

# Modelling forest dynamics for practical management purposes

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## This article<sup>1</sup> reports

on a study undertaken with simple matrix models on the three main logged species in French Guiana. These models are good substitutes for pre-existing heavily parameterised models, and provide rapid answers to questions raised on the future of logged tree species. The authors discuss the method used and show the value of investigating the future of species individually rather than in groups.

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Overview of the stand adjacent to experimental plot 16 (*Chimarrhis turbinata*, background). Undisturbed forest.  
Photo S. Gourlet-Fleury.

## RÉSUMÉ

### MODÈLES DE DYNAMIQUE FORESTIÈRE : DES OUTILS D'AIDE À LA GESTION ?

Pour garantir la durabilité de la ressource exploitable, en Guyane française comme ailleurs, les gestionnaires forestiers doivent raisonner le délai entre deux coupes. Pour les y aider, le département Forêts du Cirad a développé plusieurs modèles de dynamique forestière et les a calibrés avec des données sur la croissance, la mortalité et le recrutement, collectées depuis 1984, sur le dispositif sylvicole expérimental de Paracou. Les modèles élaborés — modèle matriciel dépendant de la densité, modèle hybride matriciel-arbre indépendant des distances et modèle arbre dépendant des distances — sont flexibles mais lourdement paramétrés. Pour estimer correctement leurs paramètres, il faut disposer d'importants jeux de données. Par ailleurs, de nombreuses espèces sont peu fréquentes dans les peuplements et elles doivent faire l'objet de regroupements pour pouvoir être correctement décrites dans ces modèles. C'est un inconvénient pour les gestionnaires dont l'intérêt se porte, en général, sur des espèces bien particulières et peu abondantes. Des modèles matriciels simples, indépendants de la densité mais qui prennent en compte l'incertitude existant sur les paramètres d'entrée, sont de bons outils de substitution et apportent des réponses rapides aux questions sur l'avenir des espèces exploitées. Cet article rend compte d'un travail effectué à l'aide de ces modèles sur les trois espèces les plus prélevées en Guyane française. Nous discutons la méthode utilisée et illustrons l'intérêt d'examiner le devenir des espèces prises séparément plutôt qu'en groupe.

**Mots-clés :** modèle d'arbre, modèle matriciel, gestion de forêt, forêt tropicale, Guyane française.

## ABSTRACT

### MODELLING FOREST DYNAMICS FOR PRACTICAL MANAGEMENT PURPOSES

A major challenge for forest managers is to define the optimal rotation period to ensure that resources are sustained on a long-term basis. For this purpose, CIRAD Forestry Department has developed several models of forest dynamics, calibrating them with data recorded since 1984 on growth, mortality and recruitment in the large experimental plots of the Paracou site in French Guiana. The models — a density-dependent matrix model, a hybrid model (matrix/single-tree distance-independent) and a single-tree distance-dependent model — are flexible but heavily parameterised. Large data sets are required to estimate the parameters correctly. As most individual tree species are infrequent in the stands, they cannot be described as such in the models and have to be clustered into species groups. This can be a serious drawback for forest managers, who are generally interested in the future of particular valuable species. Simple matrix models, which are independent of density but take into account the uncertainty of input parameters, are preferable if managers are to be supplied with quick answers. This paper describes how such models are calibrated for the three main harvested species in French Guiana. We discuss the method used and show the relevance of examining the fate of particular species separately rather than in species groups.

**Keywords:** tree model, matrix model, forest management, tropical forest, French Guiana.

## RESUMEN

### MODELOS DE DINÁMICA FORESTAL: ¿HERRAMIENTAS DE AYUDA A LA GESTIÓN?

Para garantizar la sostenibilidad de los recursos explotables, tanto en la Guayana francesa como en otras partes, los gestores forestales deben evaluar razonadamente el plazo entre dos cortas. Para ayudarlos, el departamento Forêts del CIRAD ha desarrollado varios modelos de dinámica forestal y los ha calibrado con datos de crecimiento, mortalidad y reclutamiento obtenidos desde 1984, en el diseño silvícola experimental de Paracou. Los modelos elaborados — modelo matricial dependiente de la densidad, modelo matricial mixto: árbol independiente de las distancias y árbol dependiente de las distancias — son flexibles pero hay que fijar numerosos parámetros. Para evaluar correctamente sus parámetros, es necesario disponer de un importante conjunto de datos. Por otra parte, numerosas especies son poco frecuentes en los rodales y deben agruparse para que se encuentren adecuadamente descritas en estos modelos. Es un inconveniente para los gestores que, en general, suelen interesarse por especies concretas y poco abundantes. Los modelos matriciales simples, independientes de la densidad pero que tienen en cuenta la incertidumbre existente en los parámetros iniciales, son buenas herramientas de sustitución y proporcionan respuestas rápidas a las cuestiones sobre el futuro de las especies explotadas. Este artículo informa sobre el trabajo efectuado con ayuda de estos modelos en las tres especies más explotadas en la Guayana francesa. Se analiza el método utilizado y se explica porqué es más interesante examinar la evolución de las especies de forma separada que en grupo.

**Palabras clave:** modelo de árbol, modelo matricial, gestión del bosque, bosque tropical, Guayana francesa.

## Introduction

Giving permanent financial value to tropical rain forests is considered as an alternative to over-logging, degradation and conversion of those forests. Besides new hopes generated by the Clean Development Mechanism and the establishment of an international market in carbon offsets, much progress is possible in the sustainable production of various valuable forest products.

Efforts have been focused for a long time on management for sustainable timber production (DAWKINS, PHILIP, 1998), although the potential value of biodiversity has recently widened the concept of sustainability (LESLIE, 1997; MANKIN, 1998). However, the results of those efforts appear somewhat discouraging when judged from the viewpoint of the area of tropical forests under real management (GOMEZ-POMPA, BURLEY, 1991; FAO, 1999).

In defining and implementing management plans on forested lands, the main difficulties to be overcome are more concerned with national policies, legislation, land and tree tenure and forest staff training than with technical problems. However, one important issue remains to be addressed: assessing the optimal rotation period to ensure resource sustainability on a long-term basis. The problem stems at once from the lack of appropriate and reliable field data and the complexity of data analysis. It most often requires the development of models of forest dynamics. This remains a difficult exercise which is dependent on available data, time and expertise, and on the initial inferences that are supposed to be drawn from the models (VANCLAY, 1994).

In French Guiana, which is almost entirely covered by 8.5 million ha of lowland rainforest, sustainable forest management became a real concern in the early 1990's. Logging occurs only in the coastal part of the territory. Annual production is about 60 000 m<sup>3</sup>, coming from 20 main species prospected, but only three species accounting for 2/3 of this volume are intensively harvested. These species

are: *Dicorynia guianensis* Amshoff (*Caesalpinaceae*), *Qualea rosea* Aublet (*Vochysiaceae*), *Sextonia rubra* Mez (*Lauraceae*). In order to prevent logging operations from penetrating deeper inland, the National Forest Service (ONF) has marked out units of production forests that, in the medium term, will cover 844 000 ha, mainly along the coast, and has started to implement management plans (DUTRÈVE *et al.*, 2001). During this process, researchers have been questioned intensively on optimal rotation periods. The two main questions are:

- how quickly is the harvestable stock supposed to recover after logging?
- what will be the composition of the flora of harvestable stock at the end of the first rotation?

In this paper, we aim to:

- assess how the forest dynamics models used so far by researchers in French Guiana can help in answering these questions;
- assess the performance of a simple model which is currently used in some other tropical countries for the same purpose, and suggest a way to improve its use.



Overview of the stand in a bottomland near experimental plot 14 (Paracou site). Undisturbed forest.  
Photo J.-G. Jourget.

## Do available models answer to the managers' needs ?

The data used to develop the CIRAD-Forêt dynamics models have been collected since 1984 at the Paracou experimental site (Box 1). The three types of models built up since 1992 are shown in Box 2. These models are intended as prediction tools for forest managers, which remains an objective for the medium-term given their varying degrees of readiness.

A detailed comparison of the functioning and overall value (for research as well as for management) of our models has been made by PICARD *et al.* (2004). The main conclusions of importance for our paper are the following:

- Considering the global pool of species, the three models show a steady state close to what was observed at Paracou before the treatments were implemented. This result applies to diameter structures, as well as to the total number of trees and the cumulated basal area. In detail, SELVA performs better for reproducing global stand characteristics and their variability, while the distribution-based models (matrix and hybrid) perform better for reproducing diameter structures.
- The three models do not behave identically when reconstituting a stand after logging. Figure 1 compares the predictions of the models to what was actually observed at Paracou on a plot which was logged at about 10 trees per hectare  $\geq 60$  cm dbh. SELVA reproduces the evolution of both total number of trees and basal area reasonably well, while with the matrix and the hybrid models (i) the total number of trees seems to reach its stationary value too fast, (ii) the basal area tends to be overestimated.

Let us go back to the two questions addressed in this paper.

### How quickly is the harvestable stock supposed to recover after a logging?

After logging (10 trees/ha, dbh  $\geq 60$  cm), SELVA predicts a return of the stand to equilibrium after more than 150 years, for both the number of trees and the cumulated basal area. The same time is necessary, according to the two other models, for basal area.

The return to the initial state (*i.e.* the state before logging, which is not necessarily the state of equilibrium), in terms of basal area, could be achieved in 50 years according to the matrix model, 60 yrs according to the hybrid model and 80 yrs according to SELVA. Reconstitution of the diameter class  $\geq 60$  cm, which we consider to be roughly equivalent to the harvestable stock, would occur over the same time scale: 50 years according to SELVA, 60 years according to the distribution-based models.

These are indicative results which can guide forest managers provided that they are used with caution: predictions are made for the overall pool of species and there is no guarantee that, 50 or 60 years after logging, the new stock of big trees will be made up of trees of valuable species. This leads to the second question.

### What will be the floristic composition of the harvestable stock at the end of the first rotation?

At present, none of our models is able to answer this question even if they do not ignore it. Modellers usually simplify stands by grouping species according to ecological criteria, reaching a degree of simplification that does not allow the individual examination of a particular valuable species. In some regions, as in Asia, where dipterocarps have fairly uniform ecological behaviour (*i.e.* shade tolerant species stimulated in their early stages by canopy opening, reviewed in ASHTON, 1998), models can be calibrated specifically for one or two commercial groups. However, this is usually not the case in the Amazon and Congo basin regions, where the few commercial timber species belong to a large spectrum of ecological behaviour (FAVRICHON, 1994; FINEGAN *et al.*, 1999; LAHOREAU *et al.*, 2002).

In French Guiana, the 20 species most in demand are spread over three of the five groups considered in the distribution-based models, and over 12 of the 15 growth groups considered in SELVA. The three species which make up 75% of the timber volume extracted from the forest, namely *Dicorynia guianensis*, *Qualea*

### Box 1. The Paracou experimental site.

In French Guiana, forest dynamics have been studied for a long time in permanent sample plots (the oldest were established in 1954 near Saint-Laurent du Maroni; GAZEL, 1983). One of the most intensively studied sites, at Paracou, was set up in 1982 about 50 km NW of the European space city of Kourou, at latitude 5°18' North and longitude 52°53' W.

Twelve plots of nine ha each, were marked out over a globally homogeneous substrate, on a formation called the "ARMINA series", which is characterised by schists and sandstones and locally crossed through by veins of pegmatite, aplite and quartz (PAGET, 1999). In each plot, all trees over 10 cm dbh within a central subplot of 6.25 ha surrounded by a 25 m wide buffer zone were mapped and their coordinates recorded. Since 1984, growth, mortality and recruitment of more than 46 000 trees identified at the species or species group level were recorded annually (every two years since 1996). Between 1986 and 1988, three silvicultural treatments of increasing intensity were applied to nine of the plots (each treatment replicated three times), three plots remaining undisturbed (SCHMITT, BARITEAU, 1990).

## Box 2. Available models.

Three models were built using the Paracou data bank. According to current terminology (FRANC *et al.*, 2000) they can be qualified respectively as:

- a size class model;
- a hybrid model combining size-class and single tree distance-independent components according to the diameter of the trees;
- a single-tree distance-dependent model.

They basically differ from each other by the degree to which they account for individual tree characteristics and their location in the stands.

### Size class model: FAVRICHON'S density-dependent matrix model (1995)

FAVRICHON (1995, 1998) built a transition matrix model with "regulated parameters". In this model, trees are broken down into diameter classes and five species groups. Each species group is characterised by a vector  $y_s$  that gives the number of trees in each diameter class. The variation of  $y_s$  over time is defined by a transition matrix  $A_s$  so that we have:

$$y_s(t + \Delta t) = A_s(t)y_s(t) + r_s(t) \quad [1]$$

with vector  $r_s$  representing recruitment above 10 cm dbh,  $A_s$  being a matrix with non-zero elements along the diagonal and subdiagonal only:

$$A_s = \begin{bmatrix} . & & & & 0 \\ & . & & & \\ & & . & & \\ & & & 1 - b_{si} - m_{si} & \\ 0 & & & b_{si} & . \\ & & & & . \\ & & & & . \end{bmatrix} \quad [2]$$

$m_{si}$  is the probability of death of a tree of species group  $s$  in diameter class  $i$  between time steps  $t$  and  $\Delta t$ , and  $b_{si}$  is the probability of survival of a tree of species group  $s$  in diameter class  $i$  up to the next diameter class, between time steps  $t$  and  $\Delta t$ .

This matrix model is density-dependent, as the transition probabilities  $m_{si}$  and  $b_{si}$  are functions of a stand attribute, namely the cumulative basal area. The recruitment flux,  $r_{si}$ , also depends on basal area. All the relationships are linear:

$$b_{si} = \alpha_{s0} + \alpha_{s1} \overline{D}_i + \alpha_{s2} \overline{D}_i^2 + \alpha_{s3} \frac{B}{B_0}$$

$$m_{si} = \beta_{s0} + \beta_{s1} \overline{D}_i + \beta_{s2} \overline{D}_i^2$$

$$r_{si} = \delta_{s0} + \delta_{s1} \frac{B}{B_0}$$

$\overline{D}_i$  is the average diameter of the  $i_{th}$  diameter class,  $B$  is the cumulated basal area of the whole stand at time  $t$  and  $B_0$  is the "reference" basal area, that is to say of the stand before disturbance (calculated in 1984 at Paracou). In this version, the model is entirely deterministic.

### Hybrid model (PICARD, 1999)

PICARD (1999) divided the stand into two components: trees under and over 40 cm dbh. He built a transition matrix model with "regulated parameters", similar to FAVRICHON'S model, for small trees, and calibrated an individual-based model for large trees without taking their location in space into account. The same five species groups as FAVRICHON'S are used.

The following growth equation is applied to large trees (over 40 cm dbh):

$$\Delta_t D_j = (a_{s0} + a_{s1} \frac{B}{B_0}) \Delta t$$

where  $j$  refers to the individual tree and  $\Delta_t D_j$  to its diameter increment.  $B$  and  $B_0$  are defined as in the previous paragraph and  $a_{s0}$  and  $a_{s1}$  are parameters specific to each of the five species groups. To this growth equation is added a mortality rate that depends on the diameter of the tree only.

The connection is established between the two components through the recruitment of trees above 40 cm dbh. Conditions to ensure the continuity of the whole diameter distribution of the stand result in full dependency between the parameters of the matrix model and the parameters of the individual growth equation.

### Single-tree distance-dependent model: SELVA (GOURLET-FLEURY, 1997)

In this type of model, as many tree characteristics as possible, including its spatial coordinates, are taken into account. SELVA runs submodels describing growth, mortality and recruitment in the following way.

#### Growth

Growth models have been developed for 15 groups of species (GOURLET-FLEURY and HOULLIER, 2000) in the following general form:  $\Delta_t D_{sj} = \text{average}(D_{sj}) \times \text{modifier}(IC_{sj}, \Delta_{t-\Delta t} IC_{sj}) \times \varepsilon_{sj}$  where  $s$  refers to the group of species,  $j$  to the individual tree, and  $\Delta_t D_{sj}$  to its diameter increment. The function average ( $D_{sj}$ ) is of the sigmoid family (Gompertz or Korf equation, see ZEIDE, 1993) and describes the behaviour of a tree of diameter  $j$  and group of species  $s$  in a "neutral environment". The function modifier ( $IC_{sj}, \Delta_{t-\Delta t} IC_{sj}$ ) depends on indices ( $IC_{sj}$ ) reflecting local competition around the tree  $j$  inside a circular plot of radius 30 m, and past variations in this competition (between  $t - \Delta t$  and  $t$ ). The form of these two functions as well as the type of the competition indices vary according to the dominant behaviour of the group of species considered.  $\varepsilon_{sj}$  is a log-normally distributed random variate.

When all species are grouped together, the equation is as follows:

$$\ln(\Delta_t D_j + ct) = a + \left[ \ln(m) + \ln(D_j) + \frac{1}{1+m} \ln(\ln(K) - \ln(D_j)) \right] + \left[ a_0 \sqrt{NBD_j} + a_1 \Delta_{t-\Delta t} NBD_j + a_2 (\Delta_{t-\Delta t} NBD_j)^2 \right] + \varepsilon_j$$

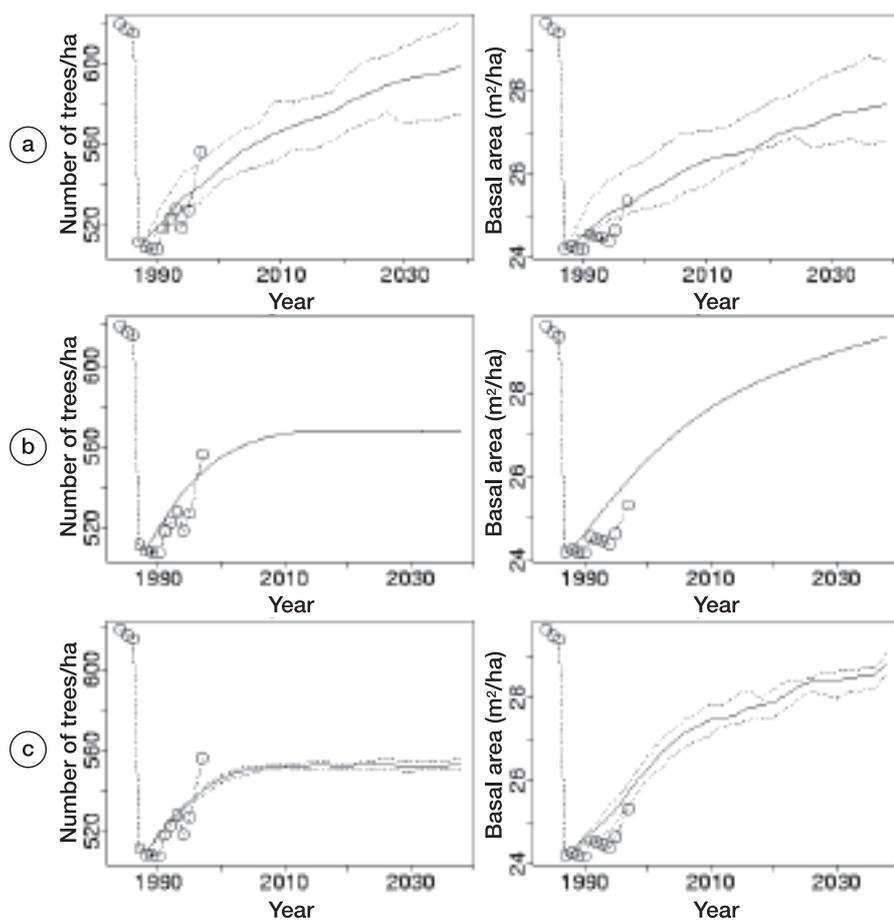
where  $a$ ,  $m$  and  $K$  are the parameters of the Korf model,  $a_0$ ,  $a_1$  and  $a_2$  are the other regression parameters.  $NBD_j$  is the total number of trees whose diameter exceeds  $D_j$  within a radius of 30 m around tree  $j$ , and  $\Delta_{t-\Delta t} NBD_j$  is the past variation of this number.  $\varepsilon_j$  is a normally distributed residual.

#### Mortality

SELVA takes four types of mortality into account. The probability of occurrence of standing mortality (age, disease, competition), primary windthrow (falling for some reason excluding the impact of another falling tree), complex windthrow (unsteadiness due to the opening of a gap) are logistic functions of the characteristics of the tree as well as of particular competition indices. The number of trees broken by the fall of big trees is described in a deterministic way.

#### Recruitment

Ingrowth is described through the probability for a certain number of trees of more than 10 cm dbh to appear in 10 x 10 m square cells of a regular grid superimposed on the stand under study. The probability is a general logistic function of the local cumulated basal area.



**Figure 1.**

Predicted (—) and observed (O) variation in Paracou plot 9, where treatment 1 was carried out.

— average variation over 12 reiterations of simulations ((a) SELVA, (c) hybrid model) or deterministic variation ((b) matrix model);

... envelopes of the 12 simulations.

*rosea* and *Sextonia rubra*, are “hidden” in one of the five species groups of the distribution-based models, which groups together 18 “emergent mid-tolerant” species. In this group, they represent 26% of the total number of trees and 38% of the basal area only. Predictions on how this group may evolve do not tell us a lot about what will happen to the three individual species.

Calibrating dynamics models requires a lot of data. Modellers basically have two options: (i) if they are interested in mechanisms, they will try to capture the behaviour of the stands as realistically as possible. To do so, they tend to parameterise the components of the dynamics heavily (regulated parameters in the transition matrix, individual-based distance-dependent growth and mortal-

ity models) and, in order to keep a large enough data set for calibration, they tend to group species according to a number of general behaviour patterns which are relevant to the construction of the model (global ecological behaviour in the distribution-based models, diameter increment in SELVA). In some ways, it might be said that species are not the important point. (ii) If they want to supply quick answers to forest managers, regarding particular species. In this case, and when the species of interest are scarce in the stands, the data needs usually require oversimplification of the dynamic model.

At present, the second option is the usual choice in several Congo Basin countries. This results in the use of non-regulated matrix models (in Côte d'Ivoire: MENGIN-LECREULX, 1990; DURRIEU DE MADRON *et al.*, 1998a; in Republic of Central Africa: BEDEL *et al.*, 1998; in Cameroon: DEBROUX, 1998) or derived simple formulae linking the percentage of harvestable stock recovery to the minimum felling diameter through mean diameter increment and mortality values (DURRIEU DE MADRON *et al.*, 1998b). Matrix models are preferred when experimental data sets on forest dynamics are available; the reconstitution formula is generally used with mean mortality and growth values taken from the literature.

In all cases, the inaccuracy of the estimated parameters has been poorly addressed in the matrices or formula. Although the estimates are given with confidence intervals, only mean values are used. For mortality rates, the situation is even worse because data are scarce and the phenomena highly variable in time. Very often, a default mortality rate of 1% is used.

The following paragraphs describe the non-regulated matrix model we built up for each of the three main commercial species in French Guiana and our studies of their behaviour, taking into account the variability of the estimated parameters based on their empirical distribution.

## Predicting variation in the harvestable stock of French Guiana's three most valuable species

### Populations, model and parameters

The three populations considered are those which were present in the 12 permanent plots (75 ha) of the Paracou site in 1984, before logging and silvicultural treatments (see Box 1). The total densities of *Dicorynia guianensis*, *Qualea rosea* and *Sextonia rubra* were respectively 520 trees, 710 trees and 210 trees. The populations were broken down by six dbh classes, 10 cm wide.

The model used is the same as [1], with  $A_S$  expressed as [2] (see Box 2). The  $b_{Sj}$  and  $m_{Sj}$  parameters are taken as constants for each simulation. The  $b_{Sj}$  are calculated from diameter increments estimated for each diameter class considering the two-year period before implementation of the silvicultural treatments. The  $m_{Sj}$  are estimated using as many observations on natural mortality as possible. For this, we used all the years available and were obliged to group diameter classes together in order to obtain meaningful information: only three classes were kept, namely 10-40 cm, 40-60 cm and  $\geq 60$  cm. We proceeded on a treatment by treatment basis in order to assess the variability of the mortality phenomenon (taking into account only mortality due to "natural causes", that is to say that death directly linked to the felling of valuable trees was excluded). In doing so, we probably overestimated values because silvicultural treatments have an impact on natural mortality. The data used for each species are shown in Table I and Table II.

For each species, the recruitment vector  $R_S$  was calculated so as to maintain a constant number of trees in the first diameter class.



Carbet of the Paracou camp.  
Photo A. Ferment.

**Table I.**

Diameter increment values used to build the non-regulated matrix models (cm/yr). Class 1 to class 5 are obtained when the interval of variation of the observed increments is divided by five:  $class_i = \min + i * [(max - \min) / 5]$ . The data under each class are the frequency of diameter increments observed between  $class_{i-1}$  and  $class_i$ . The sum for each diameter class equals 1. This information is used to sample diameter increments according to the observed frequency.

Diameter classes (cm)	Number	Mean (cm/yr)	Min (cm/yr)	Max (cm/yr)	Distribution frequency of increments				
					Class 1	Class 2	Class 3	Class 4	Class 5
<i>Dicorynia guianensis</i>									
10-20	207	0.16	0.00	0.48	0.436	0.240	0.151	0.089	0.084
20-30	93	0.31	0.00	0.56	0.158	0.158	0.341	0.221	0.122
30-40	68	0.35	0.00	0.72	0.121	0.242	0.152	0.303	0.182
40-50	55	0.35	0.00	0.80	0.269	0.250	0.308	0.154	0.019
50-60	33	0.33	0.00	0.87	0.290	0.355	0.161	0.129	0.065
$\geq 60$	48	0.23	0.00	0.64	0.350	0.275	0.200	0.125	0.050
<i>Qualea rosea</i>									
10-20	168	0.13	0.00	0.48	0.561	0.151	0.115	0.108	0.065
20-30	78	0.21	0.00	0.48	0.292	0.215	0.200	0.154	0.139
30-40	87	0.34	0.00	0.88	0.308	0.333	0.192	0.090	0.077
40-50	117	0.34	0.00	0.80	0.330	0.275	0.202	0.119	0.073
50-60	91	0.29	0.00	0.80	0.359	0.269	0.231	0.077	0.064
$\geq 60$	152	0.21	0.00	0.72	0.304	0.256	0.272	0.064	0.104
<i>Sextonia rubra</i>									
10-20	60	0.08	0.00	0.28	0.407	0.296	0.278	0.000	0.019
20-30	30	0.23	0.00	0.64	0.241	0.483	0.000	0.241	0.035
30-40	16	0.23	0.00	0.64	0.310	0.310	0.000	0.250	0.125
40-50	12	0.36	0.08	0.72	0.182	0.273	0.182	0.273	0.091
50-60	21	0.26	0.00	0.56	0.333	0.056	0.278	0.167	0.166
$\geq 60$	57	0.26	0.00	0.80	0.392	0.314	0.177	0.588	0.588

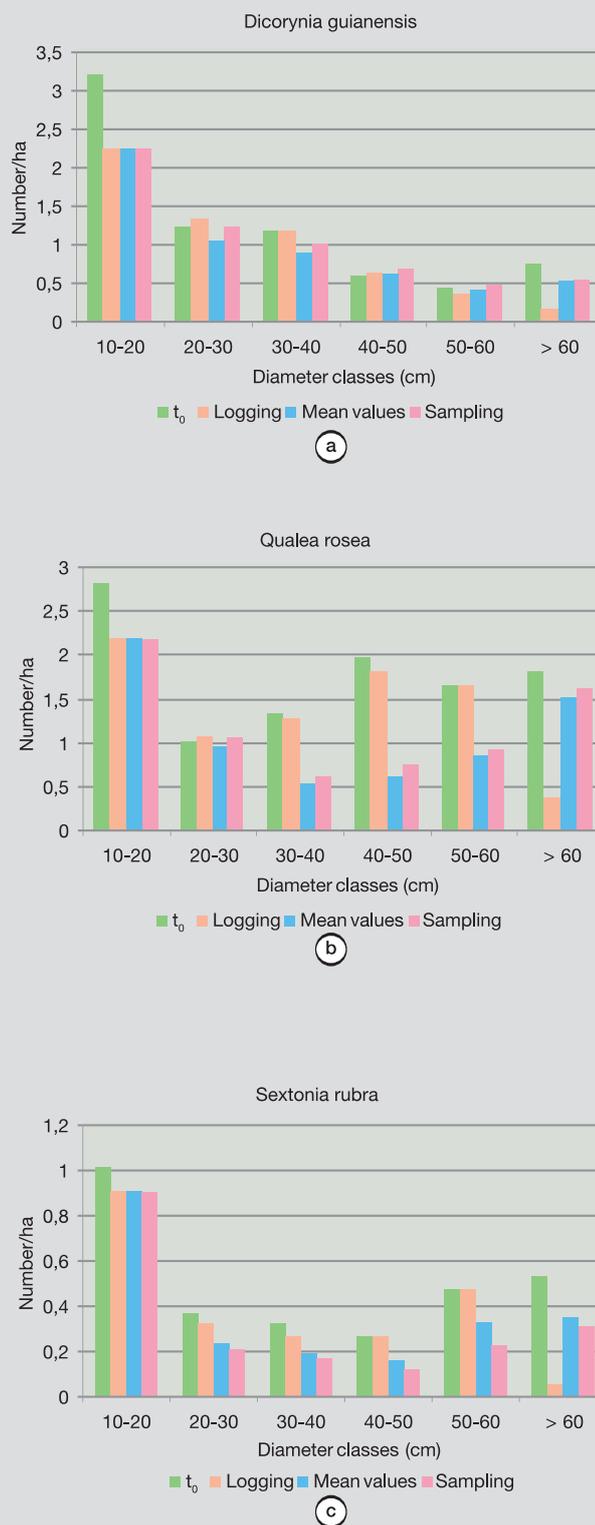
### Simulation method

The output variable of most interest is the level of stock recovery at the end of the first rotation period. At present, in French Guiana, the rotation length is 40 years, based on time projections of basal area increments observed at Paracou in the early 1990s. Since then, both the accumulation of data and improvements in calculation methods have led to recommend a longer rotation period of 50 years, which appears to be reasonable for the Paracou site (GOURLET-FLEURY, 2000). In this study, we have therefore focused on the number of trees of more than 60 cm dbh at the end of 50 years of simulation with the matrix model.

The initial state, *i.e.* the input vector, is the diameter distribution of the population under study immediately after logging. The final state is compared to the diameter distribution before logging.

For each species, two types of simulations were performed:

- one simulation using the mean values of diameter increments (6 values, for the 6 diameter classes) and the observed value of the mortality rate in the logged-over plots (*cf.* T1 in Table II, 3 values for the 3 diameter classes). The matrix model has fixed parameters, it is used once and at the end we obtain a single value for the output variable.
- 10 000 repetitions of the simulation, using values of the matrix parameters sampled inside their variation domain: (i) for mortality rates, systematic sampling is performed between the minimum and the maximum values; (ii) for diameter increments, sampling is achieved according to the observed frequency distribution of increments between the 5<sup>th</sup> and the 95<sup>th</sup> percentile of actual distribution. At the end, we obtain 10 000 values of the output variable for which we compute the mean and the variance.



**Figure 2.**

Variation in observed and simulated diameter distributions for (a) *Dicorynia guianensis*, (b) *Qualea rosea* and (c) *Sextonia rubra* at Paracou.

“ $t_0$ ” refers to the year immediately preceding the logging operations.

“Logging” refers to the year following the logging operations. “Mean value”

indicates the result of a 50-year simulation using only one set of parameters (mean values of diameter increments and observed mortality rate in logged-over plots). “Sampling” refers to the 10,000 simulations carried out with sampled parameters. The distribution shown is the mean result of those simulations.

## Results

Figure 2 shows the changes in the observed and predicted diameter distributions for each species. Results for the output variable are given in Table III.

First, it can be seen that the three species have very distinct initial diameter distribution types. They are more or less negatively exponential, with a regular downward trend for *Dicorynia guianensis*, high accumulation of trees in the intermediate classes for *Qualea rosea* and accumulation of trees in the high diameter classes for *Sextonia rubra* (Figure 2). The use of the matrix models results in a rapid loss of the initial shape, which is particularly pronounced for the two last species due to the value of the parameters estimated for the intermediate classes. Two hypothesis can be made: (i) on the scale of Paracou, the shape reflects the ecological behaviour of the species but the data set is not large enough to produce correct estimates of the parameters. The simulated loss of shape is thus probably artificial; (ii) the initial shape is transient, for historical reasons, and the parameters were correctly estimated: the trend indicated by the results of the simulation may be reasonable. The first hypothesis is probably true for *Qualea rosea* while for *Sextonia rubra*, we probably have a mixture of the two hypotheses.

Secondly, the number of trees of dbh  $\geq 60$  cm after 50 years predicted either by using one set of mean parameters, or by calculating the mean result of 10 000 repetitions with sampled parameters are close to each other, regardless of the species. No logical rule can be found as to over or under-evaluation according to the initial diameter distribution. The important point is that, by sampling parameters and averaging the results of the simulations, we obtain what can be considered as "the most probable value" given the quality of the increment and mortality estimates for the trees under study. We also obtain



Damage in experimental plot 4 caused by a falling tree (Paracou site). Logged and thinned forest. Photo J.-G. Jourget.



Pinot palms (*Euterpe oleracea*) in plot 16. Undisturbed forest. Photo A. Ferment.

**Table II.**

Annual mortality rates used to build the non-regulated matrix models (%). For each diameter class, the minimum and maximum values observed are considered as the bounds of the variation interval in which mortality rates are sampled for the simulations. To refers to the control plots, T1 to logged-over plots, T2 to logged-over + thinned plots and T3 to heavily logged-over + thinned plots.

Diameter classes (cm)	Control plots			
	To	T1	T2	T3
<i>Dicorynia guianensis</i>				
10-40	0.19	0.54	0.64	0.22
40-60	0.90	2.09	1.22	0.75
$\geq 60$	1.79	0.00	0.00	0.00
<i>Qualea rosea</i>				
10-40	1.36	1.05	0.47	1.78
40-60	0.24	1.27	0.29	1.88
$\geq 60$	1.32	1.27	0.00	0.94
<i>Sextonia rubra</i>				
0-40	1.16	1.07	1.29	2.07
40-60	2.46	0.53	0.00	0.00
$\geq 60$	1.45	0.00	0.00	1.89



Angelica sapling (*Dicorynia guianensis*, the main logged species in French Guiana) in the forest understory. Photo J.-G. Jourget.

**Table III.**

Commercial stock (number of trees  $\geq 60$  cm dbh) before and after logging, and recovery after 50 years, depending on the parameters used.

Species	<i>Dicorynia guianensis</i>	<i>Qualea rosea</i>	<i>Sextonia rubra</i>	Total
Initial state (t/ha)	0.75	1.81	0.53	3.09 t/ha
After logging (t/ha)	0.16	0.37	0.05	0.58 t/ha
After 50 years (mean)	0.52	1.51	0.35	2.38 t/ha
After 50 years (sampling)	0.59	1.68	0.31	2.58 (t/ha)
Variance	0.077	0.411	0.020	
Variation coefficient (%)	47.0	38.2	45.8	

a confidence interval on the result, which appears to be very large, excluding zero by a narrow margin. Variation coefficients are high for both *Dicorynia guianensis* and *Sextonia rubra*, whereas for *Qualea rosea* the mean result appears to be less variable because of the narrower interval of variation in mortality in the last diameter class for this species.

Third, all the simulations indicate that the initial number of trees of dbh  $\geq 60$  cm will not recover within 50 years after logging, the situation being of greater or lesser concern depending on the species. If the three species are grouped together, 83.5% of the stock could be back by the end of the felling cycle. This is consistent with what was indicated in GOURLET-FLEURY (2000)



Hemispheric photograph taken in plot 11. Undisturbed forest.  
Photo V. Gond.

## Conclusion

where, for 17 species, a 81% recovery rate after 50 years was found using other methods. However, this masks a 79% rate for *Dicorynia guianensis*, a 93% rate for *Qualea rosea*, and a mere 58% rate for *Sextonia rubra*. The latter species, in our view, deserves special attention from the ONF insofar as forest management is supposed to consider to biodiversity as well as sustainable timber production.

The models built up so far for French Guiana are capable of giving some indication about what the rotation length should be, but whatever their level of detail (based on distribution or single trees, spatially explicit or not), these indications are only based on the recovery of whole stands or groups of species clustered according to certain behavioural criteria.

In view of sustainable forest management objectives that include sustaining biodiversity as well as timber production, the ability to supply predictions on particular species is critical. The use of simple, non-regulated matrix models seems to be the most practical and efficient way to achieve this goal and to answer the two main questions addressed in this paper. However, this should not be done without caution:

- First, such models should not be used to predict long term changes after logging, in particular beyond the first felling cycle. The loss of the initial diameter distribution shape is rapid and can be a pure artefact, resulting, at the end of a 50 year cycle, in distributions that no longer reflect the characteristics of the species studied. This could be particularly true for species with local accumulations of trees like *Qualea rosea* and *Sextonia rubra*.

- Use should be made of the real information available on the variability of estimates of population dynamics parameters, at least for diameter increments and mortality rates. This can be achieved by repeated simulations with sampling of the parameters in the interval of variations observed. The mean result can thus be associated with meaningful confidence intervals, to obtain assessments of the risk taken depending on the species considered. In the case of French Guiana, results show that a 50-year felling cycle could ensure the recovery of 83% of trees of dbh  $\geq$  60 cm belonging to the three most valuable timber species. However, there are high risks to the recovery of one of them, *Sextonia rubra*, which will probably deserve more careful logging rules in future.



Clearing in the stand in plot 15 (control).  
Photo J.-G. Jourget.

## References

- ASHTON M. S., 1998. Seedling ecology of mixed-dipterocarp forest. *In: A review of dipterocarps, Taxonomy, ecology and silviculture*. Appanah S. and Turnbull J. M. (ed.), CIFOR, FRIM: 90-98.
- BEDEL F., DURRIEU DE MADRON L., DUPUY B., FAVRICHON V., MAÎTRE H.-F., BAR-HEN A., NARBONI P., 1998. Dynamique de croissance dans des peuplements exploités et éclaircis de forêt dense africaine. Dispositif de M'Baïki en République Centrafricaine (1982-1995). Série FORAFRI, document n° 1, 72 p.
- DAWKINS H. C., PHILIP M. S., 1998. Tropical moist forest silviculture and management. A history of success and failure. United Kingdom, Wallingford, CAB International, 359 p.
- DEBROUX L., 1998. L'aménagement des forêts tropicales fondé sur la gestion des populations d'arbres : l'exemple du Moabi (*Baillonella toxisperma* Pierre) dans la forêt du Dja, Cameroun. Thèse de doctorat, faculté universitaire des sciences agronomiques de Gembloux, Belgique, 283 p.
- DURRIEU DE MADRON L., FAVRICHON V., DUPUY B., BAR-HEN A., MAÎTRE H.-F., 1998 a. Croissance et productivité en forêt dense humide. Bilan des expérimentations dans le dispositif d'Irobo, Côte d'Ivoire (1978-1990). Série FORAFRI, document n° 2, 69 p.
- DURRIEU DE MADRON L., FORNI E., KARSENTY A., LOFFEIER E., PIERRE J.-M., 1998 b. Le projet d'aménagement pilote intégré de Dimako. Série FORAFRI, document n°7, Coopération Française-CIFOR-CIRAD, 160 p.
- DUTRÈVE B., JULLIOT C., BRUNAU O., 2001. Biodiversité et aménagement forestier en Guyane : approche méthodologique. Bois et Forêts des Tropiques, 269 (3) : 65-75.
- FAVRICHON V., 1994. Classification des espèces arborées en groupes fonctionnels en vue de la réalisation d'un modèle de dynamique de peuplement en forêt guyanaise. Revue d'Ecologie (La Terre et la Vie), 49 : 379-403.
- FAVRICHON V., 1995. Modèle matriciel déterministe en temps discret. Application à l'étude de la dynamique d'un peuplement forestier tropical humide (Guyane française). Thèse de doctorat, université Claude Bernard, Lyon I-CIRAD, France, 252 p.
- FAVRICHON V., 1998. Modeling the dynamics and species composition of a tropical mixed-species uneven-aged natural forest: effects of alternative cutting regimes. Forest Science, 44 (1): 113-124.
- FAO, 1999. State of the world's forests. FAO, 156 p.
- FINEGAN B., CAMACHO M., ZAMORA N., 1999. Diameter increment patterns among 106 tree species in a logged and silviculturally treated Costa Rican rain forest. Forest Ecology and Management, 121 (3): 159-176.
- GAZEL M., 1983. Croissance des arbres et productivité des peuplements en forêt dense équatoriale de Guyane. Rapport interne, ONF, 129 p.
- GOMEZ-POMPA A., BURLEY F. W., 1991. The management of natural tropical forests. *In: Rain Forest Regeneration and Management*. Gomez-Pompa A., Whitmore T. C. and Hadley M. (ed.), UNESCO, Man and the Biosphere Series, volume 6, 3-18.
- GOURLET-FLEURY S., 1997. Modélisation individuelle spatialement explicite de la dynamique d'un peuplement de forêt dense tropicale humide (dispositif de Paracou, Guyane française). Thèse de doctorat, université Claude Bernard Lyon I-CIRAD, France, 274 p.
- GOURLET-FLEURY S., HOULLIER F., 2000. Modelling diameter increment in a lowland evergreen rain forest in French Guiana. Forest Ecology and Management, 131 (1-3): 269-289.
- GOURLET-FLEURY S., 2000. Dispositif sylvicole expérimental de Paracou (Guyane française). Aperçus sur l'état et la dynamique des peuplements 13 ans après installation. Rapport CIRAD-Forêt/Silvolab-Guyane, 253 p.
- LAHOREAU G., PICARD N., GOURLET-FLEURY S., 2002. Grouping species to model forest dynamics: a case study of a forest in the Central African Republic. Bois et Forêts des Tropiques, 271 (1): 89-100.
- LESLIE A. J., 1997. Aménagement durable des forêts ombrophiles tropicales pour la production de bois. *In: Ouvrages sur l'aménagement durable des forêts*. Étude FAO Forêts, n° 122, 19-36.
- MANKIN W. E., 1998. Defining sustainable forest management. Tropical Forest Update (ITTO Newsletter), 8 (3): 7.
- MENGIN-LECREULX P., 1990. Simulation de la croissance d'un peuplement de forêt dense : le cas de la forêt de Yapo (Côte d'Ivoire). Rapport SODEFOR-CTFT, 51 p.
- PAGET D., 1999. Étude de la diversité spatiale des écosystèmes forestiers guyanais. Réflexion méthodologique et application. Thèse de doctorat, École nationale du génie rural, des eaux et des forêts de Paris, CIRAD, France, 151 p.
- PICARD N., GOURLET-FLEURY S., FAVRICHON V., 2004. Modelling the forest dynamics at Paracou: the contribution of four models. *In: Ecology and Management of a Neotropical rainforest. Lessons drawn from Paracou, a long-term experimental research site in French Guiana*. Gourlet-Fleury S., Guehl J.-M. and Laroussinie O. (ed.). Paris, France, Elsevier. In press.
- SALTELLI A., CHAN K., SCOTT E. M., 2000. Sensitivity analysis. John Wiley & Sons, 504 p.
- SCHMITT L., BARITEAU M., 1990. Gestion de l'écosystème forestier guyanais. Étude de la croissance et de la régénération naturelle. Dispositif de Paracou. Bois et Forêts des Tropiques, 220 : 3-23.
- VANCLAY J. K., 1994. Modelling forest growth and yield. Applications to mixed tropical forests. Wallingford, United Kingdom, CAB International, 280 p.
- ZEIDE B., 1993. Analysis of growth equations. Forest Science, 39 (3): 594-616.



Angelica inflorescence and leaf  
(*Dicorynia guianensis*).  
Photo P. Petronelli.