TIMBER YIELD DETERMINATION AND ALLOCATION IN SELECTIVE LOGGING SYSTEM IN GHANA

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ABSTRACT

Timber yield determination and allocation in the selection forest of Ghana has been on an interim basis due mainly to paucity of stand increment and mortality data. The current method, which is also an interim measure, was developed at the Forestry Planning Office in 1990 to replace the minimum felling diameter limit introduced in 1970 to salvage the over-mature trees over a period of 15 years. This paper reviews the mathematical logic of the current interim yield formula. The formula is modified by considering current data on mortality, felling cycle and time of passage. The idea of optimizing yield by number of stems per hectare is also applied in this revised version. The study reveals that one important premise in the derivation of the current interim formula was put in an incorrect algebraic form, resulting in an over-allocation of yield for individual species. A comparative analysis of the original and revised forms of the yield formula indicates that the latter is more effective in ensuring sustainability and is easily adaptable to different forest types, stocking levels and management prescription of felling cycle. In the revised form, the effect of the ratio between felling cycle and time of passage (F/P) on yield is very significant. To fine-tune the revised form, more accurate data on the time of passage for the various species of different diameter classes in different forest types are essential requirements.

Keywords: Timber, Yield, Formula, Selection, Forest

INTRODUCTION

Forest managers in Ghana have been grappling with the issue of sustaining yield for almost 50 years. Between 1950 and 1990, four different methods of determining yield were used in regulating timber harvesting in reserved forest in order to sustain supply and also to conserve the environment.

The first method introduced in 1950 prescribed for harvesting all stems of economic trees above a minimum felling diameter (Anon, 1959). The minimum felling diameter limit defines the maturity size of a species for timber production. At that time few species were harvested for timber and lower felling diameter limits were used (Adam, 1996). However, over-dependence on few species and localized felling depleted *Khaya ivorensis* in the south western portion of the forest zone (Taylor, 1960).

Two other methods introduced between 1961 and 1970 prescribed yield based on annual basal area or stem number recruitment into the exploitable diameter class (Adam, 1989). The lack of adequate growth data made the method unreliable. For instance, 10 years after their application the logged-over forests contained a lot of over-mature trees (Baidoe, 1976). The tendency for the two methods to retain more over-mature trees, especially in an unlogged forest during the first cycle, has been confirmed by Adam (1989).

The accumulation of over-mature trees necessitated the application of a fourth method in 1972 (Asabre, 1987). This method, like the first one, prescribed harvesting all economic trees above a specified minimum diameter. This was considered silviculturally expedient, being a cleaning exercise as well as a thinning operation to reduce mortality among suppressed under-storey trees and induce rapid growth of saplings and poles.

The spectrum of economic species broadened to about 36 in 1970. The removal of all trees above the felling limit from 1972 to 1987 resulted in high felling intensities in some forest reserves, leading to drastic decline in stocking across all diameter classes (Adam, 1989). For example, 10 years after a harvesting intensity of more than three mature trees per hectare in the Afram Headwaters Forest, the stocking of stems below 50 cm dbh and above 70 cm dbh decreased by 50 and 40% respectively (Adam, 1989). Based on these facts and data collected under the Forest Resources Management Project sponsored by Overseas Development Administration of UK, the yield regulation was modified in 1991. The team of foresters, including the author of this paper, who developed this 'interim' yield formula did not stay long enough on the project to properly document and upgrade the methodology as anticipated.

This paper presents the first derivation of the formula and a review in the light of comments and suggestions that have come during the period of its application. The first part of the paper discusses the derivation and application of the interim formula while the second part presents a new approach for upgrading it.

FIRST DERIVATION

(a) Residual Crop

Residual crop (R) was expressed as the sum of the number of stems of the replacement crop (X) and remaining stems of the exploitable class after the yield has been taken, that is (Z-Y).

Therefore,

$$R = X + (Z-Y) \ldots\ldots (1)$$

Selection forest consists of regeneration cohorts or series of diameter classes that develop progressively from lower into higher stem sizes over time. Under sustainable forest management practices, it is expected that favourable conditions will be created through logging and silvicultural operations for a continuum of regeneration of the desirable species. On these premises two assumptions were made: that the application of an appropriate felling diameter limit will ensure the removal of only trees that have reached maturity or utilizable sizes; that the adoption of an appropriate felling cycle will also guarantee the availability of continuous batches of exploitable sizes and number of stems of given economic species in the subsequent cycles.

Against this background, the interim yield formula was developed to determine the number of stems of exploitable diameter class for a particular species within a compartment that can be felled in one felling cycle. The formula was also to ensure that adequate number of productive trees are retained for natural regeneration, environmental protection and forest increment of valuable timber. The formula in its final form was given as:

$$Y = Z - \{(r.Z)/(1-m)\} + Xm$$

where

Y = Yield or number of stems to be felled for a given species in a compartment

Z = Number of stems of a given species in the exploitable diameter classes

X = Number of stems of a given species in the diameter class immediately below the felling diameter

r = Retention percent of mature stems (expressed in decimal)

m = Mortality percent during the felling cycle (expressed in decimal).

Using the prevailing minimum felling diameter as the divide, the stem population of each species was put into two groups, X and Z as already defined. The X group was considered as the replacement crop and the Z constitutes the group from which the yield is to be taken.

Based on the above management concepts and assumptions, the first yield formula was derived through the following procedure.

It was also seen as comprising all the replacement crop (X) and a certain percentage of the exploitable class (r%.Z)) retained for ecological purposes such as seed trees, and for biodiversity conservation. This was represented in the equation

$$R = r.\,Z + X \ldots\ldots\ldots (2)$$

(b) Yield

The first form of the yield equation was obtained from equation (1) by re-arrangement or change of subject.

$$Y = X + Z\text{-}R \ldots\ldots\ldots\ldots (3)$$

(c) Mortality

Consideration was given to the fact that the number of retained or residual crop will decline as a result of natural mortality. To ensure an adequate number of surviving trees for the next cycle, the residual crop as given in equation (2) was increased to account for future mortality. This operation was done by dividing the initial stem population by the survival percent (1-m) over a specified period (f) of felling cycle.

Quoting from Adam (1991), equation (2) so transformed and simplified becomes:

$$R = (r.Z/1\text{-}m) + X(1\text{-}m) \quad \ldots\ldots\ldots(4)$$

When equation (4) was substituted in equation (3) the yield equation was finally obtained as:

$$Y = Z + X - \{(r.\,Z/(1\text{-}m\,) + X\,(1\text{-}m)\}$$

$$= Z - \{(r.\,Z)/(1\text{-}m)\} + X\,m \ldots\ldots.(5)$$

where r and m were given in decimals.

Equation (5) was taken as the general formula for yield calculation. The values of r and m were fixed pragmatically. A 20% mortality over 40 years as used by Kinloch (Anon, 1961) was adopted.

Retention (r) of 40 and 60% were considered adequate for the stocking conditions in moist and dry forests respectively. This resulted in two different formulae.

For the moist forest the formula became

$$Y = 0.5Z + 0.2X \ldots\ldots\ldots\ldots (6)$$

And for the dry or open forest the formula became

$$Y = 0.25Z + 0.2X \ldots\ldots\ldots\ldots (7)$$

REVIEW

The authors of the interim formula recommended its review within 5 years of its introduction when the permanent sample plot (PSP) data was expected to be analysed to provide current information on mortality and increment.

The present form of this formula has been criticised on several counts. One main query is on the adjustment operation done on equation (2) to obtain equation (4). The idea was to increase the retention on Z to take account of mortality over the felling cycle. Thus the operation r%. Z/(1-m) is correct. What this means is that the initial retention (r%. Z) represents only (100-m)% of the number needed. To get the actual number it must be divided by (1-m). However, the value of X cannot be increased by the same method. X can only be increased by recruitment from lower diameter class but this is a future biological event that cannot be done by a management prescription as done on Z. Multiplying X by (1-m) means reducing it to account for mortality over a specific period in future but this was not the intended operation. If the foregoing correction is acceptable, then the formula following from equation (4) will be:

$$R = (r. Z)/(1-m) + X \ldots\ldots\ldots (4.1)$$

and substituting (4.1) in (3) the final form should be:

$$Y = Z + X - \{(r.Z)/(1-m) + X\}$$

$$= Z - \{(r.Z)/(1-m)\} \ldots\ldots (5.1)$$

where

R = Total number of exploitable trees to be retained
r = the assumed percentage of retention of exploitable trees
1-m= the adjustment factor on the retention to make allowance for mortality during the felling cycle
Y = Yield or actual number of trees to be felled
Z = Total number of stems in the exploitable class
X = Total number of stems immediately below the minimum felling diameter

Putting in the same values for r and m,

Y = 0.5Z for moist forests; and
Y = 0.25Z for dry forests.

The second query is on mortality. The 20% used over a 40-year cycle means an annual mortality of 0.5% which is lower than has been determined from the PSP data.

Vanclay (1993) first reviewed the implication of the interim formula on timber resource sustainability. He pointed out that when X is equal to or greater than Z, very little or no mature tree would be retained for seed trees and arboreal habitat. He suggested that the ratio between successive diameter classes (i.e. de-liocourts quotient (Q), and stem movement into higher diameter class should be investigated and incorporated into the yield formula. He also observed that the formula would ensure sustainability only when Q is greater than 3.4, a condition which may also occur rarely. Besides, when the list of exploited species increases, the formula would give more trees to be harvested than can be sustained by the total forest increment or recruitment rate.

These observations and criticisms necessitated the revision of the formula, and a new approach leading to the revision of the interim formula is therefore outlined.

New Approach

The capability of the residual crop to provide a sustainable stocking level in the next felling cycle is critically examined in the light of recent mortality data. The effect of the felling cycle, time of passage and the de-Liocourt Quotient (Q) in ensuring adequate movement of stems into the exploitable class before the next felling cycle is also examined. Finally, the formula is optimised by restricting the felling intensity in order to reduce the negative ecological impact of logging.

The re-examination of the relationship between the replacement crop (X) and the exploitable group (Z) raises an important question such as what population of replacement crop is required now to give at least the same number of exploitable trees in the next cycle as is available at the beginning of a current felling cycle? It is also important to know how fast the trees move from the replacement class into the exploitable class. The answers can only be provided from accurate mortality, increment and recruitment data.

However, it can be seen theoretically that at an annual mortality of m% and a felling cycle of f years, the present replacement crop (X) at the beginning of the next felling cycle will reduce to:

$X(1-m)^f$ (Alder 1990)

To achieve sustainable yield in (f) years time will therefore require that:

$$X(1-m)^f > Z \quad \ldots\ldots (8)$$

From the above a new equation can be formulated. It is logical that the residual crop (R) should always be:

$$R = AZ + X \quad \ldots\ldots\ldots (9)$$

where A is the % retention of the number of exploitable number of trees (Z).

The residual crop can also be determined as:

$$R = Z + X - Y \quad \ldots\ldots\ldots\ldots (10)$$

where Y is the yield of mature trees.

Substituting (10) in (9)

$$AZ + X = Z + X - Y$$

$$Y = Z - AZ \quad \ldots\ldots\ldots\ldots (11)$$

The retention factor 'A' depends on the optimum Q value, optimum number of seed trees per unit area, mortality and recruitment rates, which can only be determined through research. In the absence of such research findings, however, it is expected that the total residual crop (i.e. AZ + X) at any time should at least give the present Z value in (f) years time. So with mortality of m% per year and a felling cycle of (f) years,

$AZ + X$ will become

$AZ(1-m)^f + X(1-m)^f$ at the beginning of the next cycle and

$$AZ(1-m)^f + X(1-m)^f = Z \quad \ldots\ldots\ldots\ldots (12)$$

By change of subject it becomes

$$A = \{Z - X(1-m)^f\}/Z(1-m)^f \quad \ldots\ldots (13)$$

Substituting (13) in (11)

$$Y = Z - \{Z - X(1-m)^f/Z(1-m)^f\}Z$$

$$Y = Z - \{Z - X(1-m)^f/(1-m)^f\} \quad \ldots\ldots\ldots\ldots (14)$$

It is noted that the most important pre-requisite for a tree to become exploitable is the attainment of the minimum felling diameter. The ability of the replacement crop to attain the minimum diameter before the next felling cycle depends on the time of passage (p) which is a function of increment and diameter class width. The felling cycle should thus be long enough to ensure the movement of all or most of the trees in the X group into the Z group. This implies that at least the felling cycle should be equal to or longer than the time of passage. This consideration introduces another element into the yield calculation, the f/p ratio.

If the felling cycle is long enough to ensure movement of all trees from X to Z group, then:

$$f/p > 1$$

On the other hand, if a shorter felling cycle is used,

$$f/p < 1$$

In Ghana felling cycles have generally been shorter than the time of passage. For instance, in the 1960s most of the primary species had 30 years time of passage for stems above 50 cm dbh (Anon, 1961), but a 25-year felling cycle was applied.

Alder (1990), however, estimates that above 50 cm dbh, time of passage for pioneer species may vary between 30 and 64 years while shade bearers may range between 38 and 76 years. In the light of this, a 40-year felling cycle has now been adopted.

The ratio f/p can thus be introduced to constrain the yield. The formula may be modified to:

$$Y = f/p\{Z - \{Z - X(1-m)^f/(1-m)^f\}\} \quad \ldots (15)$$

YIELD ALLOCATION

Vanclay (1993) observed that the broadening of the economic species base will mean a direct increase in the yield per unit area.

To minimize harvesting disturbance to tolerant levels the harvestable yield will need to be constrained . This means that in the final analysis the felling intensity per compartment should not exceed a certain limit (N) such that:

$$\Sigma Y = f/p\ \{Z - (Z-X\ (1-m)^t/(1-m)^t\} < N \quad \text{..........} (16)$$

where N is the greatest felling intensity permitted that will not cause ecological damage or loss of biodiversity.

If the calculated total yield per compartment exceeds the permitted felling intensity (N), there will be the need for optimization. This can be done by proportionate allocation of the yields by the formula:

$Y_o = N.YA_i/\Sigma\ YA$

where Y_o = Optimized yield
YA_i = Actual yield of species (i) that may be taken or can be found in the forest
Σ YA = Sum of the actual yields of all species that may be taken
N = Optimum felling intensity

In order to fine-tune the yield formula, the optimum values of f and N will have to be determined through further research. The author is currently undertaking logging experiments to determine N in respect of all stem densities above 50 cm dbh. The p and m values are obtainable from permanent sample plot data, especially if assessments cover all forest types and species as is being done now in Ghana.

Felling intensity not exceeding three stems per hectare per felling cycle has been suggested (Hawthorne, 1993). This intensity gives an overall yield of nearly 384 stems in one compartment per felling cycle.This is based on the prescribed annual allowable cut of 1m³/ha by Alder (1989).

Verification

Yield is determined at compartment level for each species. The data for the yield calculation is the diameter class stem number density obtained from a 100% timber enumeration (locally called stock survey). The stock survey involves the measurement of dbh or above buttress diameter of all stems within the X and Z diameter groupings of each economic timber species occurring in the compartment (normally of size 128 ha or 320 ac).

The current and the revised formulae are applied to FIP class 1 timber species recorded in a stock survey of compartment 5 of Tano Offin Forest Reserve. The results are given in Appendix 1 and the summary is presented in Table 1.

Using an average annual mortality of 1% for larger stems (Alder, 1990) and the current felling cycle of 40 years, the yield from equation (14) will be given as:

$$Y = \frac{Z - (Z - 0.668972\ X)}{0.668972}$$

With an N value of 3 stems/per ha or 384 trees per compartment, the yield from compartments is optimized as :

$Y_o = YA_i/389 * 384$ for current formula
$Y_o = YA_i/230 * 384$ for revised formula

TABLE 1

Comparative total yield (number of trees per compartment) by the two formulae

Yield (Y)					
Current formula			*Revised formula*		
Yc	*YA*	*Yo*	*Yc*	*YA*	*Yo*
411.4	398	320.4	219.1	230	230.7

Yc = Calculated yield
YA = Actual yield that can be found in the forest
Yo = Optimized yield

The sustainability of the yield determined by these formulae is heavily dependent on the minimum felling diameter. The diameter limit should therefore be appropriated to define stem sizes that will give the maximum returns on investment and maintain a replacement crop that is also productive. Felling diameter limits of 50, 70, 90 and 110 are used in Ghana for various species. For similar species found in other West African countries, Ghana generally uses higher diameter limits (Adam, 1996).

Generally, the revised formula gives a lower yield. However, as can be seen from Appendix I, the yield for *E.angolense* and *C. giganteum* are more than the number of exploitable trees. The implication is that the number of trees in the X group now is more than adequate to give the same number of exploitable trees (as is available now) in the next felling cycle even if all the mature trees are felled. In the case of *C. pentandra* and *T. superba*, there is a negative yield. This means that though there is a good number of trees in the Z group, no felling can be allowed because the replacement crop is poor. These phenomena are explained by equation (8) where:

$$X\,(1-m)^f > Z$$

For example, in *E.angolense*

$18\,(1-0.01)^{40} > 11$, therefore all of Z can be removed now.

However, for *C. pentandra*

$$5\,(1-0.01)^{40} < 47$$
$$3.3 < 47$$

and therefore none of Z can be removed.

The relevance of the retention factor 'A' can also be verified from equation (13)

$$A = Z\text{-}X\,(1-m)^f/Z(1-m)^f$$

If we consider the stocking of *C. pentandra* which is poor now, the revised formula gives a zero yield now. Thus, more seed trees are retained for natural regeneration. In the next felling cycle the Z value is still maintained as follows:

$$A=47\text{-}5\,(1\text{-}0..01)^{40}/47(1\text{-}0.01)^{40}=43.65514/31.44168=13884$$

putting 'A' value in equation (12)

$$AZ\,(1-m)^f + X\,(1-m)^f = Z$$
$$1.388 \times 47\,(0.99)^{40} + 5\,(0.99)^{40} = Z$$
$$43.60959 + 3.34486 = Z$$
$$47 = Z$$

This means that by retaining all of the present stock of the Z, future stocking of exploitable trees is likely to improve in the next felling cycle.

It is also important to verify the effect of f/p on the yield. When f/p is 1, the yield by equations (14) and (15) will be the same. However, if f is changed the situation will be different. For instance, if the felling cycle is reduced to 25 years and the time of passage is 40 years, the yield of *T. scleroxylon* will become 80 trees under equation (14). This may not be acceptable under shorter felling cycle where disturbance should be very minimal. If the ratio f/p is applied as in equation (15), the yield will be reduced to 50 stems which is more acceptable.

When the formula is evaluated in terms of X/Z and f/p ratios, some interesting observations are made which provide important guidelines for its application. At an annual mortality of 1% and passage time of 40 years, the yields are presented as a percentage of Z in Table 2.

TABLE 2

Yields at different X/Z and f/p ratios expressed as % of Z

X/Z	*f/p*		
	<1	=1	>1
<1	<0.5	<0.5	<0.5
=1	<50	<50	<50
>1	<100	<100	<100

Thus, when X/Z is less than 1 it will not be economical to log, as the yield per unit area will be very low. In this situation logging will become economical only after a period longer than the time of passage. However, when X/Z is equal to or greater than 1, it will be ideal to operate with f/p < 1, so as to cause less disturbance.

CONCLUSION

The analysis has indicated that selective harvesting of timber trees from the natural forest can be effectively regulated by simple mathematical formula based on stem number stocking, mortality and time of passage. However, the yield can be more sustainable if appropriate felling cycle and diameter limits are applied. The optimization of the yield will help to re-allocate it among the species and also reduce felling disturbance.

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Appendix I

Yields for compartment 5 of Tano Offin South Forest Reserve (Pan Timbers Concession)

Species*	FLD	<FLD (X)	<FLD (Z)	Yield (Y) by stem numbers					
				Current formula			Revised formula		
				Yc	YA	Yo	Yc	YA	Yo
Alstonia boonei	110	8	1	2.1	1	0.96	7.5	1	1
Aningeria robusta	110	2	0	0.4	0	0	4	0	0
Ceiba pentandra	110	5	47	24.5	24	23.1	-18.3	0	0
Entandrophragma angolense	110	18	11	9.1	9	8.6	12.55	11	11
Entandrophragma cylindricum	110	3	5	3.1	3	2.9	0.5	0	0
Entandrophragma utile	110	2	0	0.4	0	0	4	0	0
Entandrophragma candollei	110	1	1	0.7	0	0	0.5	0	0
Khaya ivorensis	110	2	3	1.9	1	0.9	2.5	1	1
Khaya anthotheca	110	3	1	1.1	1	0.9	2.5	1	1
Milicia excelsa	110	3	4	2.6	2	1.9	1	1	1
Nauclea diderrichii	110	0	0	0	0	0	0	0	0
Parkia bicolar	110	9	4	3.8	3	2.9	7	4	4
Piptedniastrum africana	110	28	19	15.1	15	14.6	186	18	18
Chrysophyllum giganteum	70	1	5	2.7	2	1.9	-1.5	0	0
Pterygota macrocarpa	11	04	3	2.3	2	1.9	2.5	2	2
Triplochiton scleroxylon	110	109	102	72.8	72	6.9	58.5	58	58
Amphimas pterocarpoides	90	12	6	5.4	5	4.8	9	6	6
Chrysophyllum albidim	90	12	2	3.4	2	1.9	11	2	2
Daniella ogea	70	0	3	1.5	1	0.0	-1.5	0	0
Klainedoxa gabonensis	70	0	2	1	1	0.9	-0.9	0	0
Afzelia bella	70	0	4	2	2	1.9	-2.9	0	0
Albizia ferrugenea	70	0	6	3	3	2.9	19.1	0	0
Albizia zygia	70	31	24	18.2	18	17.6	3	19	19
Antiaris africana	110	5	4	3	3	2.9	76.3	3	3
Celtis midbraedii/zeneri	70	198	246	162.6	162	156	0	76	76
Cylicodiscus gabunensis	110	0	0	0	0	0	2	0	0
Rhodognaphalon brevicuspe	90	7	10	6.4	6	5.7	5.5	2	2
Distemonathus benthamianus	90	10	9	6.5	6	5.7	24.1	4	5
Sterculia rhinopeta	70	34	20	16.8	16	15.4	1.5	5	20
Terminalia ivorensis	70	3	3	2	2	1.9	-27.6	20	1
Terminalia superba	70	7	70	36.4	36	34.7	-	0	0
Antrocaryon micraster	50	-	1	-	0	0	3	-	0
Tieghemella heckelii	110	3	0	0.6	0	0	-	0	0
Stromlosia glausescens	50	-	15	-	0	0	-	-	0
Total	520	631	411.4	398	320.5	219.1	230	230.7	

Source: 1997 stock survey summary of compartment 5 of Tano Offin F/R issued by Nkawie Forest District Officer.

FLD = Felling diameter limit
X = Number of stems in the diameter class immmediately below FLD
Z = Number of stems in the diameter classes above FLD
Yc = Yield determined by formula
YA = Yield that may actually be found in the forest or can be taken
Yo = Optimized yield