SOME ISSUES IN THE YIELD REGULATION OF MOIST TROPICAL FORESTS

Paper presented to a workshop on *Humid and semi-humid tropical forest yield regulation with minimal data* held at CATIE, Turrialba, Costa Rica 5th-9th July 1999.

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Summary

Yield regulation is a central concept in sustainable forest management. Yield usually implies standing volume commercial timber, but can include non-timber products. Allowable cut is the harvest corresponding to sustainable yield. Felling damage must be allowed for in calculating this. Mean annual increment (MAI) is often confused with current or periodic increment, whilst different volume equations, diameter limits, and the gross or net increment can further confuse the issue. MAI is not sustainable yield as the forest is not normal and felling damage must be allowed for. Yield regulation is not sufficiently defined by the classical concepts of felling cycle and minimum felling diameter. Felling cycle does not have a definite optimum in mixed forest, whilst diameter limit alone is too simple a criterion for management. Tropical forests are spatially and structurally diverse, and practically, MAI and annual allowable cut can only be estimated by simulation or stand projection. This should be done stand by stand, with a further calculation to then determine felling series by cutting parts or aggregates of stands. A strategy is discussed for simplifying these steps and applying it where only static inventory data is available, using tabulated data and simplified modeling tools.

Introduction

The concept of yield regulation is simply conceived as the process by which the objective of sustainable yield is translated into operational forestry practice via planning, monitoring and control. Wright (1999) has presented some appropriate definitions. Armitage (1998, p. 171) states that:

> "Yield regulation or allocation involves making decisions that lead to clear specifications of where and under what conditions a harvest may be cut using AAC and technical information about a forest. It is a critically important part of sustainable tropical forest management".

Whilst yield regulation as a technique can be explained with some precision in relation to plantations, for natural tropical forests there is considerable lack of clarity and semantic confusion. This is especially true of the phrases *sustainable yield*, *mean annual increment* and *annual allowable cut*.

This paper seeks to clarify some of the issues relating to moist tropical forest (MTF) yield regulation and to suggest strategies that will provide a basis for yield regulation in situations where there is little direct information other than from forest inventories and stock surveys.

Related concepts

Figure 1 shows some of the related ideas. There are five main topics that have to be considered. The first is <u>the definition of yield</u>. Tropical forests tend to be managed as multiple use systems, with a strong emphasis on non-timber products and values. Increasingly in future, it is likely that timber production may be seen as a minor component of the whole system. These non-timber uses will impose marked constraints on timber operations and yield allocation.

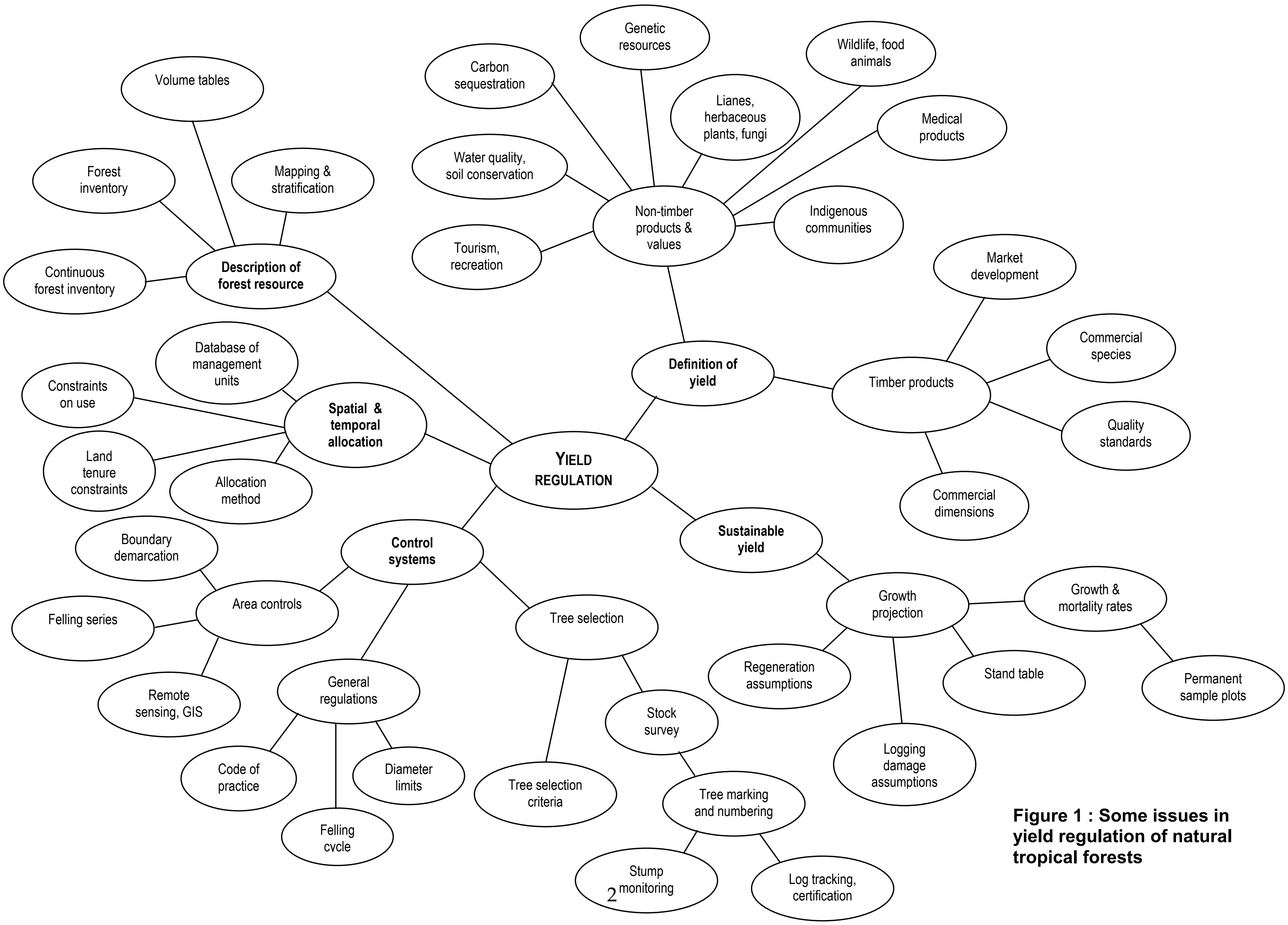


Figure 1 : Some issues in yield regulation of natural tropical forests

Timber yield itself depends on the commercial definitions of acceptable species, sizes and stem qualities. These may vary greatly over time as markets develop and change.

Yield regulation requires a description of the forest resource through forest inventory and mapping. A part of this process will involve the development of volume tables or equations.

Sustainable yield, in terms of timber production, must be analyzed through some form of growth projection or modeling. This will use the stand table information derived from inventories, together with growth and mortality data from permanent sample plots, information on logging damage, and estimates of regeneration and recruitment rates, to show the levels of production possible from typical stands in the natural forest mosaic. This sustainable yield will depend upon the commercial definitions of volume.

The spatial allocation of yield is the next necessary step. The forest mosaic is very variable, and will be subject to spatial constraints arising from other aspects of the multiple use system and from land tenure aspects. This can be a complex problem but there are numerous algorithms and methods which can be applied to the solution once a database of forest management units has been set up and the constraints and objectives of management defined.

The planned regulated yield then needs to be translated into operations that can be specified in time and space and monitored on the ground. These usually involve general regulations covering logging practices, buffer zones, and the like, diameter limits for species, and a general concept of a felling cycle. Area controls delimit blocks or compartments to be felled and assign them specific dates for opening and closure. These can be monitored by foot patrol or remote sensing depending on the scale of operation. Tree selection methods involve numbering and marking individual trees, and are likely to be increasingly emphasised as natural forest management in the tropics becomes more conscientious and silviculturally based.

Sustainable yield, allowable cut, and annual increment

Yield regulation is the means to achieving sustained yield. Sustained yield itself implies that products removed from the forest are replaced by growth, with or without artificial interventions such as re-planting, liberation thinning, etc.

For both plantations and naturally regenerated or mixed-age stands, the sustained yield was classically equated to the *mean annual increment* (MAI) of a *normal* forest (*eg.* Brasnett, 1953; Knuchel, 1953). This theoretical equivalence leads to the various 'formula' approaches to yield regulation discussed by Wright (1999). It is also a source of some confusion, as commonly the term MAI is used loosely and equated to current or periodic increment of volume, as well as, very often, to periodic mean diameter increment. By blurring these definitions and omitting the underlying assumptions we come to the type of statement often found in the literature of natural forest management and economic development reports (*eg.* Jack, 1960, Lowe 1992, 1996):

> "The sustained yield is equal to the increment of the forest"

This statement is NOT true for natural tropical forests. Current increment, as measured by permanent plots over periods of two to three years, fluctuates and shows structural changes over time. Increment of any particular species group depends on the diameter distribution of the species, especially when increment is based on volume above a given diameter limit. Volume increment of the whole stand can be calculated in at least three ways:

- *Gross periodic annual increment without recruitment (GPAI).* This is the volume increment of live standing trees measured over a relatively short period, usually less than 5 years, and averaged to an annual value.
- *Gross periodic increment including recruitment.* This is the volume increment of live standing trees, together with the additional volume of recruit trees entering the lowest measured size class, again measured periodically and averaged to an annual figure.
- *Net periodic annual increment* (NPAI) is the total change in volume over a short period including growth and recruitment, and also deducting losses from mortality, averaged as an annual value.

The NPAI is the most simply calculated value from direct observation, requiring only a measurement of volume at the start and end of a period (say V_1 and V_2 over T years), giving:

$$NPAI = (V_2 - V_1)/T \qquad \{eqn.\ 1\}$$

MAI, if used in the same sense as in plantation forestry, is equivalent to NPAI measured over the period from the last logging operation to the time of measurement. If used strictly in this sense, then MAI can be equated to sustained yield *of a plantation managed under a clear felling regime with equal areas under each age class.*

However, in natural forests, the spatial and size class distribution of the stock is very variable, especially with regard to the commercial species. Further, the losses that occur during and after harvesting from damage and mortality reduce the residual stock substantially. In classical theory we have:

Residual stock = Growing stock – Harvest

In natural forest management we have rather:

Residual stock = Growing stock – Harvest – felling damage

Figure 2 illustrates these points for a typical natural forest logging and recovery. Following a logging of some 30 m^3 ha^{-1} (the yield), the growing stock is actually reduced by 50 m^3 ha^{-1}, from 100 m^3 ha^{-1} to 50 m^3 ha^{-1}. From this point, in year 4 on the graph, MAI and NPAI can be calculated, as shown by the thin solid and dotted lines. Initially, net growth is slightly negative or static for some 10 years after logging, for two reasons:

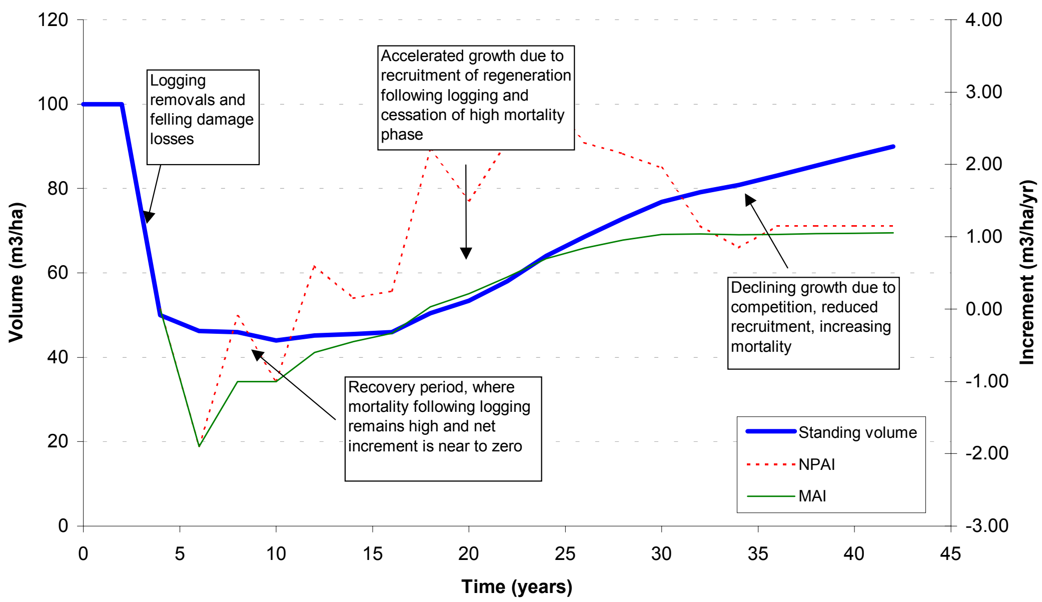
- Regeneration, although stimulated by logging, has not yet reached the measurement limit for recruitment.

- Trees damaged or disturbed by logging, especially larger trees, show a higher mortality for a period, declining over about 10 years back to typical levels.

During this period, MAI drops from zero at the time of felling (the base time for calculation) to a negative value (-2 m^3 ha^{-1} yr^{-1}) and then gradually starts to recover. NPAI is also negative, and fluctuates markedly from year to year. As recruitment starts to occur, and the mortality of larger trees declines, then there is a more rapid phase of stand development, with NPAI of the order of 2 m^3 ha^{-1} over a 10 to 20 year period. This drops away after some decades as the recruitment diminishes and growth of the trees is inhibited by competition.

This is a typical pattern, but many variations are possible, depending on the species mix and their response to logging, and the status of advance growth and saplings at the time of logging.

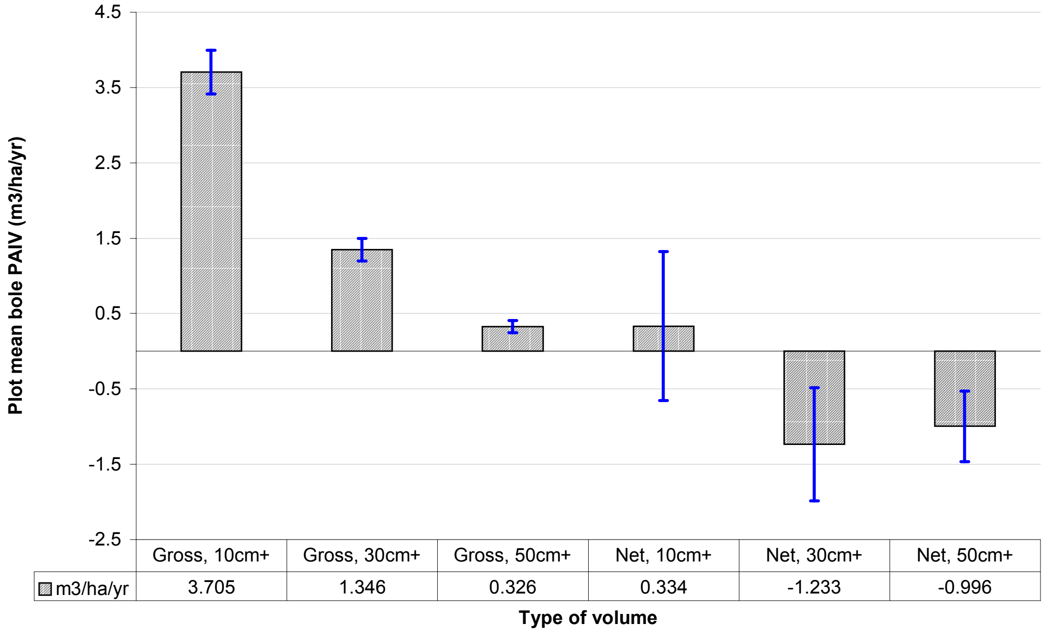
Figure 2 : Volume, current and mean annual increment in logged natural forest



Volume and increment in natural forests can be measured above different diameter limits, from say 10 cm up to 50 cm or more. This will clearly have a major effect on the values of GPAI, NPAI and MAI that are calculated. Figure 3 illustrates how these statistics can vary. It is based on the increment of 72 PSPs of 1 ha measured over intervals from 2-4 years (Alder *et al*., 1998). All the plots were established shortly after logging. The bole volume increment of all trees over 10 cm dbh is 3.7 m^3 ha^{-1} yr^{-1}, neglecting losses from mortality (gross increment). This declines to a gross figure of 0.3 m^3 ha^{-1} yr^{-1} for trees over 50 cm. The net figure, including losses from the growing stock due to natural mortality over the increment period, is negative and amounts to a net loss of 1.2 m^3 ha^{-1} yr^{-1} for trees over 30 cm dbh.

Annual allowable cut (AAC) is commonly used as loosely as MAI, and with a rather similar confusion of equivalences. AAC is the practical measure of the sustained yield and can be used to monitor forest production and set limits for timber industry supply. It is usually quoted as an aggregate figure, for all commercial species, but

Figure 3 : Gross and net volume increment to different diameter limits, ITTO sample plots, Papua New Guinea



can be broken down by species and localities for more detailed planning. It will definitely relate to commercial yield and size limits.

Again, it should be emphasised that AAC is NOT equal to the increment of the forest. Current increment, as it may be measured from PSPs (as for example in Figure 3) is almost completely irrelevant. Mean annual increment must be corrected for logging damage in order to calculate AAC. Figure 4 clarifies some of the definitions.

The total volume reduction at the time of harvesting is the yield Y plus the felling damage D. Mean annual increment is calculated as the incremental volume growth V_t over a period T from the last harvest:

$$MAI = V_t / T \qquad \textit{\{eqn. 2\}}$$

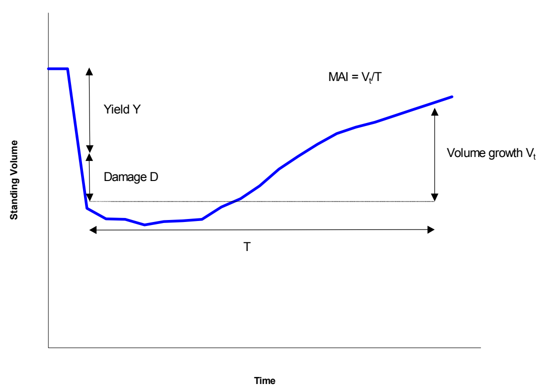
The AAC can be calculated as:

$$AAC = (1 - D\%).MAI \qquad \textit{\{eqn. 3\}}$$

Where:

$$D\% = D/(Y+D)$$

Figure 4 : MAI, yield and felling damage



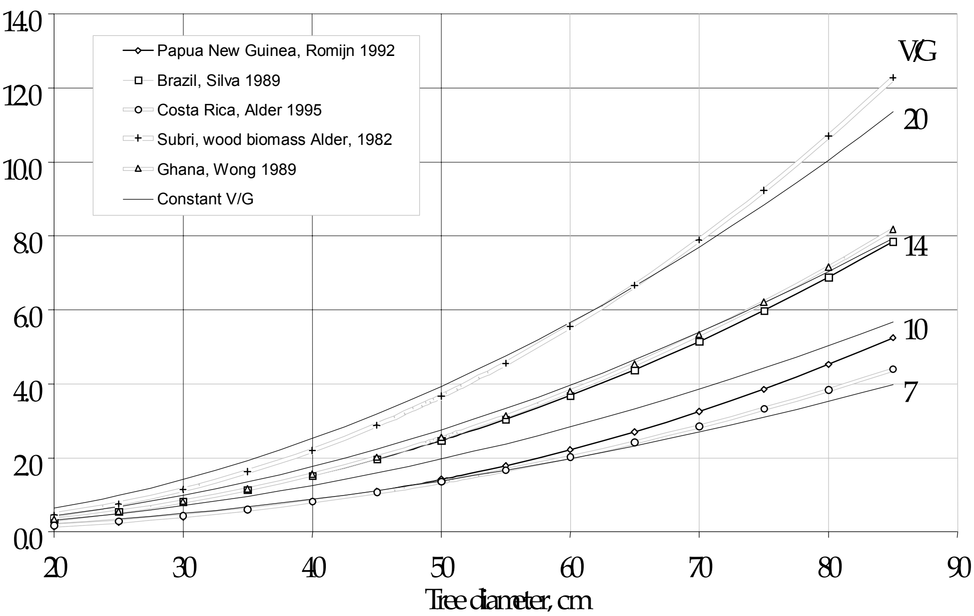
In practical terms, AAC should be about 50-70% of the estimated commercial MAI, depending on observed levels of logging damage. This refers purely to volumes calculated as standing volumes, and does not consider an allowance for within tree wastage and degrade. The latter is necessary if AAC is monitored and controlled in terms of extracted volumes, and is likely to be an additional 50-70% reduction factor. Thus Dawkins' (1964) pan-tropical mean estimated of commercial MAI of 1 m^3 ha^{-1} yr^{-1} amounts in practice to pan-tropical AACs of around 0.25-0.5 m^3 ha- yr^{-1} measured as logs at the landing or roadside.

Basal area and volume

Figure 4 illustrates how the volume equation used can influence the tree volume increment. Four general equations are shown, for Tapajós, Brazil (Silva, 1989), Ghana (Wong, 1989), Costa Rica (re-parameterized average equation, Alder, 1997), and Papua New Guinea (Romijn, 1994). For a tree of 70 cm dbh, these four equations give volumes between approximately 3 and 5 m^3 . A fifth equation, for woody biomass from a study in Subri, Ghana (Alder, 1982), is shown to illustrate how the measurement standard may influence the volume estimate.

These comparisons show that by changing or improving a volume equation, or by applying different definitions or measurement standards of tree volume, yield and

Figure 4 : Comparison of some tree volume equations and form height equivalents



increment figures may change by as much as 50%. The forester's quoted volume, based on measurement of tree boles, will usually be at least double that which can be effectively used as logs in a sawmill or plymill. Thus when relating mill capacity or intake requirement, in terms of round logs, to allowable cut and sustainable yield, a factor must be introduced for defect, length and diameter constraints, and simple operational wastage (logs felled but not transported).

For forest management purposes, basal area and basal area increment may be less ambiguous than volume. Basal area and volume can be approximately converted by using an average form height, or volume to basal area ratio. Figure 4 shows the form-height lines for some values similar to the illustrated equations. It can be seen that the lower equations are equivalent to a form height of about 7 m (Costa Rica, PNG). The higher ones (Amazonia, Ghana) are close to 14 m, and a median value is near to 10. The biomass equation illustrated is close to a form height of 20 m. As a rough rule of thumb, we may therefore say that in natural tropical forest, we may expect bole volume to be about ten times basal area, whilst woody biomass is approximately 20 times basal area. The latter is a useful figure for carbon sequestration or wood fuel considerations.

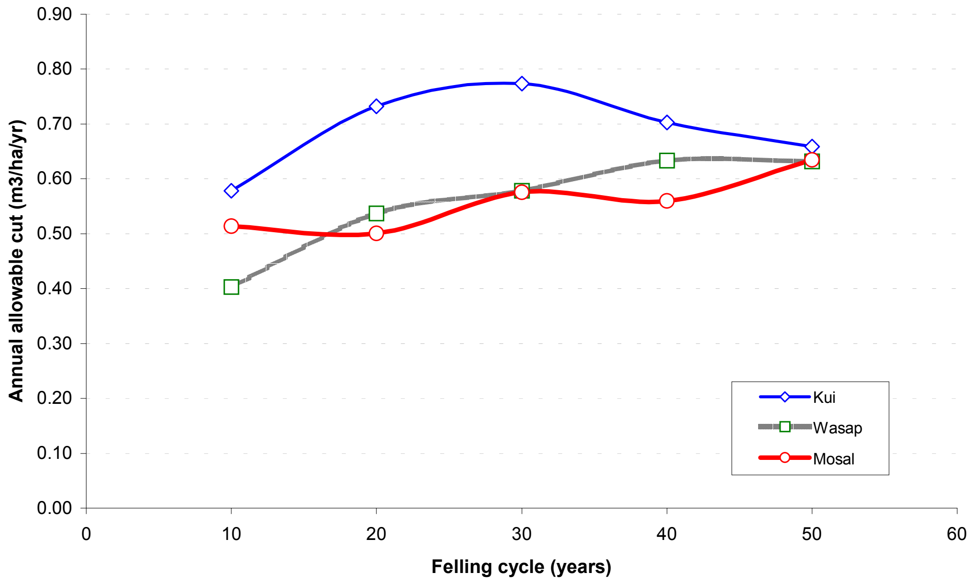
Whilst basal area and basal area increment are not subject to the variations arising from a given volume equation, it is necessary to define the lower limit of measurement, and whether the statistic refers to all species or only commercial species. Basal area increment can, like volume, be defined as a net or gross figure, with the latter also including or excluding recruitment.

Felling cycle, minimum diameter, and allowable cut

The definition of felling cycle is often regarded as the central issue in regulated yield management, as Wright (1999) indicates in relation to the discussion of Von Mantel's and similar formulae. Theoretically, once a felling cycle has been defined, the forest can be divided into annual or periodic coupes, collectively termed a felling series (*eg*. Leuschner, 1984, pp. 159-168). The coupes are mapped, and can be monitored on the ground and by remote sensing.

Figure 5 : AAC over different felling cycles for three locations in Papua New Guinea

(based on 100 years growth using the PINFORM model)



However, practical analysis suggests that there is no definite optimum felling cycle for many stands. Figure 5 illustrates this point for simulations of felling cycles from 10 to 50 years at three localities in Papua New Guinea using the PINFORM model (Alder, 1998; Alder *et al*., 1998). At Kui, there appears to be an optimum at about 30 years, but this is not obvious in the other stands, and could simply be due to variations in stand structure and species composition. The decline with very short cycles appears real however, and due to the lack of time to recover from post-felling disturbance. The AACs in this diagram are calculated as the average actual yield over a period of 100 years, and can be seen to be 0.6-0.7 m^2 ha^{-1} yr^{-1} . This is based on bole volumes of commercial species only over 50 cm dbh.

The felling cycle may be constrained by the need to achieve a certain economic level of harvest at each cut, as indicated by De Kock (1999). However, where small scale harvesting systems are involved, as in community-based projects or farmer-owned forests, then shorter felling cycles may be indicated. Shorter felling cycles should also be combined with concepts of silvicultural treatment and more intensive forest monitoring and control.

The minimum diameter limit determines directly the level of yield. A higher limit will reduce both the available stock of timber, and the commercial productivity. The most productive diameter can be determined by the method described in Alder (1992) if increment and mortality rates are known. It is likely to be necessary to reserve trees substantially above the diameter limit as seed trees if adequate regeneration is to be assured (Plumtre, 1995), whilst the spacing of such trees needs to respect their genetic and reproductive mechanisms (Kanashiro, 1998).

It is not necessarily a desirable management policy to always take the largest trees and leave the smaller ones. It may be preferable to reserve large trees as seed trees, even if, or especially if, they are deemed 'overmature'. It may also be a very desirable and effective policy to remove commercially competitors to higher valued reserved trees as a liberation thinning. Thus the diameter limit alone is not a sufficient criterion for regulating the yield in a selection forest.

Yield estimation through stand projection

Because of the complexities of stand management in natural forests, it is probably essential to have some form of stand projection model that will take into account variations in stand structure from place to place, and allow mean annual increment to be estimated, preferably over several felling cycles. Vanclay (1994, 1995) and Alder (1995) give practical information for the techniques of modelling natural tropical forests. Examples of empirical methods of stand projection are given in Vanclay (1989) for North Queensland rainforests, Howard & Valerio (1992) for Costa Rica, and Alder & Silva (1999) for Brazil, among others.

Models can be simple or elaborate, and may use extensive permanent sample plot data or simple assumptions about growth rate and mortality. Simple models can be quite effective. Both the SIRENA and PINFORM models developed by the author (Alder, 1997, 1998) use only tabulated mean increments and mortality rates, without any elaborate diameter increment functions. These are supported by stand level functions for recruitment, for stand density effects, and logging damage. There is enough similarity between the performance of these models, for Northern Costa Rica and Papua New Guinea lowland tropical forest, and also the more complex CAFOGROM model (Alder & Silva, 1999), to suggest that pan tropical tabulations of these basic functions are possible and can be used to provide a basic and easily parameterized model for provisional use.

Spatial allocation of yield by management units

Species in natural forest tend to be clustered and to follow environmental gradients, both actual and historical. In addition, the forest is a mosaic of successional phases over scales from the individual tree gap to areas of many square kilometres. Treating a whole managed area as if it had a homogeneous average stand table will rapidly result in an impossible conflict between a management plan and operational reality.

If a plan is to be feasible, it must reflect spatial variation. Yield regulation, which links the plan and operations through a monitoring and regulatory process, must reflect this spatial variation.

Essentially, there are two approaches. There first maps the forest mosaic using remote sensing and aerial photography, and uses a stratified inventory to derive average stand tables for each identified forest type or mosaic element.

The second uses a systematic inventory on a grid to map the forest mosaic directly from the inventory.

In either case, the yield regulation process should relate the allowable cut calculated for each management unit (a grid cell or map polygon) to an annual target or requirement for timber, and to operational or conservation constraints, including ownership units, access routes and sequences and the like. This spatial allocation of yield can be resolved by two basic approaches:

- *By a mathematical programming algorithm*. Conventional linear programming problems can be set up and solved using the standard facilities of *Microsoft Excel*, for example (the *Solver* module). Integer or zero-one programming are variants which would require specialised programming or packages, but are quite suitable for 'all or nothing' situations such as the allocation or non-allocation of a grid cell for felling in a particular year. These methods are widely used for yield regulation in plantations and temperate mixed forests (eg. Rorres, 1978; Clutter et al., 1983; Leuschner, 1984).
- *By trial and error*. This is involves using a combination of maps and graphs to select management units (stands, sub-compartments, blocks, etc.) for felling in a way that reasonably satisfies the more obvious constraints and practical aspects. This is the more common technique in the tropics, and is most suited when many decisions cannot be based on fully quantifiable or logical criteria. The process can be assisted by GIS, or computer simulation. There are also a variety of algorithms that can completely or partially automate the trial and error process, including recursive decision tree searches and genetic algorithms (Frey, 1977).

The outcome of the process of spatial allocation will be a felling series that involves unequal sized coupes, but producing either equal volumes of timber, or yields which are within some limits of variation over time that can allow a stable industry to develop or continue to operate. In some cases, the goal might be to produce a specific balance of species; in others, it may reflect the need to provide continuous employment in different settlements adjoining or within the forest. The constraints on the plan will typically include a number of conservation factors.

Within a given stand, a further layer of yield regulation may be required, to respect fine scale conservation principles and ensure that logging is properly controlled. This will typically involve stock surveys to map and number larger trees, and the allocation of specific trees for felling.

Monitoring and control

A system of yield regulation will at the end amount to nothing if there is no monitoring and control, no matter how elaborate or complex the mathematical systems used, or how beautifully detailed and coloured the maps. A part of the process of yield regulation is to define specific targets for monitoring. In terms of areas, this involves having definable geographical boundaries. With modern GPS systems, this is a much easier task than formerly, and it may be less necessary nowadays to physically demarcate boundaries, since the location of operations can be checked directly against a GPS reading. However, a system of monitoring does need to be set up whereby the forest is patrolled, and reports made of the locations of any forest operations.

For tree level monitoring, felled stumps need to be identified and checked against lists of trees permitted to be felled. This requires a suitable numbering system, that will survive on the stump, and a tree map to check for ambiguities.

The monitoring party should not be engaged directly in enforcement. The latter is a simple recipe for corruption. Instead, monitoring data should be fed back into a main database which contains forest areas, yield lists, and operating rights and agreements. Where discrepancies occur which exceed those that can be tolerated as data errors, then a separate enforcement unit should be assigned to investigate.

A strategy for yield regulation with minimal data

The present workshop represents an initial step for the DFID project *Humid and semi-humid tropical forest yield regulation with minimal data*. The direction the project will take will be informed by the conclusions for the workshop. However, the author considers that the following are the key elements that the project will address:

- A clarification of issues and terms, especially in relation to the concepts of yield, sustainable yield, allowable cut, and mean annual increment.
- A handbook of pan-tropical statistics, showing typical growth and mortality rates for many species from published sources, recruitment functions, logging damage, maximum basal area, volume and biomass, typical volume equations, and the like. Ideally, these will be provided in database form on a CD-ROM, as well as in a printed publication.
- A basic model for estimating allowable cut using the pan-tropical data, and combined with suitable inventory data. To assist this a simple inventory program will be provided, although it will also be easy to configure inventory data from other sources. This model will be supported by a user's guide.
- A spatial allocation model that will interface with the stand model and use a simple recursive decision tree approach to define coupes and felling series subject to various constraints and objectives.

Conclusion

A number of points have been discussed in this paper. Yield regulation is at the core of sustainable forestry practice, and must be based on the real world. This means especially taking account of some of the complexities of natural tropical forest management, which include strong human, conservation, and marketing constraints, a general lack of knowledge of species dynamics and ecology, and the spatial diversity of the forest at a variety of scales.

Even the simplest yield regulation method will therefore be relatively complex if it is to correspond to anything that can be practically implemented. However, the author feels that the basic data exists on general growth and yield to provide a start in this direction, and there is enough experience in empirical stand projection methods to show how reasonable estimates of sustainable yield and allowable cut can be made. A fundamental objective of the DFID project *Humid and semi-humid tropical forest yield regulation with minimal data* will be to serve this data and systems up in a simplified, useable format. This will hopefully help to bridge the rather large gap between the ideal of sustainable forestry and its realization in practice in the tropics.

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