*
GC	*Guarea cedrata*	TRI	*Triplochiton scleroxylon*
GE	*Guibourtia ehie*	TUR	*Turraeanthus africanus*

The growth and mortality figures shown in Table 1 are comparable to those given by Mervart (1972) for similar species in western Nigeria. Diameter increment is typically small in the lowest size classes, rises to a maximum, and then falls again for the largest trees. This probably reflects the interaction of two factors in an uneven-aged stand. Firstly, the smaller trees are more heavily shaded, and therefore will grow more slowly. As they increase in size, they have more access to light, and the growth rate increases. On the other hand, the large trees are also the oldest, and increment tends to decline with age given equal competitive status.

Table 1. Growth and mortality rates of some high forest species in Ghana.

Species	Parameter	<---------------- Diameter class (cm) ---------------->						
		0-10	0-20	20-30	30-40	40-50	50-60	60+
ANT	No. trees	108	168	118	58	30	22	76
	D-inc (mm yr^{-1})	1.19	2.53	2.64	4.04	6.26	5.79	7.12
	Mort (% yr^{-1})	4.63	1.38	1.42	1.55	0.67	0.76	1.47
EA	No. trees	201	253	166	71	19	16	31
	D-inc (mm yr^{-1})	1.51	2.10	2.18	3.91	3.90	5.28	4.25
	Mort (% yr^{-1})	3.08	0.85	1.26	0.37	1.25	3.56	4.20
EC	No. trees	202	204	142	48	35	20	65
	D-inc (mm yr^{-1})	1.59	2.24	3.70	5.97	6.61	6.54	5.70
	Mort (% yr^{-1})	1.45	0.50	0.82	0.37	0.65	0.00	3.58
EU	No. trees	157	91	46	13	6	3	15
	D-inc (mm yr^{-1})	2.01	3.25	3.75	4.92	10.07	12.53	5.83
	Mort (% yr^{-1})	2.38	0.85	0.65	0.83	1.67	0.00	1.41
GC	No. trees	1,697	545	191	62	41	16	16
	D-inc (mm yr^{-1})	1.14	2.68	3.40	5.18	4.87	3.67	4.30
	Mort (% yr^{-1})	3.29	1.60	0.85	1.46	0.94	4.67	1.25
GE	No. trees	294	121	41	22	19	15	21
	D-inc (mm yr^{-1})	1.44	2.39	3.80	3.59	4.67	3.62	1.31
	Mort (% yr^{-1})	2.14	0.59	1.49	2.78	0.53	1.41	3.49
KI	No. trees	229	77	53	27	16	14	37
	D-inc (mm yr^{-1})	1.40	3.46	4.62	7.63	7.84	5.83	6.09
	Mort (% yr^{-1})	5.16	0.87	2.84	1.98	1.52	2.00	5.23
MAN	No. trees	281	73	67	53	69	26	9
	D-inc (mm yr^{-1})	2.17	4.06	4.73	3.79	3.41	2.18	1.68
	Mort (% yr^{-1})	3.89	2.22	0.60	1.97	1.36	2.05	3.70
NES	No. trees	1,339	353	281	156	82	45	11
	D-inc (mm yr^{-1})	1.37	4.03	3.77	3.69	3.99	3.41	2.77
	Mort (% yr^{-1})	3.47	0.77	1.05	1.07	0.46	1.73	0.00
P	No. trees	356	281	150	65	41	22	44
	D-inc (mm yr^{-1})	2.30	4.63	6.21	8.52	8.40	9.37	9.56
	Mort (% yr^{-1})	4.26	2.33	2.18	0.65	1.08	2.00	0.83
TRI	No. trees	374	280	233	152	136	104	172
	D-inc (mm yr^{-1})	5.14	9.04	8.40	8.56	7.19	6.35	5.96
	Mort (% yr^{-1})	3.16	0.49	1.11	0.83	1.21	0.93	1.35
TUR	No. trees	21	54	54	68	55	44	12
	D-inc (mm yr^{-1})	5.25	4.64	3.52	3.65	3.18	3.68	5.13
	Mort (% yr^{-1})	6.83	1.46	1.60	2.58	1.43	0.00	0.00
ALL	No. trees	5,259	2,500	1,542	795	549	347	509
	D-inc (mm yr^{-1})	1.72	3.81	4.46	5.47	5.51	5.23	5.91
	Mort (% yr^{-1})	3.38	1.20	1.22	1.18	1.01	1.46	2.15

Mortality shows a different pattern. It is highest for the smallest trees, declines into the middle size classes, and then appears to rise again for the larger sizes. It is not clear from the data whether the increase in mortality is a genuine effect, or possibly a confounding with harvesting of mature trees. The plot records are somewhat ambiguous, simply recording disappearance of the tree without clear attribution of cause. However, it will be noted that species such as GE, for which there is little commercial demand, also show this effect, whilst TRI, which is in heavy demand, does not.

Figure 1 contrasts the increment patterns for three species, TRI, KI, and GC. TRI is a light-demanding species that may be almost classified as a pioneer. KI is a non-pioneer light-demander (NPLD), according to the terminology of Hawthorne (1990), whilst GC is a typical shade-bearing tree. There is not necessarily any strong correlation between ecological guild and the growth and mortality rates, but it does provide some rational basis for assigning presumed growth data to the many species for which no observation exist when attempting to make yield projections. In particular the class of non-pioneer light-demanders includes the majority of forest tree species, and can encompass a wide range of growth behaviour. It would be useful to consider possible sub-divisions of this guild in ways that may correlate with growth.

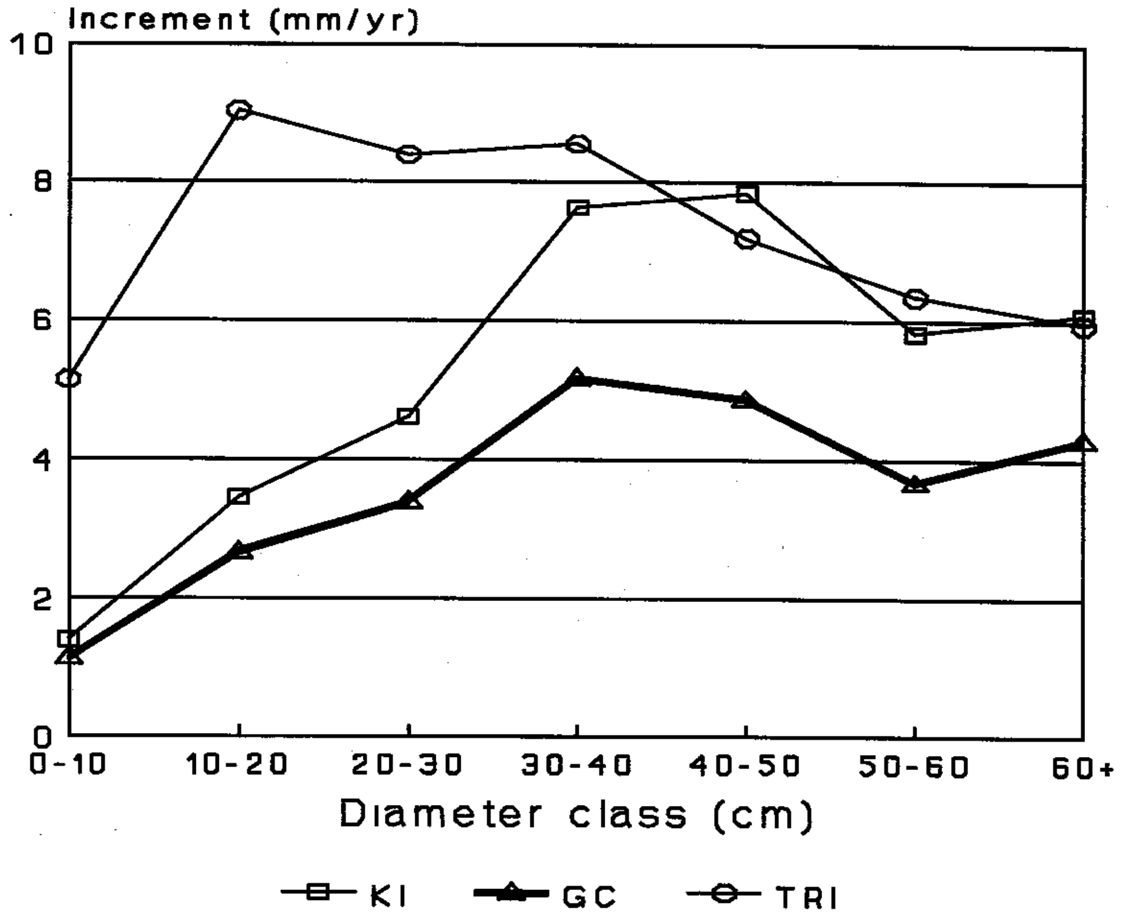

Figure 1. Pattern of diameter increment contrasted for three species.

Figure 2 shows the mortality patterns of the same three species. There is much more variability in mortality than increment, and to present a clearer picture, the average trend line is shown for all species (see ALL in Table 1).

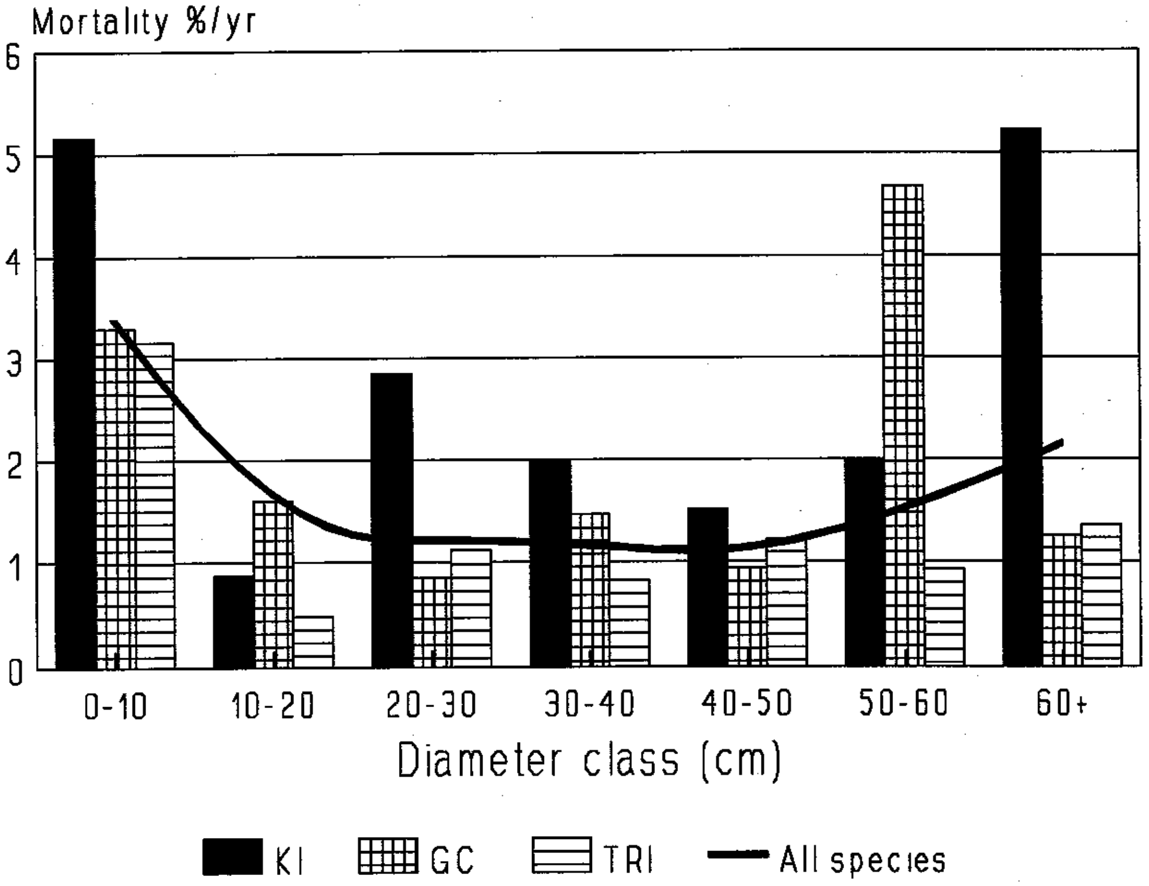

Figure 2. Mortality rates for three species, with trend line for all species.

FELLING GIRTH LIMITS FOR MAXIMUM PRODUCTION

It is possible from the data in Table 1 to calculate the felling girth limits that are appropriate for a given species in order to maximize bole volume production, using simple spreadsheet methods. The example calculations are shown in Table 2. In this, the pooled species mortality rates are used. Individual species mortality rates are based on data that is too limited and is particularly uncertain for the largest size classes.

The calculations are directed at calculating mean annual increment for a cohort of 100 seedlings (MAI%). This is analogous to MAI in a plantation crop, but the production will vary according to initial regeneration success. The diameter which maximizes MAI% represents an efficient maximum size to which the species should be grown. Beyond that size, reduced growth and natural mortality implies that retention of the trees will diminish the productivity of the forest as a whole. Productivity, in this context, assumes timber production to be the primary goal; there may be other, non-timber benefits that require larger sized trees to be retained.

Table 2. Estimation of optimum diameter from increment and mortality data.

Spp	Diam. class upper bound, cm	10	20	30	40	50	60	70	80	90
	Tree volume table, bole m^3	0.07	0.34	0.83	1.56	2.54	3.80	5.33	7.16	9.27
KI	*Khaya ivorensis*									
	Increment (mm yr^{-1})	1.40	3.46	4.62	7.63	7.84	5.83	6.09	6.09	6.09
	Mortality (% yr^{-1})	3.38	1.20	1.22	1.18	1.01	1.46	2.15	2.15	2.15
	Time of passage	71	28	21	13	12	17	16	16	16
	Cumulative age	71	99	120	133	145	162	178	194	210
	Cumulative % survival	8.70	6.21	4.80	4.11	3.64	2.83	2.00	1.41	1.00
	MAI% m^3 yr^{-1}/ 100 seedlings	0.009	0.021	0.033	0.048	0.064	0.066	0.060	0.052	0.044
TRI	*Triplochiton scleroxylon*									
	Increment (mm yr^{-1})	5.14	9.04	8.40	8.56	7.19	6.35	5.96	5.96	5.96
	Mortality (% yr^{-1})	3.38	1.20	1.22	1.18	1.01	1.46	2.15	2.15	2.15
	Time of passage	19	11	11	11	13	15	16	16	16
	Cumulative age	19	30	41	52	65	80	96	112	128
	Cumulative % survival	52.03	45.56	39.81	34.93	30.62	24.55	17.34	12.25	8.65
	MAI% m^3 yr^{-1}/ 100 seedlings	0.202	0.514	0.802	1.046	1.198	1.166	0.963	0.783	0.627
GC	*Guarea cedrata*									
	Increment (mm yr^{-1})	1.14	2.68	3.40	5.18	4.87	3.67	4.30	4.30	4.30
	Mortality (% yr^{-1})	3.38	1.20	1.22	1.18	1.01	1.46	2.15	2.15	2.15
	Time of passage	87	37	29	19	20	27	23	23	23
	Cumulative age	87	124	153	172	192	219	242	265	288
	Cumulative % survival	5.02	3.21	2.25	1.80	1.47	0.99	0.60	0.36	0.22
	MAI% m^3 yr^{-1}/ 100 seedlings	0.004	0.009	0.012	0.016	0.019	0.017	0.013	0.010	0.007

In Table 2, the calculations proceed as follows:

- The diameter class upper bounds, increment, and mortality % are entered as data into the spreadsheet using the PSP summaries shown in Table 1.

- The volumes equivalent to each diameter class upper bound are entered from a volume equation of table appropriate for the species. In this example, the general bole volume equation of Wong (1989) was used, namely:

$$\text{Bole volume} = 0.0004634 \times \text{Tree diameter}^{2.201}$$

- Time of passage is calculated as:

$$(\text{Class upper bound} - \text{class lower bound})/(\text{Increment in cm})$$

- Cumulative age sums the time of passage for a class with all preceding classes to give the mean age at which the tree reaches a given diameter.

- Cumulative % survival gives the number of trees which survive to the age corresponding to the class upper bound, from an initial cohort of 100. It is calculated as:

$$(\%\ \text{survivors in preceding class}) \times (1 - m\%)^{\text{Time of passage}}$$

where m% is the class annual mortality as a fraction (e.g. 3.1% is 0.031).

- MAI% is the mean annual increment achieved by a cohort of 100 seedlings and calculated as:

(Cum. % survival) x (tree volume) ÷ (Cumulative age)

Figure 3 plots the MAI% for the three species shown in Table 2. It will be noted that different axes are used for TRI and for KI and GC, as the former species shows much faster growth and consequently greater total survival to a given age or diameter. Conceptually, this measure of MAI is fully equivalent to that used in determining the optimum rotation for a plantation crop. Diameter is treated as a direct function of age; it follows that expressing a felling regime in terms of diameter limit is equivalent to using a rotation age for a crop.

The principal weakness of this approach is that there are interactions of growth rate with stand density, and of mortality with logging damage. However, for moderate levels of extraction, and with a matrix of non-commercial species that effectively buffer variations in stand density with felling regime, these factors are unlikely to greatly influence the felling regime. The diameter limits suggested by this simple method are similar to those that appeared optimal in trials using the GHAFOSIM simulation model (Alder, 1990). It is however, a good deal easier for decision-makers at the political level to absorb the logic of the simpler method. A complex simulation model is an esoteric entity, which the decision-maker must accept or reject in its entirety.

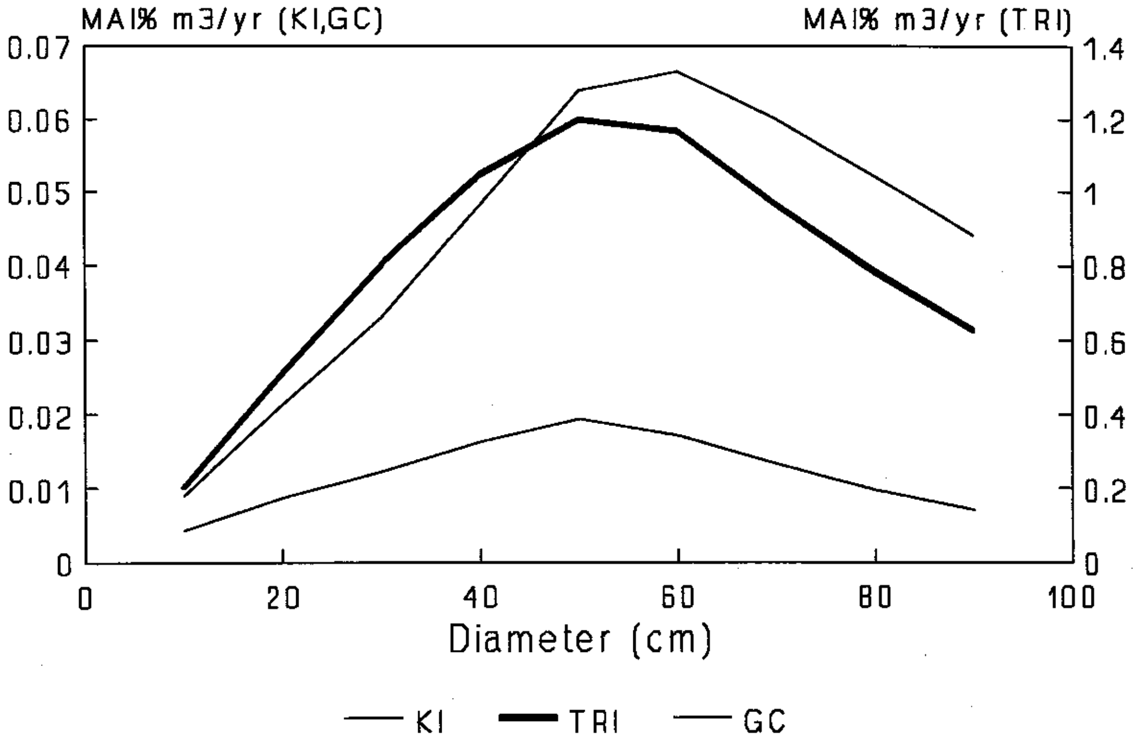

Figure 3. Maximum mean annual increments of regenerating cohorts occur at about 60 cm diameter for TRI, KI and GC.

FELLING CYCLE AND SUSTAINABLE YIELD

There is no obvious way to determine optimum felling cycle from tree growth rate data alone (Leuschner, 1984). If factors relating to felling damage and regeneration are considered, together with the ecology of major crop species, then long cycles combined with heavy felling (a uniform system) may be preferred, as argued by Dawkins (1958) and widely adopted in the management of dipterocarp forest. On the other hand, if the objective is to create the minimum change in the ecosystem, frequent light fellings (a polycyclic system) would appear preferable. These imply short felling cycles. Buongiorno and Lu (1990) have shown how given economic objectives and data, and a growth model formulated as a modified Usher matrix (Usher, 1966; Buongiorno & Michie, 1980) it is possible to determine an optimum cutting cycle through the use of linear programming. This approach requires more extensive hard data than is usually available in the tropical situation.

An important factor that should determine the felling cycle in many tropical countries is the availability of resources for forest management activities in the field. The longer the felling cycle, the smaller the area that must be controlled each year under strict supervision (ie. the smaller the annual coupe), and hence the more effectively resources can be used.

In Ghana, a 40-year felling cycle has been adopted on the basis of various considerations. Given such a prior decision as to felling cycle, it is possible, from growth rate and mortality data, to develop simple spreadsheet methods to show how particular forest reserves should be managed to give a sustainable yield.

It can be seen by inspection from Table 1 and Fig. 2 that an annual diameter increment of 5 mm is a conservative average figure for many economic species above 20 cm diameter. Given a 40-year felling cycle, this rate of increment corresponds to diameter classes of 20 cm. By compiling inventory data into 20-cm classes, therefore, one obtains an impression of the yields of trees that will be available in the present and succeeding felling cycles.

The numbers of trees in the smaller classes need to be discounted by the anticipated mortality rate. As a reasonable approximation, annual mortality for trees of 20 cm or above may be taken as 1.25%. This corresponds over a 40-year cycle to $(1-0.0125)^{40}$ or 60.5% survival.

Table 3 shows a typical pattern of inventory data for a group of commercial species in natural tropical forest grouped into 20-cm classes. The inventory data is taken from published tables for Tinte Bepo Forest Reserve in Ghana (Owen, 1987), and includes all *Entandophragma, Khaya* and *Tieghemella* species. The table shows the actual numbers currently observed, and then the numbers discounted to allow for mortality prior to maturity. Exploitation is assumed to occur above 60 cm. (This is based on the preceding analysis of optimum diameter, and not on current felling diameter regulations in Ghana, which are 110 cm for these species).

Table 3. Calculation of sustainable yield, using data for class Ia species, Tinte Bepo Forest Reserve, Ghana

Felling cycle	+80 yrs	+40 yrs	Present	OverSize
Present diameter class	20-40	40-60	60-80	80+
Stocking (N km^2)	289	39	11	35
Survival %	36	60	100	100
Final stocking (N km^2)	104	23	11	35
Accrual from last cycle	0	8	NA	NA
Harvest	32	32	8	24
Retained trees (N km^2)	72	0	3	11

The table is organized by diameter class columns, each of which corresponds to a single felling cycle. The stocking is derived from sample inventory data. The survival % row uses the average 60% survival over a 40-year period to calculate net survival to harvest. For the 20-40 cm class, with 80 years to maturity, this net survival will be approximately $(60\%)^2$ or 36%. For the currently mature and over-sized trees, survival to harvest is 100% as they are currently available for harvest.

The survival % is applied to the inventory stocking to give a final stocking at the time of harvest. This fluctuates considerably between felling cycles, and it is desirable to calculate a constant number of trees to be removed that will give approximately uniform production for each cycle. This is achieved through an iterative trial-and-error technique in the spreadsheet, using the last 3 rows of the table. The grey-shaded cell in Table 3 is given by the user; all other data relating to trees harvested, retained, and accrued from previous stocks depend on it.

In the spreadsheet, the harvest is copied across from the year 80 (third cycle) harvest entered by the user as a guess at the sustainable yield (Y). In the two right-most columns, for the present cycle and the stock of over-mature trees, the harvest Y is distributed proportionately between the two columns, so that some current stock and some over-mature stock will be removed to make up the desired number of trees. The retained trees (R) in each column are calculated as the final stocking, plus any accruals from the previous cycle, minus the harvest Y.

The accruals (A) comprise the retained trees from the preceding cycle (i.e. the column to the right), reduced by the survival factor of 60%. These are the trees which were retained at the previous cycle and carried over to the next cycle.

By incrementing Y the spreadsheet will recalculate the values of R and A until a state is reached where the number of retained trees in a given cycle becomes negative. At this point, the given value of Y in the shaded cell is reduced fractionally until R just becomes zero. This will represent the maximum sustainable yield.

The same method can be applied using volumes rather than tree numbers, but in this case, control in the field should be applied on a volume rather than stocking basis. In calculating volumes, the volume table for mature sizes (60-80 cm) should be used, not that for the current size of a class; however, for over-sized trees, actual volumes should be used. Because some individual over-sized trees may contribute very large volumes, the results with volume control may be difficult to translate into field instructions.

The method is predicated on the assumption that stocking from the inventory will be uniform between periodic felling blocks. If there are substantial variations between blocks, then the levels of harvest/retention derived from this calculation may still lead to considerable fluctuations in yield from block to block. A more perfect analysis requires a linear programming formulation or simulation model which takes into account the different stockings in each block.

The method is quite general, and can be used for planning to any diameter limit and felling cycle. With faster growth rates or shorter felling cycles, then narrower diameter classes would be used.

APPLICATION TO THE CONTROL OF YIELD

The method is intended to be applied in the formulation of working plans for natural forest, and requires as an input a management level inventory which should be able to give stocks of commercial species above 20 cm diameter to a reasonable precision (e.g. ±10%) for each diameter class and periodic felling block.

It is not necessary to perform 100% stock surveys to achieve viable felling control and conformity to the plan by contractors. Figure 4 shows the general procedures that are required. The schedule of removals and residual stems for a periodic block is calculated from the inventory and the PSP data, using the methods described above or some more elaborate and possibly more precise procedure (such as matrix models/linear programming).

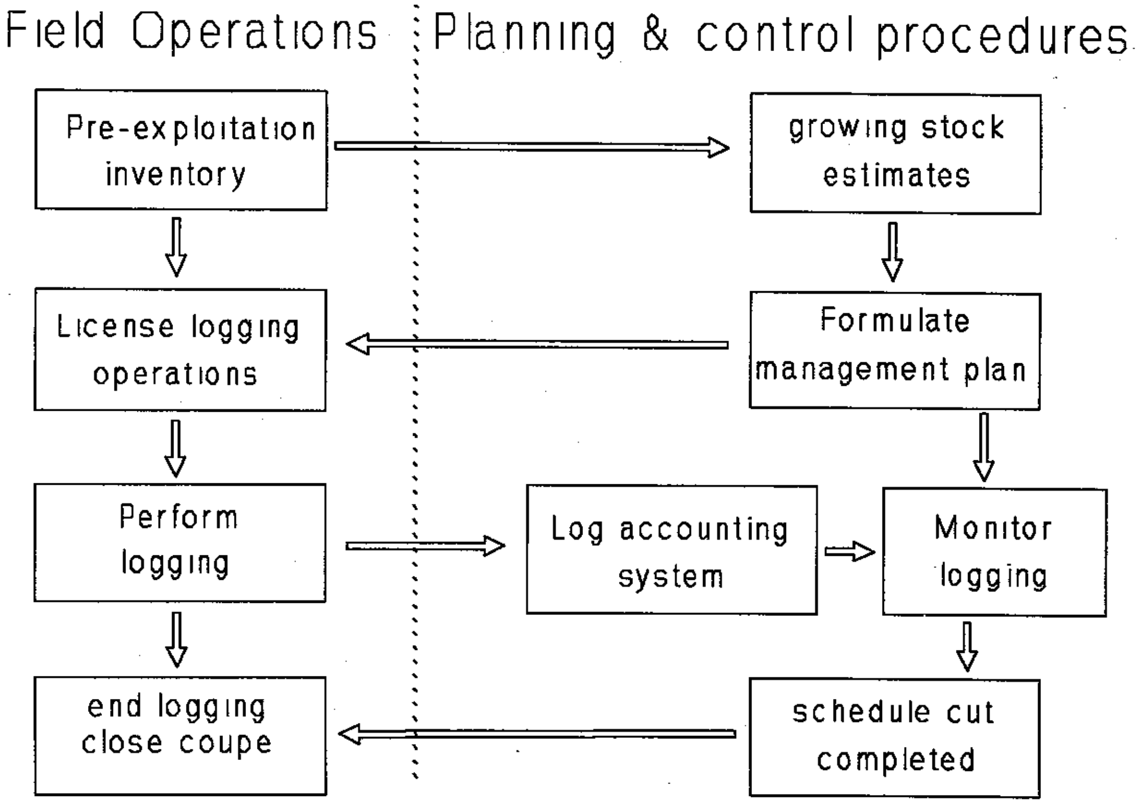

Figure 4. System for planning and control of logging operations.

The felling plan should be classified by species, but in groups that equate to general levels of demand. If species for which there is a high and inelastic demand such as *Khaya ivorensis* are grouped with species of weak and variable demand such as *Piptadeniastrum africanum* within a single aggregate figure, then loggers will inevitably concentrate on the former until exhaustion, without the control system being able to exercise any regulation. On the other hand, too many species groups will make the plan too complex to operate effectively in practice. It is probable that four to six commercial groups reflecting different levels of demand represents an optimum compromise between control and complexity.

During felling, a log accounting system is strictly operated, in which all logs removed are enumerated and measured. This needs to be done by an independent organization specializing in surveillance and audit operations in order to reduce fraud and malpractice. The log accounting requires measurement and tagging at log landings, and provides a full and current record of removals by felling coupe.

From the record of removals, a comparison is made with the planned cut from the inventory. As it approaches permitted levels for each species group, the contractor is given notice that the coupe will be closed; with final closure being completed as the cut reaches the scheduled level. A new coupe is then opened, and the cut-over coupe is closed to logging for the period of the felling cycle.

CONCLUSIONS

The simple methods of calculating optimum felling diameter and sustainable yield described in this paper can form the basis for effective management planning in natural tropical forest. They are appropriate where PSP data is of limited quantity and quality, and can be progressively enhanced to higher levels of complexity and sophistication as better data becomes available. The linkage between planning and control, through pre-exploitation inventory and rigorous log accounting, is an essential one for the meaningful operation of any type of selection system in the natural forest.

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