Models for basal area dynamics of mixed tropical forest: Neo-tropical experience and prospects for application in Ghana

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Summary

Stand projection which is not corrected for stand-level increment and mortality tends to overestimate achievable yields in natural forest. Two recent models, SIRENA and CAFOGROM.XLS, for Costa Rica and Brazil respectively, are discussed. The stand basal area increment, mortality, and recruitment functions for SIRENA are illustrated, and various simulation trials with CAFOGROM shown. The modelling system uses a pre-processor, CIMIR, for raw permanent plot data, and can be operated by non-programmers, but its application under current institutional arrangements in Ghana would be controversial, as each specific forest would need local management regimes to achive optimal results.

Introduction

Since the earliest models of tropical forest growth were proposed by Brandeis in 1856, it has been an implicit assumption of the *stand projection* approach that it is possible to determine the growth of a forest by analysis of individual tree increments (Brasnett, 1953; Husch et al. 1982). Stand projection may be defined as a type of forest model in which trees are grouped into diameter classes and transition probabilities calculated between diameter classes to project changes over time. In more recent times such models have often been formulated as Markov or Usher-matrix type models (Buongiorno & Michie, 1980;Usher, 1966).

However, the underlying assumption, that empirical regressions on tree increments can be summed to give reasonable dynamic responses for the forest as a whole do not appear to hold up well in practice. Over the past few years the author has developed several growth models for natural tropical forests in different localities. GHAFOSIM was the first of this group (Alder,1990, 1995). This was constructed as a classical stand projection model using individual tree increment data from permanent plots established in Ghana between 1968 and 1983 (Baidoe, 1968). GHAFOSIM was characterised by a tendency to linear response that lead to exaggerated estimates of yield over the longer term.

In Brazil in 1994 another model was developed called CAFOGROM.C (CPATU[1] Amazon Forest Growth Model, C version). This was designed on the basis of work by Vanclay relating to the North Queensland forest growth model (Vanclay, 1989, 1994), as a cohort rather than diameter class model. It was based on a much stronger data set (Silva & Lopes 1984, Silva et al., 1994), and for moderate conditions of management, gave realistic responses over the long-term, with stands tending to achieve a basal area of around 40 m^2/ha and then fluctuate at around that level. However, when drastic

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[1] CPATU is an acronym for *Centro de Pesquisa Agroflorestal da Amazonia Oriental*.

interventions such as clear felling were applied, basal area would rise during recovery to levels or around 80 m^2/ha. These would eventually revert to lower figures over time, but would typically stabilise at unnaturally high levels of around 60m^2/ha (Alder, 1995).

Both GHAFOSIM and CAFOGROM.C were based primarily on the modelling of individual trees by empirical regressions of tree increment on tree diameter, with different regressions for crown classes. There was no implicit control in the model for the maximum achievable basal area for the stand, or for basal area increment at stand level. However, it was clear that the absence of this stand-level analysis of basal area dynamics was a general weakness for empirical models constructed from individual tree increments.

SIRENA: A model driven by stand basal area dynamics

Subsequent modelling efforts sought to address these problems by developing empirical regressions for the basal area dynamics of the stand as a whole. SIRENA (*Simulacion del rendimiento de bosque natural*) was the first model developed by the author of this type (Alder, 1996a). It is written in Visual Basic for Applications (VBA) and runs under Microsoft Excel 5.

SIRENA was developed on the basis of a relatively limited set of data from forests in Northern Costa Rica. This comprised 26 1-ha plots and 27 ¼-ha plots managed by Tecnoforest del Norte SA and CODEFORSA[2] and measured at that time over a single interval of 2-3 years. The 16 Tecnoforest plots were all of 1-ha and occurred in a forest type characterised by significant proportions of *Carapa guianensis*. Undisturbed plots typically had basal areas in the region of 28-32 m^2/ha. The CODEFORSA plots comprised 9 plots of 1 ha, and 27 of ¼ ha. These were mainly in forests characterised by the presence of *Vochysia* and *Dipteryx* species and absence of *Carapa*, and were typically of lower basal areas, of 20-25 m^2/ha.

For each plot, increment on live standing trees was calculated as standing basal area increment (SBAI) in m^2/ha/yr. This included all trees over 10 cm dbh. Mortality basal area (MBA) was calculated as the basal area of trees recorded as dead or lost, excluding those marked as harvested or treated for liberation thinning. This periodic figure was divided by the measurement interval to give an annualised rate of losses through mortality in m^2/ha/yr. Recruitment basal area (RBA) was calculated as the basal area of trees observed on the second measurement but not at the first. This was annualised by dividing by the measurement interval to give recruitment in m^2/ha/yr.

Figure 1 shows the data and regression function for basal area increment. Two outliers have been omitted from the regression, which is a logarithmic equation with the form:

$$\text{SBAI} = 0.0419\ \text{SBA}^{0.8449} \qquad\qquad \{\text{eqn 1}\}$$

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[2] Comisión para el Desarollo Forestal de San Carlos

where sBAI is stand basal area increment and sBA is stand basal area. The R^2 was 0.336 with 48 degrees of freedom, which is statistically highly significant[3].

Examination of the data points suggests that the CODEFORSA and Tecnoforest plots probably follow different regressions. The Tecnoforest plots (triangles) show a very weak, non-significant regression, and have a mean sBAI of about 0.65 m^2/ha/yr over a range of stand densities. This almost certainly reflects differences between the forest types, but is not necessarily purely biological in origin. In order to simplify the model however, the two data sets have been aggregated within the version of SIRENA described in this paper.
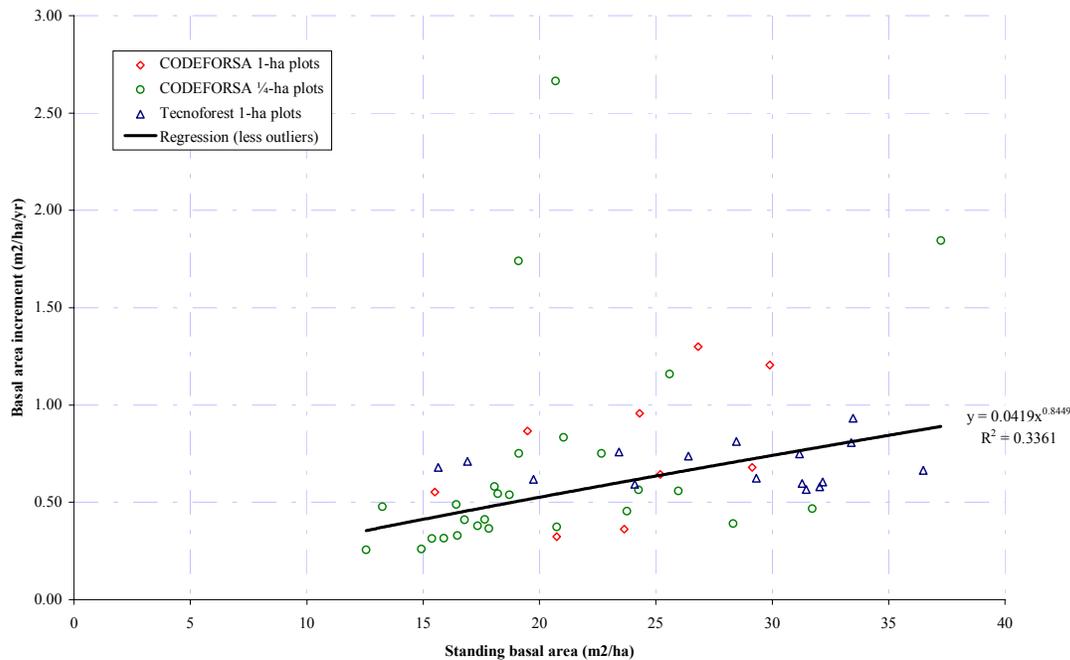

Figure 1 Basal area increment for sample plots in northern Costa Rica

Similar data can be plotted for mortality and recruitment basal area, as shown in the graphs in Figures 2 and 3. For mortality, the regression is very weak, and with an R^2 of only 0.0931. However, with 52 data points, this is statistically significant[4]. The separate regression considering only the 1-ha CODEFORSA plots shows a much steeper slope.

The recruitment function shows a much clearer relation than that for mortality. It is modelled by an exponential equation, which has the desirable properties that:
- Recruitment tends to a positive constant as basal area tends to zero.
- Recruitment tends to zero as basal area becomes large and the stand increasingly dense.

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[3] *Highly significant:* That is, there is a probability of less than 0.01 that this degree of correlation could occur by chance.
[4] The correlation coefficient is 0.305. The critical value at P=0.95 is 0.235 with 50 d.f., and at P=0.99 it is 0.328. The regression is thus significant but not highly significant using conventional termonology.
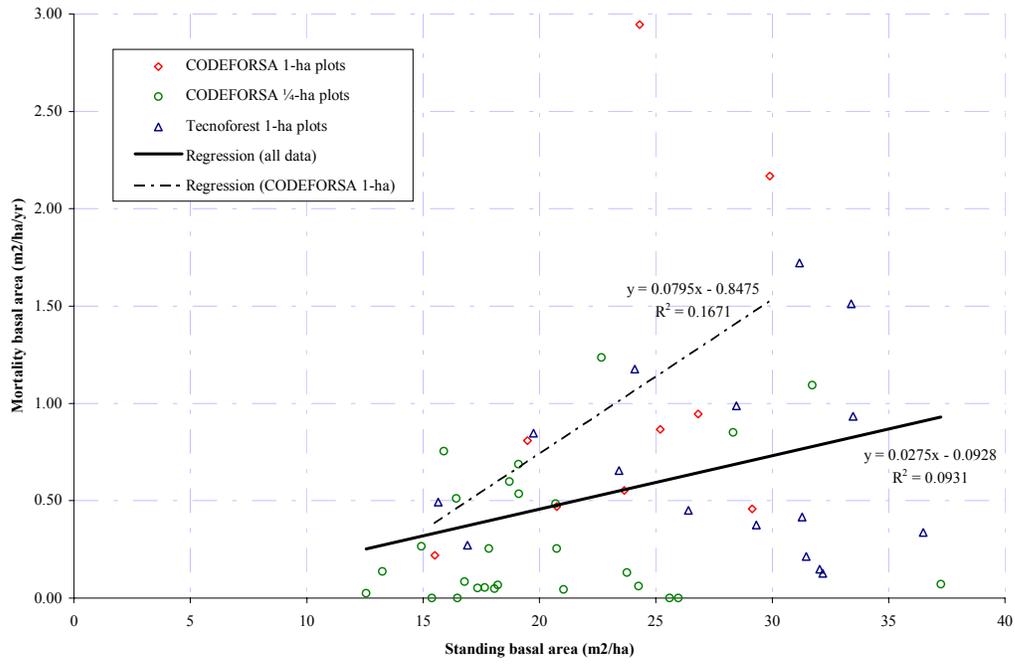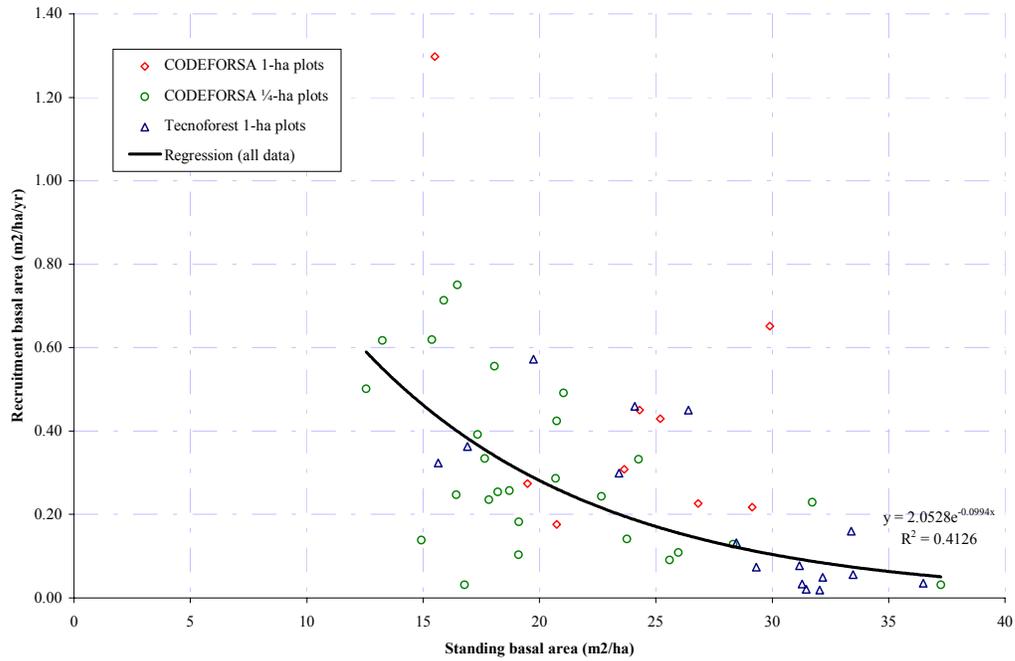
Figure 2 Mortality basal area for sample plots in northern Costa Rica

Figure 3 Basal area of recruits above 10-cm for sample plots in Northern Costa Rica

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The equation fitted is:

$$\text{RBA} = 2.053 \exp(-0.0994 \text{ SBA}) \qquad \{\text{eqn. 2}\}$$

where RBA is recruitment basal area and SBA is standing basal area as previously defined. The R^2 is 0.413, which is highly significant with 52 data points.

These three functions completely define the development of stand basal area, and are used in SIRENA in this form. SIRENA uses species and size dependent functions of diameter increment and mortality, but then adjusts the individual cohort estimates proportionately to ensure that the stand-level estimates of growth are respected.

Basal area dynamics in CAFOGROM.XLS

The SIRENA model was based on a limited set of data from a single remeasurement of permanent plots in Costa Rica. The CAFOGROM model was based on much stronger data. During May and June 1986 the author had the opportunity to revise and improve that model (Alder, 1996b). It was completely re-written in VBA to run under Excel 5, and was correspondingly supplied with a better user interface than the original program. The model was extended to automate the analysis process as much as possible, with a pre-processor program called CIMIR[5].

In terms of basal area dynamics, it was found that, as with the Costa Rica data, the Brazilian plots showed reasonable correlations between standing basal area and basal area increment or recruitment basal area. Mortality basal area showed a correlation, but was too weak to be directly useful. The existence of several measurement periods, or experimental treatments, and of different plot sizes on different experimental areas allowed several points to be noted during analysis. These included:

- The correlation of recruitment with initial standing basal area was strongest 2-4 years after logging. This included recruitment above 5 cm dbh.
- Basal area data from 1-ha plots gave better correlations than from ¼-ha plots. This applied especially to logging damage effects.

As with SIRENA, CAFOGROM.XLS uses individual tree functions for diameter increment and mortality. The mortality functions are not regulated at the stand level. The increment function is however limited for conformity with the stand basal area increment function. This ensures that the model performs in a reasonable manner even under extreme scenarios such as clear felling. The performance of the model was found to be sensitive to the way in which the stand basal area increment was allocated to individual trees. In SIRENA, a simple proportional adjustment was used for each cohort increment. However, with the better data available for the CAFOGROM revision, it was found that this method tended to overestimate the increment of small trees, and resulted in unrealistic stand structures over long periods. A different method was used to allocate

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[5] CIMIR is an acronym for Calculation of Increment, Mortality, and Recruitment.

basal area increment which gave long-term projections with stand structures similar to those found in real undisturbed stands. This involved the following logic:

- Increment was added first to the undamaged trees in the upper canopy, using the species-size tree increment function.
- Increment was then added to the understorey and damaged trees.
- Both phases were executed from largest to smallest tree in each category, and were terminated if the total basal area increment exceeded the stand increment function.

Thus, when increment is limited by stand density, large, canopy trees continue to grow. Smaller trees, those in the understorey, or damaged trees will show no diameter increment.

Both SIRENA and the revised CAFOGROM apply the recruitment function in the same way, involving several steps. During analysis, different species lists are built up for recruitment at different levels of stand disturbance. These contain two statistics for each species: The proportion of total recruitment by numbers for that species, and the mean diameter of recruit trees. The stand-level recruitment function is used to calculate recruitment basal area. This is used to determine the disturbance class, with high levels of recruitment being indicators of high disturbance. The appropriate list is selected according to the disturbance class. The basal area is then allocated proportionately to the species on the basis of their numbers and mean diameters.

Figure 4 Basal area damage from the CODEFORSA logging study
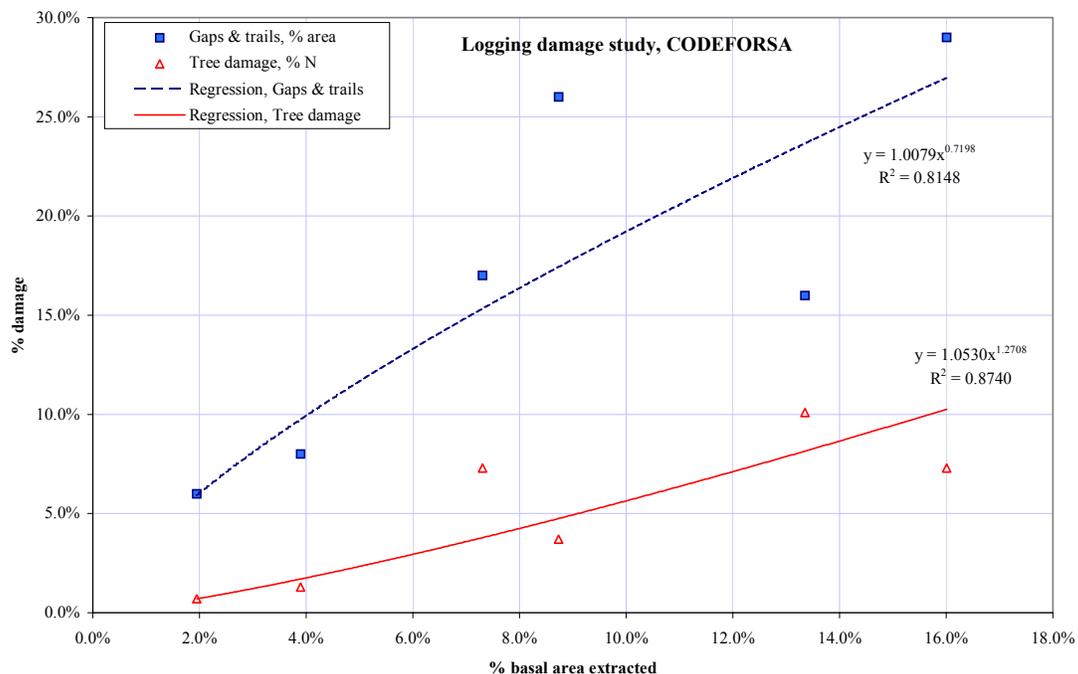
### *Logging damage as a component of basal area dynamics*

Both SIRENA and CAFOGROM incorporate empirical functions for logging damage. For the SIRENA model, a specialised study was carried out by CODEFORSA (Gordon, 1995). This involved detailed sampling on six study areas before and after normal logging operations. From this data, the graph and functions shown in Figure 4 were produced.

These show logging in terms of the percentage of basal area extracted, and range from 2 to 16%. In terms of actual basal areas extracted, the heaviest logging comprised about 3 m^2/ha removed.

SIRENA has separate functions for trees severely damaged and for areas lost to skid trails and gaps. The area losses are applied only to trees below 20 cm, on the assumption that the tractor driver will avoid destroying larger trees. The tree damage function is applied through all sizes, with severely damaged trees being assumed to die during the period. The data exists from the study for a more detailed analysis of damage by size classes, and additional data is now being gathered by CODEFORSA to strengthen this information. It is likely that future revisions of SIRENA will therefore incorporate a more sophisticated approach.

CAFOGROM is, unlike SIRENA, not based on fixed pre-calculated functions, but develops the functions dynamically from the data set supplied, and is therefore both more flexible, and less easy to characterise in a simple way. Figure 5 however shows some typical logging damage data from the 1-ha experimental plots near Jarí. Two functions are developed. The lower line shows mortality during the measurement period following logging in terms of basal area. The upper line shows the combined losses from mortality

Figure 5 Logging damage data from CPATU plots near Jarí, Brazil

**Models for logging damage**

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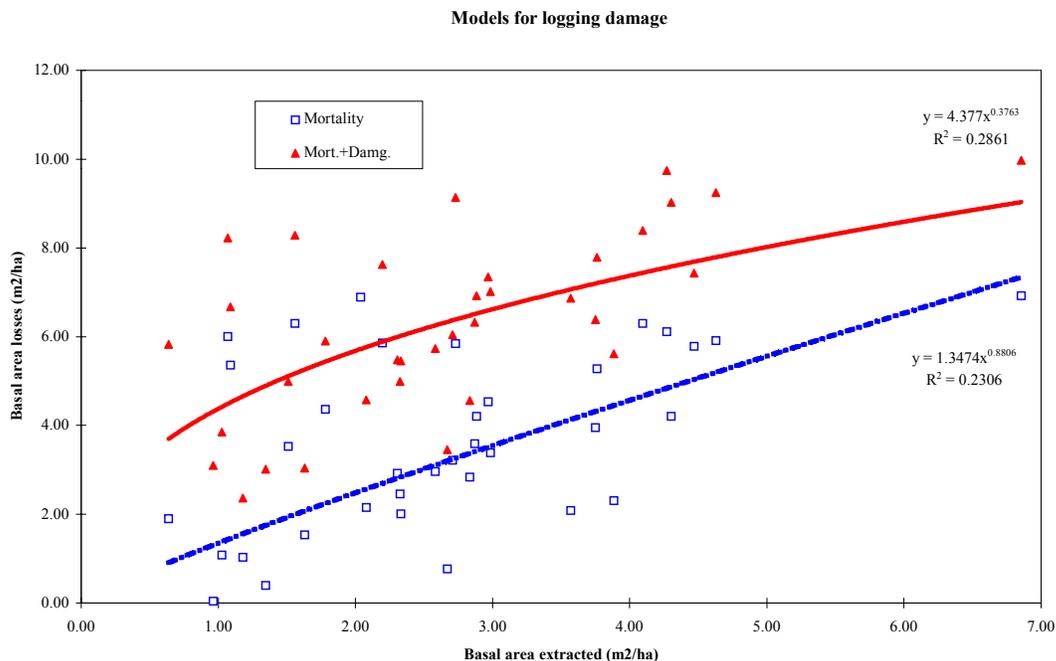
and severe damage.

In CAFOGROM, the mortality function following logging is applied instead of the natural mortality function when a simulated logging has been carried out. The damage function is used to create cohorts of trees which are marked as severely damaged. Separate analysis carried out during model parameterization will typically show mortality rates for these damaged trees that are approximately double those of undamaged stems. The damaged cohorts are also retarded in their diameter increment.

Both the CODEFORSA and CPATU data show a similar story. For each unit of basal area extracted, a similar quantity will be lost through damage or mortality. Thus the CODEFORSA function shows that with 16% logging, 10% of the remaining trees will be severely damaged, and 27% of the forest area will be damaged by skid trails or felling gaps. The CPATU data in the example shows that with 6 m^2/ha extracted (about 20% of the basal area), 6 m^2/ha will die during the following 2-year period and a further 2 m^2/ha are severely damaged. It may be noted that neither of these situations are 'worst-case' logging scenarios. Forest owners in the CODEFORSA area use low impact methods based on agricultural tractors and cable extraction, whilst the CPATU plots are in an experimental area felled under supervision.

Trial simulations with CAFOGROM

Some aspects of the dynamics of mixed stands can be illustrated with trial simulations using the CAFOGROM model. Figure 6 shows the *Basal area components* diagram

Figure 6 CAFOGROM simulation of recovering logged forest over 200 years

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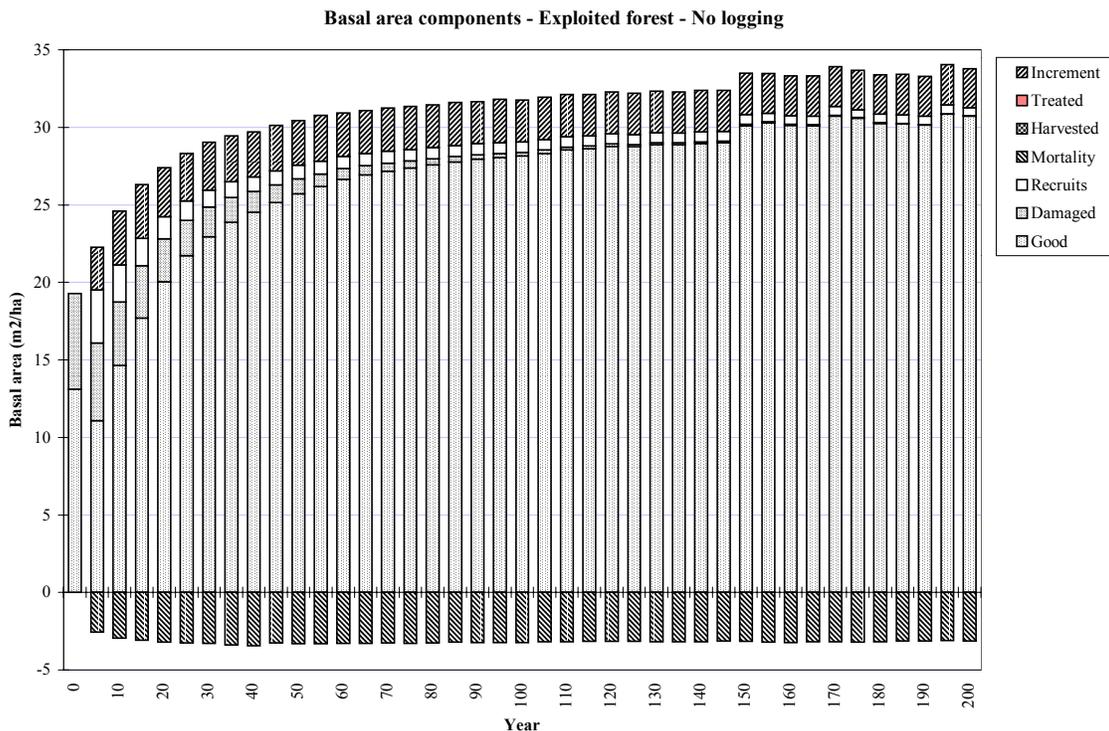
produced by the model for a run based on a heavily logged Amazonian forest (Tapajos km 67, as described in Silva, 1989). The simulation has no logging, and is run for 200 years, in order to indicate the equilibrium behaviour. The diagram shows the standing basal area, and mortality, increment and recruitment over each 5-year step. The stand moves towards a long-term equilibrium of about 32-35 m^2/ha. In the equilibrium condition, net increment is approximately zero, but both mortality and growth remain active processes, with about 2.5 m^2/ha growth over a 5-year period, 0.6 m^2/ha recruitment, and 3.1 m^2/ha mortality.

Figure 7 CAFOGROM stand structure diagram for 200 year simulation without logging
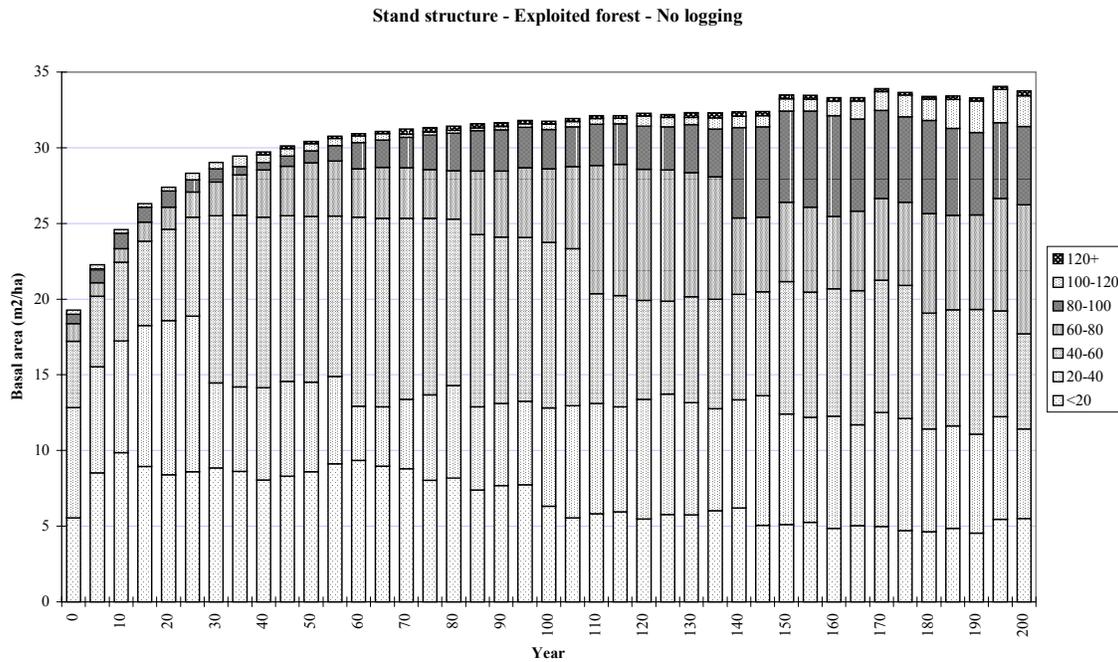

Figure 7 shows another output from the same simulation run. This is called the *stand structure diagram*. For each 5-year period it shows the basal area categorized by size classes. It can be seen that although total basal area remains more or less constant after the first 60 years of recovery from logging, there is a progression in terms of size classes. After 200 years, basal area is more or less evenly split into the 20-cm classes. This corresponds to the pattern for undisturbed primary forest in the same locality.

Figure 8 shows a more complex simulation of the same forest. In this, felling is specified under basal area control, with all commercial trees over 50 cm dbh being eligible for harvesting. However, felling is limited to a maximum basal area for extraction of 3 m^2/ha, and the model does not harvest trees which are severely damaged or of bad form. A thinning is specified 5 years after harvesting to remove up to 3 m^2/ha of non-commercial trees over 40 cm dbh, and also to remove relict commercial trees which are severely damaged or of bad form. In this basal area diagram, the removals through harvesting and thinning can be seen in the lower portion of the graph. Mortality can also be seen to be much higher during the 5-year period in which the logging is performed.

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Felling frequency is controlled purely by basal area, being permitted whenever the stand recovers to 25 m²/ha.

Figure 8 Simulation with felling under basal area control and post-harvest treatment

Basal area components - Exploited forest - BA 25/3 + Thin 3
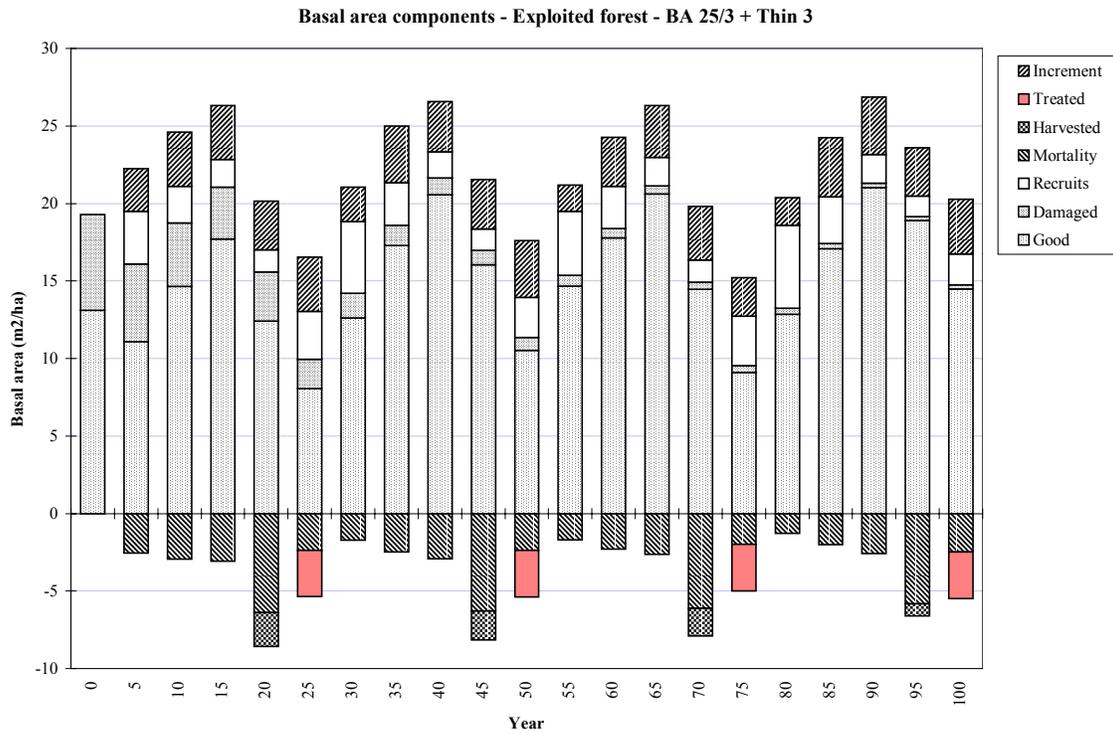
CAFOGROM has two other types of graphical output: A volume graph showing components of volume by species group, and a comparisons graph allowing one of the volume components to be compared between successive runs. The volume components graph is shown corresponding to the above regime in Figure 9. In this case, the four lines have been defined to show commercial and non-commercial volumes above 50 cm dbh, and for all trees above 5 cm dbh. The effect of the thinning in reducing the level of non-commercial volume can be seen clearly.

Figure 9 Volume components for a simulation with felling and thinning under basal area control

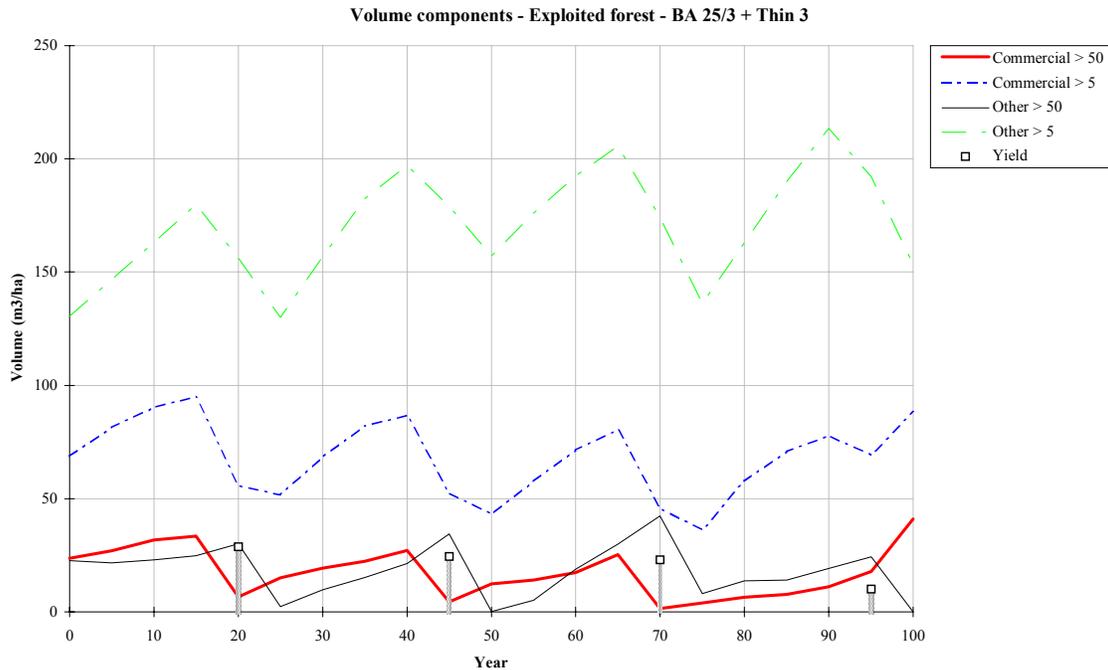**Volume components - Exploited forest - BA 25/3 + Thin 3**

Figure 10 shows the *comparison of simulations* graph from CAFOGROM. In this up to five successive runs can be compared, using the first defined volume component. In this case, this is the volume of commercial trees above 50 cm dbh. The three lines show a forest recovering from logging over a 100 year period, the same forest logged under basal area control, and logging plus thinning under basal area control. The basal area control is specified to permit the extraction of 3 m^2/ha when the stand reaches 25 m^2/ha. Thinning is applied under the same regime 5 years after felling to remove a further 3 m^2/ha of non-commercial species and relict trees of commercial species. The thinning undoubtedly increases commercial yields, although whether it thereby constitutes a feasible economic or political proposition is another question.

These examples illustrate the main outputs of CAFOGROM and the related SIRENA model. SIRENA is being used for management planning in Costa Rica by CODEFORSA. In their situation, questions of short-cycle low impact logging are of great importance, as are questions relating to thinning. CAFOGROM is primarily a test-bed for research concepts in relation to the Amazonian rainforest, but it has been designed to evolve into a management tool over the next two or three years.

Conclusion: Prospects for application in Ghana

Given the quality of data that is potentially available from Ghana's permanent sample plot system, a CAFOGROM-type model could be readily adapted to the needs of forest planning.   Associated with CAFOGROM is a pre-processor program, CIMIR, which can undertake all the required analyses directly from raw plot measurements. The system has

Figure 10 Comparison of three simulation runs: Unlogged, logged, and logging plus thinning

Comparison of simulations - Exploited forest - BA 25/3 + Thin 3
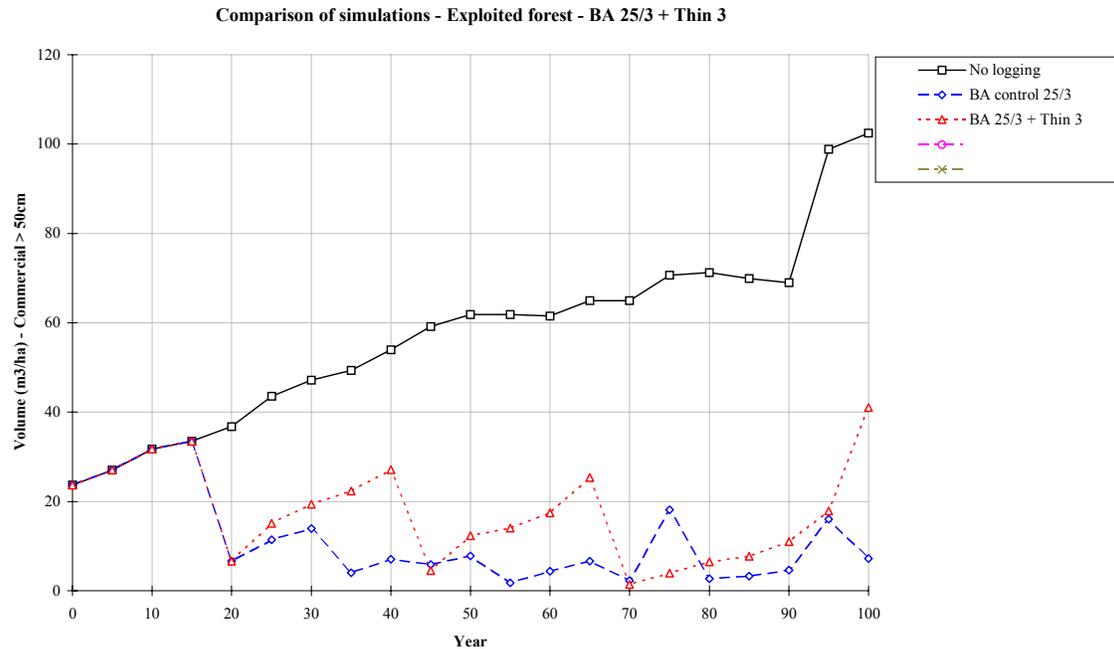
been designed so that specialised computer programming skills are not required. However, the users would need a reasonably good knowledge of statistics and forest dynamics, as well as general computer skills[6].

The institutional arrangements for using a model of this type need to be carefully considered. In Costa Rica and Brazil, effective forest management is primarily a matter for the private sector, with the state imposing only a requirement for sustainable management to be demonstrated. In this context, a model is very useful, as when applied to a particular growing stock and with specific species and size requirements, it can be used to justify a particular management regime.

In Ghana, on the other hand, forest management has so far been a top-down affair, with a single regime being imposed nationally on all high forests. This embraces several forest types, a great variety of species compositions, different industrial demands, and a great variety of exploitation histories. A model would show that for many situations, the general regulations might not be appropriate. But what then should be the next step? In the author's opinion, there is a need for a more flexible and localized approach to forest planning, with a greater participation of the private sector in the planning process. In this context a model can be very useful in helping to develop management plans and tailor felling regulations to local situations.

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[6] Another feature of CAFOGROM interface is that it has been designed from the outset as a multilingual system. Currently it operates with English and Brazilian Portuguese menus, captions, and messages, but the system is open, and additional languages can be added readily.

The basic thesis of this paper has been to show that forest models must incorporate whole stand information if accurate simulations are to be achieved. Analysis of individual tree data in terms of empirical coefficients is driven too much by the coincidental combinations of species, size classes and increments that occur in the data set. Empirical models developed on this basis cannot be reliably generalized to different management situations without some overall regulation or feedback at the forest level. This control can be applied empirically from models of stand basal area dynamics, or it could be derived from a more process-related approach. The latter would be very interesting to explore, and in the author's opinion should constitute the most fertile field for future research.

Acknowledgements

References

Alder, D (1990) GHAFOSIM: A projection system for natural forest growth and yield in Ghana. Consultancy report to the Ministry of Lands and Natural Resources, Ghana. 114 pp.

Alder, D (1995) Growth modelling for mixed tropical forests. Department of Plant Sciences, University of Oxford. *Tropical Forestry Papers* **30**, 231 pp.

Alder, D (1996a) SIRENA: A simulation model for tropical forest management in Northern Costa Rica. ODA Integrated Natural Forest Manegement Project/CODEFORSA Internal Document. 26 pp.

Alder, D (1996b) CAFOGROM.XLS: A simulation model for natural tropical forest management. ODA Silvicultural Research Project/CPATU Internal Document. 40 pp.

Brasnett, NV (1953) Planned Management of Forests. George, Allen & Unwin Ltd., London. pp128-135.

Buongiorno, J; Michie, BR (1980) A matrix model of uneven-aged forest management. *Forest Science* **26** (4) 609-625.

Gordon, J (1995) Evaluación del impacto de aprovechamiento para el modelo de crecimiento CAFOGROM: Análisis preliminar. ODA Integrated Natural Forest Management Project/CODEFORSA Internal Document. 8 pp.

Husch, B; Miller, CI; Beers, TW (1982) Forest mensuration, Third edition. John Wiley & Sons, New York, 402 pp.

Silva, JNM (1989) The behaviour of the tropical rainforest of the Brazilian Amazon after logging. D.Phil. thesis, Department of Plant Sciences, Oxford University. 302 pp.

Silva, JNM; de Carvalho, JOP; Lopes, JCA; Almeida, BF; Costa, DHM; de Oliveira, JC; Vanclay, JK; Skovsgaard, JP (1994) Growth and yield of a tropical

rainforest in the Brazilian Amazon 13 years after logging. Forest Ecology *and Management*.

Silva, JNM; Lopes, J do CA (1984) Inventario florestal continuo em florestas tropicais: A metodologia utilizada pela EMBRAPA/CPATU na Amazonia brasileira. Documentos, Centro de Pesquisa Agropecuaria do Trópico Úmido, EMBRAPA, Brazil, No. 33, 36 pp.

Usher, MB (1966) A matrix approach to the management of renewable resources with special reference to selection forests. *Journal of Applied Ecology* **3**(2)355-367.

Vanclay, JK (1989) A growth model for North Queensland rainforests. *Forest Ecology and Management* 27:245-271.

Vanclay, JK (1994) Modelling forest growth and yield. CAB International, Wallingford. 312 pp.