Propositions
being part of the PhD thesis
'TROPFOMS, A Decision Support Model for
Sustainable Management of South-Cameroon's Rain Forests'
by Richard Eba'a Atyi

1. Environmental awareness has a strong positive correlation with economic development: poor people's main concern is to-morrow's meal rather than environmental issues.

2. The purpose of mathematical programming is insight, not numbers (D.P. Dykstra, 1984).

3. An attractiveness of a quantitative analysis is that it provides a common language for different stakeholders (this thesis).

4. There is no country where all the rights contained in the Universal Declaration of Human Rights are honoured for all citizens (C. Short, Department for International Development, 1998).

5. There are ways to reconcile forest conservation with both industrial timber harvesting and forest utilisation by the local population (this thesis).

6. Mankind has made substantial progress in technology during the twentieth century, unfortunately, the same cannot be said about morality.

7. The primary role of an analyst in forest management is to provide decision makers with a basis for their decisions, not to make decisions (this thesis).

8. Un bon forestier doit avoir les pieds sur terre et la tête dans les nuages (J.J. Faure, 1984, during a lecture in forest management).

TROPFOMS, a decision support model for sustainable management of south Cameroon's rainforests

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TROPFOMS, a decision support model for sustainable management of south Cameroon's rainforests

by

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Proefschrift
Ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
Dr. C.M. Karssen,
in het openbaar te verdedigen
op dinsdag 15 februari 2000
des namiddags te 16.00 uur in de Aula

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Eba'a Atyi, Richard
TROPFOMS, a decision support model for sustainable management of south Cameroon's rainforests
Thesis Wageningen University. - With ref. - With summaries in English, Dutch and French

ISBN: 90-5808-194-X

Also published as Tropenbos-Cameroon Series 2.

Cover design: Duotone, Wageningen University, the Netherlands
Cover photo: Tali (*Erythrophleum ivorense*). Photo by B.S. van Gemerden
Printed by: Ponsen en Looijen, Wageningen, the Netherlands

ABSTRACT

The present study aims to support decision-making in rainforest management in Cameroon. A model called TROPFOMS (TROPical Forest Management support System) has been designed to guide decisions on the cutting cycle and timber yields during the steady state and the conversion period, taking ecological, social, economic and technical aspects into account. TROPFOMS includes a mathematical programming module, a growth and yield module, an economic module and a constraint definition module. It uses quantitative methods (transition matrices, cluster analysis, logistic regression analysis, mathematical programming, stumpage prices derivation). The model results in an optimal cutting cycle of about 30 years, and a harvest of 13.4 m^3/ha for species currently commercialized. It would require about 120 year to convert forest at the study site into a steady state forest.

Key words: Tropical rainforest, Forest management, Decision-making, Sustainability, Cameroon.

TABLE OF CONTENTS

ABSTRACT	**v**
LIST OF TABLES	**x**
LIST OF FIGURES	**xiii**
LIST OF ACRONYMES	**xiv**
PREFACE	**XVI**
1. INTRODUCTION	**1**
1.1 Background on the forestry sector of Cameroon	**1**
1.1.1 A synthesis of Cameroon's forest resources and logging activities	1
1.1.2 Cameroon's forestry institutions	2
1.1.3 Synthesis of current forest management options in Cameroon	2
1.2 General context of the study	**5**
1.2.1 Administrative setting of the research project	5
1.2.2 The research site	6
1.2.3 The research problem	7
1.3 Organization of the document	**8**
2. REVIEW OF FOREST MANAGEMENT AND DECISION-MAKING	**9**
2.1 Sustainability and sustainable management	**9**
2.1.1 The general concept	9
2.1.2 Sustainability and forest management	9
2.2 The sustainable management of tropical forests: issues and opportunities	**13**
2.2.1 The occurrence of tropical forests	13
2.2.2 Some characteristics of the tropical rainforests	14
2.2.3 The management of tropical forests: technologies, problems, constraints and prospects	17
2.3 Decision-making in forest management	**20**
2.3.1 The importance of decision-making in forest management	20
2.3.2 The process of decision-making in forest management	21
2.3.3 Decision Support Systems (DSS) and forest resources management	23
2.3.4 Decision-making in tropical forestry	34
2.3.5 Integration of non-timber aspects in forest management strategies	36
2.4 Conclusion: research orientation	**40**
3. RESEARCH OBJECTIVES AND CONCEPTUAL APPROACH	**41**
3.1 Synopsis of research gaps	**41**

3.2 Research objectives 41
3.2.1 General objective 41
3.2.2 Specific objectives 42

3.3 Conceptual framework 42

3.4 Research questions 43

3.5 The research process 46

3.6 Synopsis of the research methods 47

4. TROPFOMS: ARCHITECTURE, PROCEDURES AND THEORETICAL APPROACHES IN THE MODEL 50

4.1 Expected outputs from TROPFOMS 50

4.2 The architecture of TROPFOMS 52

4.3 The procedural design of TROPFOMS 53

4.4 The theoretical approaches in TROPFOMS 55
4.4.1 The approach in growth and yield modeling 55
4.4.2 The economic objective function 59
4.4.3 Constraints 61
4.4.4 The conversion strategy 61

4.5 Conclusion on the design of TROPFOMS 62

5. RESEARCH METHODS 63

5.1 Methods for the estimation of growth and yield parameters 63
5.1.1 Species aggregation 63
5.1.2 Estimation of growth and yield 68

5.2 Stumpage derivation 69

5.3 Analysis of inventory results 74

5.4 Analysis of forestry sector organization and regulations 74

5.5 Forest utilization by local populations 75

5.6 Mathematical programming methods 75

6. PARAMETERS AND COEFFICIENTS USED IN TROPFOMS 77

6.1 Growth and yield coefficients 77
6.1.1 Species groups 77
6.1.2 Transition probability estimates 78
6.1.3 Ingrowth equations 82

6.2 Stumpage prices 83
6.2.1 FOB prices per species group 83
6.2.3 Commercialization coefficients 85
6.2.4 Costs of availability 86

6.2.5 Stumpage price 87

6.3 Forest inventory **88**

6.4 Forest utilization by the local population **88**

6.5 Conclusion on the coefficients used by TROPFOMS **90**

7. OUTCOMES OF TROPFOMS FOR THE STEADY STATE FOREST **91**

7.1 Recapitulation of basic constraints specifications **92**

7.2 Steady state characteristics under economic objective **94**

7.3 Constraining TROPFOMS for alternative forest management objectives **106**
7.3.1 Including constraints for species-size diversity 106
7.3.2 Restrictions related to the local population 108

7.4 Conclusions on the steady state characteristics **110**
7.4.1 Conclusions on the steady state characteristics with alternative management objectives 110
7.4.2 Trade off between management objectives 113

8. THE OUTCOMES OF TROPFOMS FOR THE CONVERSION OF THE TROPENBOS CAMEROON RESEARCH SITE **115**

8.1 Management actions during the conversion period **115**

8.2 Simulations of the duration of the conversion period **117**

8.3 Revenues expected during the conversion period **120**

8.4 Conclusion on the conversion period **126**

9. REFLECTIONS, CONCLUSIONS AND RECOMMENDATIONS **127**

9.1 The design of TROPFOMS and its mathematical programming approaches **127**
9.1.1 Reflections on the design of TROPFOMS 127
9.1.2 Reflections on the mathematical programming approaches of TROPFOMS 128
9.1.3 Conclusion on the reflections about the design and the mathematical programming approaches of TROPFOMS 128

9.2 Reflection on the data needs and methods of analysis **129**
9.2.1 Methods of analysis and data needs for forest stands characterization 130
9.2.2 Methods and data for the derivation of stumpage price 132
9.2.3 Conclusion on the data needs and methods of analysis for forest stand characterization 133

9.3 Reflections on the outcomes of TROPFOMS **133**
9.3.1 The outcomes related to the steady state 133
9.3.2 Outcomes related to the conversion period 136
9.3.3 Conclusions on the outcomes 136

9.4 Final conclusions **137**

9.5 Recommendations **138**
9.5.1 Recommendations for policy and management 138
9.5.2 Recommendations for further research 140

SUMMARY 155

SAMENVATTING 161

RESUME 167

ANNEX 1: LIST OF SPECIES ANALYZED FOR GROUPING 173

ANNEX 2: CORRESPONDENCE BETWEEN PILOT AND SCIENTIFIC NAMES FOR TREE SPECIES INVENTORIED AT THE TCP RESEARCH SITE 175

ANNEX 3: SPSS CLUSTER ANALYSIS OUTPUT FOR SPECIES AGGREGATION 179

ANNEX 4: SUMMARY OF DATA USED FOR THE DEVELOPMENT OF BOLE VOLUME EQUATIONS 182

ANNEX 5: STATISTICS OF THE ESTIMATION OF BOLE VOLUME EQUATIONS FOR DIFFERENT SPECIES GROUPS 183

ANNEX 6: SUMMARY OF PERMANENT SAMPLE PLOTS DATA 184

ANNEX 7: STATISTICS ON VARIABLE SELECTION FOR THE ESTIMATION OF TRANSITIONS PROBABILITIES BY LOGISTIC REGRESSION ANALYSIS 185

ANNEX 8: DATA FOR TESTING THE HOMOGENEITY OF MEASUREMENTS 186

ANNEX 9: ESTIMATED GROWTH MATRICES PER SPECIES GROUP 187

ANNEX 10: SAMPLE LIST FILE OF AIMMS FOR THE DETERMINATION OF STEADY STATE CHARACTERISTICS FOR THE 30-YEAR CUTTING CYCLE 189

CURRICULUM VITAE 203

LIST OF TABLES

Table 1.1: Vegetation types of the Tropenbos Cameroon Research site

Table 1.2: Extract of the Zoning Plan of the Tropenbos Cameroon research site

Table 3.1: Summary of linkages between research objectives, questions and methods

Table 5.1: Definition of diameter classes

Table 5.2: FOB prices for log exports from Cameroon in 1997

Table 5.3: Data used for the test of difference for volume estimation techniques

Table 6.1: Species groups

Table 6.2: Coefficients for the estimation of up-growth with logistic regression analysis

Table 6.3: Upgrowth probabilities per species group and diameter class

Table 6.4: Transition probabilities used in TROPFOMS

Table 6.5: Statistics for the ingrowth equations

Table 6.6: Average FOB unit prices for different timber species groups

Table 6.7: Results of the paired T test on differences between measurements on standing and felled trees

Table 6.8: Coefficients of determination (R^2) and standard errors (*E)* of different equation models and different species groups

Table 6.9: Average tree volume (m^3) per diameter class for different species groups

Table 6.10: Distribution of trees among species groups

Table 6.11: Volume losses at different stages of logging and commercialization coefficients for each species group

Table 6.12: Average logging costs in FCFA

Table 6.13: Stumpage price (1000 FCFA/m^3) per species group

Table 6.14: Tree prices (1000 FCFA/tree) per species group and diameter class

Table 6.15: Summary of forest inventory results in the Tropenbos Cameroon research site

Table 6.16: Important tree species for the local population and the logging company at the TCP research site

Table 7.1: Basal area for an individual tree per diameter class

Table 7.2: Impact of the cutting cycle and the discount rate on the sustainable timber value (STV 1000 FCFA) (maximum basal area removal of 35%)

Table 7.3: Stand structure before harvest and harvest (trees/ha) for a cutting cycle of 10 years (discount 5%) and a basal area removal of 35% (uncorrected prices)

Table 7.4: Stumpage prices (1000 FCFA) by species group and size class corrected for logging waste and costs

Table 7.5: Effects correction of tree prices of the STV (1000 FCFA), discount rate 5%, maximum basal area removal of 35%

Table 7.6: Stand structure before harvest and harvest for cutting cycle of 25 years, discount rate of 5% basal area removal restriction of 35%

Table 7.7: Stand structure before harvest and harvest for a cutting cycle of 25 years (discount rate 5%, basal area removal restriction of 25%)

Table 7.8: Effects of logging damage on the cutting cycle and the STV (1000 FCFA) at 5% discount rate and allowable basal area removal of 35%

Table 7.9: Steady state stand structure before harvest and harvest for a cutting cycle of 30 years (discount rate of 5%, basal area removal restriction of 35%)

Table 7.10: Effects of diversity constraints on the cutting cycle and the STV (discount rate of 5%, maximum basal area removal of 35%)

Table 7.11: Steady state stand structure before harvest and harvest for a cutting cycle of 30 years (discount rate 5%, basal area removal restriction of 35%, minimal 0.05 trees per species-size class)

Table 7.12: Steady state stand structure before harvest and harvest for a cutting cycle of 30 years (discount rate 5%, basal area removal restriction of 35% and a ban on logging of NTFP trees)

Table 7.13: Steady state stand structure before harvest and harvest for a cutting cycle of 30 years (a discount rate 5%, basal area removal restriction of 35% and a harvesting limit of 50% on NTFP trees)

Table 7.14: Characteristics of steady state forests associated with alternative management options

Table 8.1: Comparison between current stand characteristics at the TCP research site and the steady state stand before harvest

Table 8.2: Numbers of trees to be removed per species and diameter class at the beginning of the conversion period

Table 8.3: Simulated stand structure (trees/ha) before harvest after 30 years

Table 8.4: Simulated stand structure (trees/ha) before harvest after 60 years

Table 8.5: Simulated stand structure (trees/ha) before harvest after 90 years

Table 8.6: Simulated stand structure (trees/ha) before harvest after 120 years

Table 8.7: Simulated stand structure (trees/ha) before harvest after 150 years

Table 8.8: Expected harvest (trees/ha) and associated values (1000 FCFA) during the conversion period

Table 8.9: Maximum and minimum NPV (1000 FCFA) for a discount rate of 5%

LIST OF FIGURES

Figure 3.1: Conceptual framework for integrated decision-making in tropical forest management

Figure 3.2: Phases of the research process

Figure 4.1: Main components of TROPFOMS

Figure 4.2: The architecture of TROPFOMS

Figure 6.1: Diameter class distribution per hectare for different species groups at the TCP research site

Figure 7.1: Steady state diameter class distribution for different species groups before harvest (discount rate 5%, corrected prices, logging damage included and maximum permitted basal area reduction of 35%)

Figure 8.1: Comparison between diameter class distributions of the current and the steady state stands (after harvest) for different species groups

Figure 8.2: Comparison between steady state and projected TCP stand (all species combined) at years 0 and 120

LIST OF ACRONYMES

ATO:	African Timber Organization
DGIS:	*Directoraat Generaal voor Internationale Samenwerking* (Directorate General for International Cooperation)
DSS:	Decision Support System
DME:	*Diamètre Minimum d'Exploitabilité* (Minimum Diameter for Felling)
FMU:	Forest Management Unit
FSC:	Forest Stewardship Council
FV:	Forest Value
IRAD:	*Institut de Recherches Agronomiques pour le Développement* (Institute of Agricultural Research for Development)
IRGM:	*Institut de Recherches Géologiques et Minières* (Institute of Geological and Mining Research)
IRR:	Internal Rate of Return
ITTO:	International Tropical Timber Organization
LEV:	Land Expectation Value
LP:	Linear Programming
MAI:	Mean Annual Increment
MINEF:	*Ministère de l'Environnement et des Forêts* (Ministry of Environment and Forestry).
NPV:	Net Present Value
NWO:	*Nederlandse Organisatie voor Wetenschappelijk Onderzoek* (Foundation for the Advancement of Scientific Research)
ONADEF:	*Office National de Développement des Forêts* (National Office for Forestry Development)
PAI:	Periodic Annual Increment

PNW: Present Net Worth

PSP: Permanent Sample Plot

SC-DLO: *Staring Centrum, Instituut voor Onderzoek van het Landelijk Gebied* (Winand Staring Center for Integrated Land, Soil and Water Research)

STV: Sustainable Timber Value

TCP: Tropenbos-Cameroon Programme

TFAP: Tropical Forestry Action Plan

TROPFOMS: TROPical FOrest Management support System

UDS: *Université de Dschang* (University of Dschang)

UY1: *Université de Yaoundé 1* (University of Yaoundé 1)

WAU: Wageningen Agricultural University

PREFACE

The research reported on in this document is one of the 14 research projects identified for implementation during the first phase of the Tropenbos Cameroon Programme (TCP). TCP is a multidisciplinary research programme which includes five main disciplines namely: Agronomy, Forestry, Ecology, Social Sciences and Forest Management and Economics. This research falls within the discipline of Forest Management and Economics and started in 1994.

The Management and Economics research projects were designed to be synthetic in nature, which means that they integrate results from other disciplines to develop strategies for sustainable forest management. Therefore, the success of this research was dependent upon the collaboration of other research projects of the TCP. Without the support of many people inside and outside the TCP, this thesis would not have been completed.

I express my deep gratitude to Prof. ir. A. Van Maaren who accepted in May 1993 to act as my promotor and to support this work within the institutional and academic settings of the Wageningen Agricultural University (WAU). My thanks go also to my co-promotor Dr. ir. W.B.J Jonkers who, not only provided scientific advice, but also made necessary arrangements with the Tropenbos Foundation to guarantee logistic and financial support for this research.

I am deeply indebted to Drs. A.M. Filius of the WAU Forestry Department who provided the closest support for this research from the identification of the research project in 1992, through its implementation, analysis of data and reporting earlier this year. My special gratitude goes to him.

My commitment to conduct this research would not have been successful without the administrative arrangements made with my employer, the University of Dschang. I am thankful to the Head of the Forestry Department, the Dean of the Faculty of Agronomy and Agricultural Sciences and the Rector of the University of Dschang for all the administrative facilities provided to me for this research.

I received a great deal of support from the Tropenbos Foundation, I thank its director Ir. E.M. Lammerts van Bueren. Similarly, I am thankful to the management team of the TCP especially Ir. W. van Driel, Dr. O. Eyog Matig, Mr. J.P. Tsimi Mendouga, Dr. B. Foahom and Dr. Ir. P. Schmidt.

I am grateful to many colleagues of the TCP who exchanged ideas and provided information to me while conducting this research. These colleagues are: Gart van Leersum, Marc Parren, Han van Dijk, Bibani Mbarga Roger, Onguene Awana Neree, Françis Nkoumbele, François Tiayon, Maarten Waterloo, Barend van Gemerden, Gerard Hazeu, Jean Claude Ntonga, Ngibaot Flavien, Jolanda van den Berg, Karen Biesbrouck and Guillaume Lescuyer.

Part of this research relies on data collected outside Cameroon, I am grateful to researchers who made such information available to me. This is particularly the case of Dr. Wöll of the GTZ project in Côte d'Ivoire who provided forest growth data from Liberia, Mr. Doumbia Fako of IDEFOR in Côte d'Ivoire, and late Mr. Ben Aninakwa and Mr Afum Bafo of the Planning Branch of the Forest Service in Ghana.

I have received important support for the use of the mathematical programming package AIMMS from Ir. G.D.H. Claassen of the WAU Department of Mathematics, I am thankful to him. Similarly Mr. Venkateswarlu, a biometrician from CIFOR assisted me in organizing the data for statistical analysis, I express my gratitude to him. Two students of the University of Dschang, Minya Nicole and Mfou'ou Mfou'ou Bruno contributed to this research by collecting data for the development of bole volume equations, my thanks go to them. This document would not have the current readability without the comments of Ir. A.H. Druyff who help with his editorial comments; I thank him for that.

Finally, I acknowledge the precious help received from the support staff of the TCP and especially Mr. Essiane Mendoula Edouard, my research assistant from 1995 to 1998, he assisted me in data collection, formatting and analysis.

Kribi, June 1999

Richard Eba'a Atyi

Chapter 1

Introduction

Cameroon is a country of about 15 million inhabitants located on the west-coast of central Africa. Most people of Cameroon live in rural areas where they directly use the forests as a life supporting system. In addition, the developing economy of Cameroon is still heavily based on the trade of raw materials among which timber products harvested from natural forests have considerable importance. For these reasons, the management of forest resources in Cameroon is of special importance. This importance has increased in recent years due to raising international consciousness about environmental issues and efforts are made in Cameroon to move towards sustainable management of forest resources. The efforts include both institutional and technical aspects, but also need a scientific basis that should come from research.

This document reports on a contribution from research to improve forest management in the tropical region in general and particularly in Cameroon. A brief review of the forestry sector of Cameroon is given in order to provide insight into the complex framework of forest management in Cameroon, and to describe the context of the research including a general presentation of the research problem.

1.1 Background on the forestry sector of Cameroon

1.1.1 A synthesis of Cameroon's forest resources and logging activities

Cameroon has a total land area of 475,000 km^2 (47,500,000 ha), and presents a high diversity of tropical vegetation types. These vegetation types range from the equatorial rainforests in the South Province, to the sparsely covered and dry grasslands of the Far North Province near the Sahara desert. Among these vegetation types, the closed forests account for 22.5 million hectares including productive forests on drained land (17.5 million hectares), degraded forest (4.5 million hectares) and swampy forests (0.5 million hectares).

An objective of the Cameroon forest policy is to maintain 30% of the National territory as a permanent forest estate. An indicative zoning plan has been developed for 14 million hectares of closed forests (C⊥tϑ 1993; Government of Cameroon, 1995b). Of these 14 million, about 9 million are proposed to be part of the permanent forest estate within which there are about 6 million ha of production forests divided in 90 Forest Management Units (FMUs). The main objective of the production forest is timber production.

Cameroon produces about three million m^3 of roundwood logs per year, which makes it a major producer of tropical logs in Africa. Logging contributes about 7% to the Gross Domestic Product and 20% to exports (Eba'a, 1998). Most of the production is exported to foreign markets either as roundwood or as processed products (first processing only).

1.1.2 Cameroon's forestry institutions

Since 1992, the forestry policy of Cameroon is designed by the Ministry of Environment and Forestry (MINEF). Before that year forestry matters were dealt with by the Ministry of Agriculture (MINAGRI). MINEF has two technical departments: the Department of Wildlife and Protected Areas and the Department of Forestry. In addition, MINEF has representative offices scattered all over the national territory. MINEF not only designs forestry policy, but it also implements and particularly enforces regulations related to forest management and wildlife, such as the accreditation of logging enterprises and granting of logging rights. In addition, MINEF includes a service of forestry education that supervises two technical schools; one of which trains forestry technicians and the other wildlife management technicians. Attached to MINEF is the National Office for Forestry Development (ONADEF). ONADEF is an implementing agency that carries out technical assignments on behalf of MINEF. It is ONADEF that conducts forest regeneration by artificial plantations of trees wherever the situation permits. It also carries out forest inventories and manages a number of forestry development projects.

Apart from MINEF, there are many more ministries involved in the public forestry sector, the main ones are:

- The Ministry of Higher Education which trains forestry specialists and performs forestry research mainly through the University of Dschang,
- The Ministry of Scientific and Technical Research which conducts forestry research with its Institute of Agricultural Research for Development (IRAD) and,
- The Ministry of Territorial Administration and Planning which coordinates land use at the national level.

Timber harvesting is conducted by private companies that have to apply for logging rights after they have been accredited by MINEF.

1.1.3 Synthesis of current forest management options in Cameroon

In Cameroon, the State (Government) is the primary body responsible for the management of forests for timber production. Although timber harvesting is performed in the field by private companies, it is the State which designs the forestry sector policy, grants logging rights, and defines and enforces forest management regulations. This remains true even though efforts are made to involve the other stakeholders at every step. Therefore, state forest management policy deserves particular attention as it coordinates all practices in the logging industry.

In Cameroon, existing forest management options adopted by the State can be classified in two: options on the national level and options on the FMU level.

a) Forest management options on the national level

Management options on the national level consist mainly of forest policy statements and choices that are designed to govern the management of all national forests. The options for forest management in Cameroon on the national level are described in three main policy documents: the National Forestry Policy statement written in 1993 (Government of Cameroon, 1993) and revised in 1995 (Government of Cameroon, 1995a), the Forestry Law (Government of Cameroon, 1994) and its Decree of Implementation (Government of Cameroon, 1995c). The above three policy documents are supported technically by a Zoning Plan (Côté 1993) which was approved by the State in 1995 (Government of Cameroon, 1995b).

Forest policy statements. The forest policy centers around the achievement of five objectives associated each with a set of action strategies. These objectives are:

1) To ensure the protection of Cameroon's forest heritage and to contribute to the safeguarding of the global environment and to the preservation of biodiversity. This objective is to be attained through three action strategies that are:

- creation of national forest reserves and protected areas which are representative for the national biological diversity,
- integration of a component on "environment and balanced ecosystems" in the national policy of land management,
- development of protection, conservation and improvement measures for all forest resources.

2) To improve the participation of the local populations in the conservation and the management of forests so that forestry can contribute to raising their living standards. This objective is to be achieved through:

- improvement in the organization of the timber products sub-sector,
- promoting the preservation of forest resources by local authorities,
- promoting the development of private forests and game ranching in rural areas,
- development of agroforestry in land utilization systems.

3) To enhance the forest resources in order to improve their contribution to the Gross Domestic Product of Cameroon while preserving their productivity. The action strategies adopted for the achievement of this objective are:

- improvement of the supply of firewood and other non-industrial roundwood while maintaining the productive potential through a more judicious utilization of available resources,
- orientation of the national energy demand towards less expensive sources and substitutes,
- improvement of the participation of all stakeholders in the management of firewood and non-industrial roundwood resources,
- better organization of the informal sub-sector,
- improvement of the logging industry,

- improvement of the management of the raw material in order to optimize benefits from the productive potential,
- promoting the use and the diversification of processed timber products.

4) To ensure the regeneration of forest resources by plantations in order to perpetuate their potentials. This objective is to be achieved through:
- artificial plantations using tree species whose silviculture is well-known,
- promotion of the participation of all stakeholders in forest regeneration,
- improvement of the management of watersheds.

5) To revitalize the forest sector by setting up an efficient institutional framework. Actions and strategies to be undertaken include:
- overall definition of the tasks of those involved in the sector,
- improvement of the organization and coordination of the institutions involved in the use of forest resources,
- the promotion of training activities adapted to the objectives of the new forest policy,
- the improvement of the management of the human resources,
- insuring the financing of forest sector activities as a priority.

The forestry law. The forestry law divides the national forest estate in permanent forests that should cover at least 30% of the total area of the national territory and reflect the country's ecological diversity, and non-permanent forests. Permanent forests consist of state forests that include areas protected for wildlife and forest reserves among which are also production forests. Non-permanent forests include communal forests, community forests and forests belonging to private individuals.

In addition to the classification of forests in different forest types, the forestry law of Cameroon gives broad guidelines about the management of each forest type, as such it provides a legal setup for the exploitation and management of production forests which are of special interest in this study. There are two types of logging rights in production forests: the sales of standing volumes and the exploitation contracts. A sale of standing volume is an authorization to exploit, "for a fixed period, a precise volume of standing timber which may not exceed the annual logging potential" (Government of Cameroon, 1994). An exploitation contract is an agreement in which the license-holder is granted the right to collect a specific volume of wood from a forest concession. The total area of a forest concession "may not exceed in any case 200,000 hectares" (Government of Cameroon, 1994). Forest exploitation contracts have to be concluded for a maximum renewable duration of 15 years. A licence holder for a forest concession concludes a provisional exploitation contract with the forest department prior to signing the final contract. A provisional contract has a maximum duration of three years and the management plan is "a compulsory clause of the specifications made during the execution of the provisional contract."

The Zoning Plan. The Zoning Plan is a proposed broad Land Utilization Plan drawn by the State. However, it is open for negotiations during its implementation in the field. To date, it covers only about 14 million ha which represent about 30% of the total area of Cameroon. This Plan covers almost all the closed forests of Cameroon. Of the 14 million ha planned, about 9 million are proposed to constitute the permanent forest estate, among which production forests cover 6 million ha. The Zoning Plan proposes boundaries for each production forest on a map.

b) Forest management options on the Management Unit level

The main options on the FMU level are presented in four technical documents which contain standards for forest inventory with the purpose of management planning (ONADEF, 1992a), standards for the stratification of forest lands for their mapping at the scale of 1:50,000 (ONADEF, 1992b), standards for the verification and evaluation of forest inventories (ONADEF, 1992c) and guidelines for the elaboration of forest management plans for production forests (Ministry of Environment and Forests, 1998b).

These documents provide indications for sampling designs during different types of forest inventories. For example, the sampling intensity of forest inventories for management planning purposes should be at least 0.5% of the total FMU area. They also regroup tree species in three groups based on the frequency of their demand in the timber products markets. According to the official grouping of tree species, group 1 contains the 27 species most regularly exported from Cameroon forests irrespective of the prices, the only limitation to the export appears to be their supply from the forests; group 2 consists of 14 species that are commercialized less regularly and group 3 contains 49 species considered as potentially commercial. The minimum diameters eligible for harvesting (DME) are also set by species (See annex 1). The guidelines for the elaboration of management plans for production forests set the minimum cutting cycle at 25 years and makes it mandatory to estimate the annual allowable cut on the basis of at least 20 species making up a minimum of 75 % of the standing harvestable volume. A standard canvass for management plans is also provided as well as standard contracts and drafts of specifications that should define the rights and obligations of different stakeholders.

The interest of the current research is on the management strategies at the FMU level, particularly as concerns forests stands of production forests.

1.2 General context of the study

1.2.1 Administrative setting of the research project

This research project was conducted within the general context of the Tropenbos Cameroon Programme (TCP) which consists of 14 research projects in five research areas which are: Agronomy, Ecology, Forest Management and Economics, Social Sciences and Forestry. The global objective of the TCP is to develop an appropriate technology for sustainable management of the tropical forest of southern Cameroon.

The TCP was initiated by an agreement between the Tropenbos Foundation of The Netherlands and the Government of Cameroon. The TCP is under the administrative supervision of the Ministry of Environment and Forestry of Cameroon (MINEF). On the Cameroon side, five more institutions are involved including the Institute for Agricultural Research and Development (IRAD) which is the main implementing agency, the National Office for Forestry Development (ONADEF), the University of Dschang (UDS), the University of Yaoundé I (UY1) and the Institute for Geological and Mining Research (IRGM). On the Dutch side the main implementing agency is the Wageningen Agricultural University (WAU). Other participating agencies include: the Winand Staring Center for Integrated Land, Soil and Water Research (SC-DLO) and Leiden University.

Not only did the TCP provide funds and logistic means for research operations, it also encouraged co-operation among researchers especially the exchange of developed or gathered information.

1.2.2 The research site

The TCP research site is situated in Cameroon, approximately 80 km from Kribi, a coastal town were the head offices of the TCP are located. The site stretches out from 2°47' to 3°14' E longitude and from 10°24' to 10°51 N latitude (van Gemerden and Hazeu, 1999) and it covers a total land area of about 200,000 hectares.

The zoning plan (Côté, 1993) of Cameroon distinguished different forest types within the TCP research site as shown in table 1.1, while the orientations given by the Zoning Plan for the Tropenbos Cameroon research site are summarized in table 1.2. It can be noted that production forests are the least important in area compared to other types of forest.

Table 1.1: Vegetation types of the Tropenbos Cameroon research site

Vegetation types	Area (ha)
Dense humid forests	61,820
Dense humid forests (inaccessible)	22,300
Old secondary forests	71,980
Young secondary forests	22,550
Agriculture (young fallow)	1,420
Agriculture (farms)	15,920
Housing	170
Total	**196,160**

Source: Côté (1993)

Nevertheless, it is thought that they should be managed as carefully as possible because of their status as permanent forests. In contrast to protection forests (the other type of permanent forest on the TCP research site), production forests are more subjected to utilization by different stakeholders among which are loggers and the local populations.

The climate is typically equatorial and characterized by rainfalls that occur all the year long although there are two rainy seasons and two dry seasons. The mean annual temperature is about 25°C. The altitude ranges from 40 m above sea level to about 1000 m.

Table 1.2: Extract of the Zoning Plan of the Tropenbos Cameroon research site

Proposed land utilization type	Forest category	Land area (ha)
Production forests	permanent	15,470
Protection Forests	permanent	41,190
Community forests	Non permanent	17,170
Agroforestry and habitat	Non permanent	122,310
Total		**196,140**

Source: compiled from Côté (1993)

Administratively, the TCP research site belongs to the South Province, one of the ten administrative provinces which constitute Cameroon and touches two administrative divisions, the Ocean Division (with the head town Kribi) and the Mvila Division (with the head town Ebolowa).

1.2.3 The research problem

Forestry is becoming increasingly important in Cameroon, especially in the national economy (Eba'a, 1998). According to the Tropical Forestry Action Plan (TFAP) of Cameroon (FAO/UNDP, 1988) "Faced with forestry resources which are becoming exhausted in some of the traditional producing countries, and with other potential producers having difficulty rising to the position of power", Cameroon has the potential to become the most important African producer and exporter of forestry-based products. Forest exploitation goes on, but, unfortunately, as pointed out by the TFAP, "there is currently no managed forest in Cameroon that represents a very serious threat for the future and the perpetuation of the forest." The lack of sustainable forest management may lead in the long run to depletion and/or the failure of the forestry sector to contribute as much as it potentially can to the improvement of the wellbeing of Cameroon nationals.

Diagnoses of the prevailing situation show that the absence of sustainable management of Cameroon's forests is the result of both an inadequate institutional context and insufficient scientific and technical knowledge. The Government of Cameroon and its forestry officials who have become more and more conscious about the need for sustainable management of the national forests are taking some steps towards improving the current situation (Eba'a and Essiane, 1998). One of the recent efforts made is the provision within the current forestry law (Government of Cameroon, 1994) that there must be a written and approved management plan for each forest concession before a long-term grant can be concluded. In order to approach the ideal of sustainable development, forest management planning should be based on sound scientific and technical knowledge and it should integrate concerns of forest users. A forest management plan includes a set of decisions to affect the forest now and in the future. Therefore, it should use the best available methods, which combine knowledge collected in different scientific fields to support decision-making and generate practical management strategies for field implementation.

The intent of the research presented here is to contribute to the development of the necessary technical and scientific basis for forest management planning in the tropical region in general and in south Cameroon particularly. This requires first a review of both the general principles of forest management and the status of forest management in the tropical region. Such a review helps to identify the important parameters on which sustainable forest management is based and to detect knowledge gaps in order to orient the research and defines its objectives more specifically. The review and the definition of research objectives are presented in chapters 2 and 3 respectively.

1.3 Organization of the document

The whole document is about the development of a model (TROPFOMS) which can be used to support decision-making for forest management in south Cameroon. After this introductory chapter that briefly presents the forestry sector of Cameroon and the context of the study, chapter 2 reviews different approaches and principles related to sustainable forest management with special emphasis on decision-making, and it identifies research gaps in tropical forestry; one of which is addressed by the current study. Chapter 3 presents the problem tackled by the research, defines the research objectives and shows the conceptual approach which underlies the research. Chapter 4 gives information about the constitution of TROPFOMS and the way the model approaches decision-making forest management and derives solutions. Chapter 5 describes the methodological approaches for conducting the research, developing necessary parameters for TROPFOMS and searching solutions within the model. The actual numerical values obtained by the methods described in chapter 5, which are used by TROPFOMS to provide quantitative guides to support decision-making, are presented in chapter 6. The outcomes of running TROPFOMS as well as their implications for forest management strategies, are shown in chapters 7 and 8 for the steady state and the conversion period respectively. Finally, chapter 9 reflects on the whole research, highlighting limitations and identifying conditions for improvement, and it concludes and makes recommendations for future studies.

Chapter 2

Review of forest management and decision-making

In recent years, forest management has received much attention. Much of the renewed interest in forest management by the public at large is related to the concept of sustainability and its corollary sustainable development. This concept has emerged since the mid 1980s as a basic ideology to orient and assess the management of natural resources among which are forests. Therefore, it appears important to briefly introduce the concept of sustainability and discuss its relationships with forest management before reviewing different approaches used in forest management with special emphasis on tropical forests.

2.1 Sustainability and sustainable management

2.1.1 The general concept

For about the last two decades the notions of sustainability, sustainable development and sustainable management have been among the top issues in almost all debates related to natural resources and their utilization. Yet, as Hadley and Schreckenberg (1989) put it "sustainability is difficult to define." The main reason given by these authors to explain that difficulty is that sustainability has a "multifaced character", this makes it difficult to achieve it because of the large number of constraints that need to be overcome.

Nonetheless, many organizations or individuals have proposed definitions for these concepts. The World Commission on Environment and Development (1987) proposed a definition of the broader concept of sustainable development as being "a process of change in which exploitation of resources, the direction of investments, the orientation of technological and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations." This definition suggests that, in searching for sustainability, one should bear in mind the satisfaction of the needs of the current generations at the same time as the conservation of resources for future generations. Pezzey (1989) identifies two major concerns that the concept of sustainable management of natural resources tries to address:

i) A concern for a lasting improvement in the well-being of people and

ii) A concern for protecting and maintaining the capacity of the natural resource systems that provides the basis for such improvement.

2.1.2 Sustainability and forest management

Although the quest for sustainability can be seen as a new focus in the management of other natural resources (renewable or not), it has been one of the most important aspects in forest management since the earliest development of forestry as a science. In its earliest stages, the forestry profession appeared to have been oriented towards the conservation of forest reserves for hunting by kings and nobles (FAO, 1993). Forest management quickly turned to focus mainly on sustainable timber extraction. Winters (1974) reported that as early as in the 1700s "German forest masters were applying mathematical formulae to calculate forest growth, developing cutting budgets to spread the volume yield of a forest equally over the number of years required to produce a new crop of timber, and were preparing systematic forest operational plans." Already in 1768, a school of forest practices disseminating these techniques was established in Germany. The idea of harvesting no more timber than the growth has been ever since the driving force behind the notion of sustainable forest management.

Trained forestry professionals began working in the search of the so-called "sustained yield". With that notion, forest managers aimed at "achieving a balance between growth and harvest taking into account the fact that the forest is a renewable resource, as contrasted with minerals which cannot be replenished except over a geologic time span" (Meyer *et al.*, 1961). The main idea was to balance the volume harvested against the growth predicted from regeneration. A forest managed in a sustainable way meant that continuity of timber harvest was assured (Davis, 1966). Such a forest, which theoretically produces an even flow of timber forever, is called a "fully regulated forest". The essential requirements of a fully regulated forest are that age and size classes be represented in such proportions and be consistently growing at such rates that an approximately equal annual or periodic yield of products of desired sizes and quality may be obtained in perpetuity. A progression of size and age classes must exist such that an approximately equal volume and size of harvestable trees are regularly available for cutting. Forest regulation deals with changing unregulated forests to fully regulated ones. As such, it addresses the questions of how many hectares and how much volume to cut. Classical forest management specialists have used two basic approaches to convert an existing non-regulated forest into a fully regulated one (Davis and Johnson, 1987). These approaches are:

i) **Area control**: the principle is to harvest and to regenerate the same number of hectares each year or period that would be harvested in a fully regulated forest. The harvested volume results then from the standing timber on the area scheduled for cutting each year. This approach is the easiest way to regulate an unmanaged forest once the appropriate rotation or cutting cycle is determined. For even-aged forests regulation should be achieved in one rotation. For an unregulated uneven-aged forest, the number, size, and species of trees harvested depend on growth rates, the existing and desired species and the diameter distribution of the stands making up the initial forest. Regulation in this case can require more than one cutting cycle.

Area control is simple, direct and has the virtue of portraying the harvest in terms of area to cut that is something all regulation techniques must do eventually. However, its main disadvantage has been the lack of control on the volume harvested.

ii) **Volume control**: the essential question addressed with this approach is how much volume to cut periodically (for example each year). The area to cut is chosen to satisfy this volume. The determination of the volume to cut is approached through the amount and distribution of growing stock and its increment. Several formula methods have been developed for determining the cut by volume control. Some of them are:

- Formula methods based on current growing stock and potential growth. One representative of these methods is the so-called *Hundeshagen's formula* which reads:

$$Cut = Y_a = \frac{Y_r}{G_r} G_a \tag{2.1}$$

where: Y_a = growth or harvestable yield in existing forest
Y_r = growth of regulated forest (long term sustained yield)
G_r = growing stock in regulated forest
G_a = growing stock in existing forest

- A method based on the growing stock only, which is derived from the preceding formula and reads:

$$Y_a = 2\frac{G_a}{R} \tag{2.2}$$

where: R is the rotation age chosen.

- Formula methods based on growing stock and its increment. Some formulas to determine annual cut representatives of this line of reasoning are:

. The *Austrian formula*:

$$Cut = I + \frac{(G_a - G_r)}{a} \tag{2.3}$$

where a is the adjustment period in years and I is the annual increment.

. The *Hanzlik formula:*

$$Cut = \frac{V_m}{R} + I \tag{2.4}$$

where: V_m is the volume of commercial timber above rotation age.

The major advantage of volume control is that it allows managers to provide the industry with a constant flow of timber during the regulation period, which usually is desired by the managers. Disadvantages include the lack of formal control over the area cut per year making it difficult to ensure that the forest moves toward a regulated condition. In addition, growth information on unmanaged stands are often difficult to obtain. Because of the disadvantages presented by each of these two approaches, forest management specialists have also used some combinations of both.

In forest management, there has been an important evolution in the scope and meaning of sustainability. At first, sustainable forest management basically meant continued supply of timber products from the forest. Such a perception of sustainable forest management is now highly criticized by natural resources scholars operating in a context characterized by a greater national and international concern for long-term environmental quality. The FAO (1993a) illustrates this change stating that "The sustainable management of forests for the production of wood is based on the deceptively simple principle... harvest the wood at an annual rate no greater than the forest in question can grow it." Gregersen and Lundgren (1990) proposed a definition of sustainable development as applied to the field of forestry that represents a contemporary approach to the problem of sustainable forest management. They see it as "... development involving changes in the production and/or distribution of desired goods and services from forests and from trees which result, for a given target population in an increase in welfare that can be sustained over time." However, one may argue that the target does not need to be a single specific population component (target population), but can be the society as a whole; each component of which has an interest in specific forest products. Nowadays, the orientation is more toward a multipurpose management of a forest so that its capacity to provide goods and services is not diminished. Particularly suitable for a tropical moist forest is the objective of providing timber on a sustainable basis while continuing to provide fuelwood, food and other goods and services for those living in and around the forest (FAO, 1993a). The International Tropical Timber Organization (ITTO), which focuses primarily on tropical forests and which is trying to ensure that all timber traded from tropical countries is harvested in sustainably managed forests by the year 2000, defines sustainable management of tropical forests as "the process of managing permanent forest land to achieve one or more clearly specified objectives of management with regard to the production of a continuous flow of desired forest products and services without undue reduction of its inherent values and future productivity and without undue undesirable effects on the physical and social environment" (ITTO, 1992).

Gregersen *et al.* (1993) identified the following four major operational implications that the concept of sustainable development has on forestry projects:

- Avoid damage to critical natural capital and be wary of starting processes that are irreversible;
- Where the resource can be maintained, limit exploitation to sustainable levels; where it is to be run down (e.g. to release land for agriculture), set aside and invest enough of the proceeds to produce a permanent income stream or alternative sources of forest products for those who depend upon them;
- Where possible, put economic values of social environmental costs and benefits so that they are taken into account in decisions; and

- Ensure to the fullest extent possible that impacts normally treated as externalities are internalized within the design of the project (e.g. by including compensatory measures where necessary).

Thus, in addition to addressing current and future human needs, the concept of sustainable forest management includes not only timber production but that of all other goods and services expected from a forest by different people utilizing it. This will sometimes bring forest managers and forest policy makers to face interests. But, as the FAO (1993b) puts it "accepting the fact that most of these interests are legitimate is an essential first step if progress is to be made in reducing today's rate of forest loss."

To make the notion of sustainability more practical, less confusing and less abstract, ITTO (1992), a leading organization committed to sustainable utilization of tropical forests, has proposed criteria for the measurement of sustainable tropical forest management at national as well as at management unit levels. At the national level the criteria proposed are:

- the forest resource base;
- the continuity of flow of forest products;
- the level of environmental control;
- socio-economic effects of forest product harvesting;
- institutional frameworks.

To measure sustainability at the level of the forest management unit the proposed criteria are:

- resource security (one example of indicators given is among other things the existence of a management plan);
- planning and adjustment to experience;
- the continuity of timber production (examples of indicators given include: the presence of clear official harvesting rules, the number of trees and/or volume of timber per hectare harvested, and provision for monitoring the residual growing stock after logging);
- the conservation of flora and fauna;
- an acceptable level of environmental impact;
- socio-economic benefits (including the number of people employed and the nature and extent of benefits from forestry activities).

These criteria are considered as relevant in this study and will be kept in mind in addition to unhampered use of forest resources.

2.2 The sustainable management of tropical forests: issues and opportunities

2.2.1 The occurrence of tropical forests

The world's tropical forests were estimated to cover a total land area of about 1,756.3 million ha in 1990 (Nyyssönen, 1993), decreasing from the estimated 1,910.4 million ha estimated in 1980. This represents a loss of 15.4 million ha per year (an average deforestation of 0.8% per annum). The main cause for such a phenomenon was found to be the expansion of agriculture. For example shifting cultivation was estimated by FAO (FAO/UNEP,1981) to be responsible for about 70% of deforestation in Africa. However, commercial logging is also one of the important causes of deforestation, especially as shifting cultivators use logging roads to ever more deeply penetrate the forests. But a more global cause that gives various incentives for deforestation is poverty (Nemetz *et al.*, 1992).

In Cameroon, the annual rate of deforestation was estimated by FAO (1993b) to be about 0.6%; which corresponds to 122,000 hectares per year. In addition, the estimated loss in biodiversity concerns about 2% of the total number of species each year.

The passionate character of the debate over the magnitude of the loss of tropical forests results partly from the fact that the shrinking of the tropical forests represents a great loss for the human kind because these forests are the richest and the most diverse forest ecosystems on earth even though millions of species are still not described (Poore and Sayer, 1991). For example in Cameroon alone, about 297 species of mammals have been identified. In addition, there are 818 bird species and about 9000 plant species of which 156 are endemic (IUCN, 1992).

This means that a major objective in any contemporary attempt to manage the tropical moist forest nowadays is the protection of the biological diversity (Poore and Sayer, 1991).

2.2.2 Some characteristics of the tropical rainforests

a) Physical and bio-ecological characteristics

The physical and bio-ecological characteristics of the African tropical rainforest environment can be summarized as follows (Willan, 1989):

- tropical forests grow in a wide range of climate types ranging from the equatorial rainfall (over 1500 mm/year) to the intertropical belt with one or two dry seasons. However, the rainforest is encountered mainly in the equatorial climate;
- most soils in rainforests are rather nutrient-poor because there is a high potential for leaching due to the heavy equatorial rainfall. Some authors (Hall, 1977) have signaled some correlation between species composition and soil parent material.

As described by Aubréville (1938), Eggeling (1947), Lanly (1966), Longman and Jenik (1974), and Hall (1977), the features that are most relevant for the management of the evergreen moist forest are:

- a large number of species per unit area;
- a multi-layered and a multi-storied canopy. Each layer contains species of which the height at maturity is limited as well as species typical of the layers above;
- highly frequent buttresses;
- abundant herbaceous and woody climbers, especially in disturbed forests;
- complex spatial pattern and species distribution.

These characteristics suggest that the management of natural tropical forests will be more complicated than it is the case with other forest types. Because of the high level of diversity involved, important aspects of forest management, such as the dynamics of forest stands, are difficult to comprehend. For example, in temperate zone forestry, growth and yield figures are usually developed for every tree species. Such an approach is often highly impractical in tropical forestry because of the broad diversity of tree species. Instead, species are typically grouped for growth and yield estimation. In addition, only a fraction of these species are currently known to the forest products market. Thus, the commercial value of stands calculated on the basis of timber products derived from known species tends to be low as the number of harvestable trees per unit area is rather small.

b) Socio-economic characteristics

The socio-economic context, both at the national and the local levels, is characterized by poverty. As such, forest products are used to meet urgent needs, and forest management is conducted primarily on the basis of short-term objectives. Willan (1989) described the uses of forest products to which such objectives lead.

i) At a national level forest products are used as:

- a means of substituting imports and saving foreign currency,
- a means of earning foreign currency,
- a vehicle to promote development and raise national income.

ii) At the local level the forest is used to provide:

- land on which to grow food and cash crops,
- fuelwood, and roundwood and sawnwood for building,
- non-wood forest products such as food, rattan, medicine, vines, barks etc...;
- material for the local culture.

In addition to these uses, the forestry sector is also often seen as one of the most important sources of income for the government budget. The pressure created on the tropical forest by all these needs is often aggravated by increasing population figures, political instability and the poor quality of related government institutions.

In the direct utilization of tropical moist forests there are three principal players which often have apparently conflicting interests (FAO, 1993).

1. The government seeks to meet the people's needs in a general context characterized by: worsening terms of trade (decreasing export prices and raising import costs); tremendous debt burden; technical, financial and institutional shortcomings with respect to effective forest management. In the role of defender of the public interest, the government is also charged with the enforcement of laws governing forestry practices, often leading to restricting the activities of others in the interest of conservation.
2. Logging companies pursue profit by extracting timber. They supply forest products for local, national and international markets where there is an increasing demand for forest products. As has been done throughout history, they exploit a natural resource in the interest of human development (Gregersen *et al.*, 1990; FAO, 1993a).

3. The local population relies on forest land for food production and cash crops. They also use many wood and non-wood forest products for needs such as shelter, tools, medicine and food.

The preceding paragraphs demonstrate that in tropical forest management conservation is as important as production for the wellbeing of the people. Apparently, three p-words give the bulk of management objectives in tropical forestry, **Production** and **Protection** for the **People.**

c) The international context.
In addition to the physical, ecological and socio-economic characteristics mentioned above, the management of the tropical moist forest is also much influenced by the overall international context. This international scene is characterized by legitimate concerns about deforestation and its negative consequences on biological diversity (Botkin and Talbot, 1992) and the global ecological environment (Woodwell, 1992) at one hand, and a hostile economic environment for developing countries (FAO, 1993c) at the other hand.

Concerns for the needs for a better quality of the ecological environment and the preservation of biological diversity have led the donor community of developed countries, under pressure from their public opinions, to link aid for development with national strategies for a sustainable management of tropical forests (Poore, 1991). Unfortunately, these legitimate concerns have sometimes been transformed to more emotional campaigns. Some ecologists advocates have portrayed in a very simplistic and counter-productive way the "complex issue of forest depletion as a struggle between the good forces of conservation and the evil of short-sighted greed and recklessness" (FAO, 1993). Hamilton (1990) has listed some misleading expressions and statements often used about some issues in tropical forestry. Part of this has resulted in suggestions of extreme measures such as boycott of tropical timber by many organizations (Goodland, 1990) claiming to be defenders of the ecological environment. The opinion of many authors is that such measures may be of little help or even harmful in the fight against deforestation. For example, Jagels (1990) thinks that the blame about deforestation should not be put totally on the timber firms and Rowe *et al.* (1992) have identified agricultural expansion as being the major direct cause of deforestation and subsistence farmers in developing countries as being responsible for more than 60% of the loss of tropical forest annually. Other causes include overgrazing, fuelwood gathering, infrastructure and industrial development and obviously commercial logging. Hamilton (1990) expressed the opinion that, pointing logging as a major cause of loss of tropical forests "is not a general truth, moreover it diverts attention from the real causes and therefore from the solutions".

All this suggests that the fight against deforestation needs a rather global approach which focuses not only on the utilization of the forest for timber production, but also on forest as a land base for agricultural production and any other form of forest utilization. The basic force behind forest depletion is certainly the search by inhabitants and governments of developing countries to improve the living standards and this is done through the utilization of available natural resources which has always been the case in any part of the world. The challenge is to shift from forest resources depletion to sustainable utilization, and this will require that the interests of all actors interested in the management of tropical forests be taken into consideration.

2.2.3 The management of tropical forests: technologies, problems, constraints and prospects

a) Technologies available for tropical forest management

During the course of this century, there have been numerous attempts with variable success to develop appropriate technologies for the management of both artificial plantations and natural tropical forests.

There have been many trials for artificial full forest plantations throughout the tropical zone for many decades now. Some of the most successful are planted with tropical pine species (CTFT, 1966), Eucalyptus (FAO, 1976) and some tropical hardwood species such as teak (Mathur, 1973; de Maerschalk, 1973) and *Gmelina arborea.* Less successful results have been obtained with other hardwood species, some of which are nonetheless still considered to be promising. Some have even seen plantation forestry as the only realistic direction for sustainable forest management in the tropics (Office of Technology Assessment, 1984). However important tropical forest plantations may be for supplying people with needed wood products, they are less appropriate for the conservation of biological diversity (Leslie, 1987). They do not provide the same products as the natural forests and thus cannot replace them. Some forest economists value tree plantations over natural forests (Richardson, 1970; Spears, 1979), basically because they do not recognize the value of external effects (e.g. watershed protection, wildlife habitat, non-wood forest products, biological diversity) in their analyses. Once the external effects are internalized, it becomes evident that "...the financial returns to natural tropical forest management are much better than generally recognized" (Sedjo, 1992).

As a result of the research efforts enumerated above, the necessary minimum of knowledge and techniques are available to commence sustainable forest management of artificial plantations anywhere in the world; although more research is needed both in general and on a case by case basis.

As concerns the management of natural forests, the current state of technology is less auspicious. Most research efforts in this field have concentrated on the development of silvicultural techniques (Mergen and Vincent, 1987). The most promising techniques include: in tropical Asia, the modified versions of the Malayan Uniform System (MUS) and the Selective Management System (SMS) both developed in Malaysia (Hon Tat Tang, 1987); in tropical Africa, the work done in Ghana since the 1950's and modified more recently (Asabere, 1987) and the SODEFOR trials in Côte d'Ivoire (Maitre, 1986); in tropical America, the CELOS silvicultural system developed in Surinam (de Graaf, 1986).

These silvicultural systems are mostly based on operations such as inventory of standing stock, selective logging, climber cutting and additional removal of the canopy. Sometimes inter-planting with commercial species is also undertaken. In fact, Schmidt (1987) identifies five important factors to be taken into account in any natural tropical forest silvicultural system, these are:

a) presence of adequate stocking of regeneration;
b) removal of the partially harvested canopy;
c) absence of tending until regrowth has passed the ephemeral climber stage;
d) maintenance of adequate new canopy to prevent the development of climbers;
e) linear sampling to assess the regeneration status.

However, these factors are most relevant for monocyclic systems. For polycyclic systems the most important factors include:

1) presence of adequate numbers of crop trees;
2) partial removal of the canopy to stimulate the growth of trees of commercial species while maintaining the ecological functioning of the forest.
3) adequate opportunities for the establishment of regeneration of commercial species.
4) establishment of permanent sample plots to monitor the development of stands.

Although not enough, compared to the efforts given to the development of silvicultural systems, some research effort has also been devoted to the improvement of logging techniques and, as reported by Willan (1989) "a spectacular progress has been made this century concerning the equipment and the range of saleable species. However, harvesting still constitutes a severe economic constraint to the more efficient utilization of the forests resources." Dykstra and Heinrich (1992) have stressed the importance of improved harvesting systems for the sustainability of tropical moist forest and have identified the work of Jonkers (1987) and Hendrison (1989) in Surinam as the most promising in logging efficiency. In general, improved harvesting techniques should be based on activities such as careful planning of road and skidtrail construction, pre-harvest cutting of climbers and post harvest assessment. A recent study by Barreto *et al.* (1998) in eastern Amazonia on the technical feasibility, efficiency and profitability of "best" logging practices came to the conclusion that careful planning of logging operations can reduce logging waste by up to 25% and increase the present net value of timber extraction by 38 to 45 %. As cited by Willan (1989) the following items have been identified by Catinot (1987) as important problems related to logging in tropical forests: high rainfall, topography, soils, large size of trees, distances between the forests and the markets, inadequate knowledge of the forest and the heterogeneous composition of the forest. Important progress has also been noted in the area of forest inventory (Nyyssönen, 1993) where both computer techniques and satellite imagery are currently used very efficiently.

More recently, non-timber forest products in relation to the management of tropical moist forests have become a subject of great interest. Some studies have already been completed (e.g. Okafor, 1977) while many more are underway. The general impression given by these studies is that the integration of non-timber forest products in forest management should be adopted on a case by case basis, meaning that each nation should investigate "the present relation between resources and population, the present standard of living and the distribution of wealth, predictions about all these, and national social and economic objectives" (Poore *et al.*, 1989).

Other attempts to develop appropriate technologies for the management of tropical forests for sustainability have been made in the areas of growth and yield prediction (Michäel, 1987), stand modeling (Vanclay, 1991; Noble, 1989), forest policy (Nemetz *et al.*, 1992; Repetto and Gillis, 1988) and forest economics (Leslie, 1987; Grut *et al.*, 1990; Filius, 1998a).

b) Problems and constraints in tropical forest management

Despite the considerable efforts made to develop appropriate technologies for the sustainable management of tropical forests mentioned above, the results in the field have been rather disappointing. Management plans are scarce and in the few cases where they exist, they are often not implemented. Poore (1988) has estimated that less than 1% of tropical moist forests were under any kind of management regime. Fontaine (1986) also made the sad observation stating that "... deforestation, degradation and mismanagement of tropical forests continue while successful models of the integrated sustainable development and conservation of humid tropical forest remain desperately scarce." Authors such as King (1990) have not hesitated to use the word "failure" in the description of the prevailing situation in tropical forestry.

Many analyses have also been made to identify the causes of this situation. Many authors agree that there is still a lack of necessary technical and scientific knowledge due mainly to the complexity of tropical rainforest ecosystems (Wyatt-Smith, 1987; Fontaine, 1986; King, 1990; Willan, 1989). As a result of such a complexity, the functioning of the tropical forest ecosystem is difficult to understand. Significant gaps in relevant biological knowledge include: insufficient understanding of mechanisms of secondary succession and formation of the final stand after modification; and the relative stability of tropical moist forest ecosystems; the silvics of important tree species; and damage from pest, diseases and animal species. However, one of the most important telling omissions frequently identified as limiting the progress in the management of moist tropical forests is the lack of growth and yield data (Fontaine, 1986) or as King (1990) put it "... the absence of mensuration studies capable of yielding information on the performance of different species under varying ecological conditions."

In addition to obstacles in the biological fields, King (1990) went on to state that: "It is the lack of application of socio-economic principles to tropical forest management that constitutes the greatest weakness of tropical forestry, [because] very few foresters seem to realize that production forestry is an economic activity that is conducted within biological constraints and not vice versa." Forest management should be based on biological and socio-economic research. Unfortunately, the general impression is that research efforts in biological fields have outweighed efforts in socio-economic fields in the past. This should be corrected for all the people involved in the utilization of tropical forest resources to have a more positive stand toward sustainable forest management in the tropics. To that end, one must keep in mind that: "nothing will be achieved unless people's legitimate rights and interests are recognized" (FAO, 1993). The people involved here include the local populations, the national governments and loggers as mentioned before. Important problems remain dealing with methodologies to combine available information from different fields in one coherent strategy to achieve optimal utilization and conservation of forest resources for a better planning process. Also ways to assess the evolution toward sustainability are needed.

Brünig *et al.* (1989) came to the conclusion that, even when sufficient technical experience and expertise as well as scientific knowledge might exist they are not applied; this is mainly due to external constraints (Fontaine, 1986) rather than internal biological ones. Brünig *et al.* (1989) blamed the general institutional context surrounding the utilization of tropical forests saying that "tropical forests are not being underused but misused...The utilization of tropical rain forests as sources of timber and land is dominated by short-sighted exploitation philosophies. Consequently, utilization is wasteful, destructive and unsustainable." Factors external to the forest itself that contribute to the lack of appropriate management strategies include inadequate legislation, unstable political environments, illegal clearing, lack of trained manpower, concentration of market demand for timber on a few well known species and human activities (such as agriculture and grazing).

c) Prospects

Although there are still many obstacles, the quantity and quality of technologies already developed suggest that the management of tropical moist forest is now technically feasible (Schmidt,1987). At least for some countries, financial analysis in some cases yield optimistic results (Leslie, 1987; Sedjo, 1992). In the biological fields, even though more profound understanding is needed, the results already available need mostly to be adapted to local applications. Such an adaptation requires building networks between the research organizations involved (Foelster *et al.*, 1987; King, 1990). In addition, the international community is increasing its commitment to search for solutions to problems related to the management of tropical forests through organizations such as the Tropenbos Foundation, ITTO, FAO etc. The once neglected disciplines in forestry research are receiving more attention. New research efforts are more oriented towards science "that allows the optimization of a number of products and not the maximization of one, that treats forests in their social context and does not pretend that they exist in a "people free" environment and it requires management that can adapt quickly to changing social and economic conditions" (Sayer, 1997).

The most important obstacles now appeared to be related to the institutional and socio-economic environment. In this respect, some governments of developing countries appear to be more seriously engaged in improving the context and are following the suggestions made by the Tropical Forestry Action Plan (TFAP) with the assistance of the donor community.

2.3 Decision-making in forest management

2.3.1 The importance of decision-making in forest management

Poore (1988) defined forest management as the taking of firm **decisions** about the future of the forest, the implementation of these **decisions**, and the monitoring of this implementation. Similarly, Duerr *et al.* (1979) emphasized that forest management is carried out by means of decisions. The above-mentioned authors intended to show that decision-making is characteristic of forest management like in management sciences applied to any other field. In fact, Davis and Johnson (1987) stated that: "A central role of the forest manager is decision-making, choosing among alternative courses of action." For them successful forest management specialists identify relevant goals (or objectives), issues and resource limitations of problems and come up with alternative solutions that are workable and beneficial. This suggests that decision-making is the essence of forest management and thus, the process of decision-making should be taken very seriously. In addition, the decisions taken must be aimed at achieving well-defined objectives. Decisions made in forest management often concern the distant future due to the time spans dealt with in forestry activities; especially those related to forest regeneration. Therefore, they call for predicting the future and a plan for each and every decision (Duerr *et al.*, 1979). This shows why forest management relates to the concept of planning which can be defined in general as " a process of preparing a set of decisions for action in future, directed at achieving goals by perfect means" (Dror, 1972). In fact, for some forest management specialists forest management is almost a synonym for forest planning (ONF, 1969). Typical decisions confronted in forest management include: land allocation, production levels (including timber and non-timber forest products), cutting cycle or rotation period, silvicultural operations.

2.3.2 The process of decision-making in forest management

The French national Office of Forests defined managing a forest as deciding on what to do in it, based on what can be done in it, and deducing what must be done in it (ONF, 1969). This definition (even though too short to be complete) in a way outlines the steps in the process of decision-making in forest management, the steps evoked here are: the definition of objectives (what to achieve), the analysis of the current and potential situations of the forest (what can be done) and the final decisions (what to do). If these steps are followed, one should end up with a management plan. This also suggests that decision-making in forest management should follow a well designed process combining identified objectives, information gathered in the field and rational means to process available information. Jonsson (1982) gave an idea about some of the information and processing tools needed by stating: "Forest inventory methods, forecasting methods and optimization methods should be integrated into a mensurational computational system with the purpose of creating among other things a basis for formulating relevant goals".

Li (1988) went a step further in trying to identify the elements to be included in a forest management system for making desirable decisions. These elements include:

- data collection for the description of the forest state;
- prediction of future effects and their valuation for a given management program;
- development of different management programs;
- evaluation of the effects of the management programs;
- formulation of the management objectives and choice of the optimal program according to a certain decision procedure.

This list may present some problems especially as it concerns the order in which these elements are listed because one might argue that the formulation of management objectives should come earlier in the chronosequence of activities to be carried out. However, it gives a good idea of elements to be taken into account in the decision-making process in forest management. The following steps can be identified in the basic process of planning and decision-making (Hufschmidt *et al.*, 1983):

1. Perception and definition of a problem, need or opportunity;
2. Specifications of basic social objectives;
3. Development of associated planning guides and criteria including economic criteria: specification of analysis conditions;
4. Basic physical, economic and social analyses and formulation of alternative plans (Plans include implementation incentives, physical measures, and institutional arrangements. Economic analyses which include cost-benefit analysis are important);
5. Review and evaluation of alternative plans and selection of a preferred plan for execution (cost-benefit analysis plays a key role);
6. Execution of the selected plan; monitoring of progress and result of execution;
7. Ex post evaluation of execution of the plan (benefit cost analysis plays a key role).

Of course, it is very important to have feedback between steps. Because the decisions made in forest management are all oriented towards meeting the management objectives (Duerr *et al.*, 1979), the identification of problems and issues and the setting of these objectives are of primary importance within the process of decision-making as a whole. As one might think, the whole process would be easier to carry out if there was only a single objective. This was almost the case a few decades ago with timber production as the dominant objective. Presently, this is seldom the case. In most cases, forest management tries to achieve a multitude of objectives rendering the decision-making process complex and difficult. However, forest management scholars have tried to develop approaches to decision-making in the case of multiple objectives.

There appear to be two extreme approaches to the search for solutions for multiple use management of forestry resources (Gong, 1991). In the first approach, the so-called "primary use management", the forest is divided and each subdivision is designated for a primary or dominant use. Other uses then become secondary and the management decisions concern mainly the dominant use. This approach can be of interest in some cases (Gregory, 1987), but is generally criticized because most forest areas are suitable for several uses and some of these uses are more or less compatible. By choosing a primary use, other uses are excluded and that may be proven to have an important opportunity cost.

The second is the "complete combination management" according to which each and every hectare of the forest is managed for the combination of products and services which would maximize the forest owner's utility (Helliwell, 1987). Like primary use management, this approach is rarely adopted for it is very difficult and costly to implement. Criticizing the idea, Clawson (1974) once stated: "If by multiple use one means that every use should occur on every acre of forest every year (or every day), then it is absurd, it has never occurred and never can."

Some intermediary approaches between these two extremes have been developed. Forest managers recognize that the forest resource as a whole should be managed for timber and non-timber benefits, but that a specific forest area may be used for a single primary use or for several uses according to its characteristics (the suitability of the forest area for different uses and the compatibility of these uses). Many theories have been developed to tackle the problem of multiple uses in natural resources management (particularly in the field of resource economics) these include: joint product theory (Gregory, 1955), input-output analysis (Flick, 1974), cost-benefit analysis (Johansson and Löfgren, 1985), and multi-attribute decision theory (Hyberg, 1987).

2.3.3 Decision Support Systems (DSS) and forest resources management

General aspects of DSS

The term "Decision Support System" originated in the planning process of industry and commerce (Thieraf, 1982; Bennett, 1983). DSS "is contemporary jargon for an integrated approach to the age-old problem of helping people make better decisions" (Stuth and Smith, 1993). DSS improves decision-making by offering a mechanism for increasing the objectivity of the process, especially where complex interactions are involved. The objectivity and thus the quality of the decision depends on both the available technology for computations and the methodology of the information-decision system (Kami, 1978). The term DSS has been given many definitions, one of the most representative ones is the one suggested by Bonczek *et al.* (1981) who thought of DSS as being "an information processing system embedded within a decision-making system. DSS may be a human information processor, a mechanical information processor, or a human/machine information processing system". The machine evoked here is likely a computer. Covington *et al.* (1988) have also defined DSS as flexible, integrated software for accessing, retrieving and generating reports on database information plus simulation and decision models for conducting further analysis including alternative testing, sensitivity analysis and automated goal seeking. Computers have gained considerable importance in this field for the last two decades; because of this, some authors have seen DSS mainly as computer based systems that help decision makers confront unstructured problems through direct interaction with data and analysis models (Sprague and Carlson, 1982). Although the computer plays an important role in DSS due to a more and more complex definition of problems, it should not be seen as an obligatory part of a DSS.

The characteristics of a DSS (Sprague and Watson 1986) are:

- It tends to be aimed at the less well-structured, under-specified problems that upper levels managers typically face;
- It attempts to combine the use of models or analytical techniques with traditional data access and retrieval functions;
- It specifically focuses on features which make them easy to use by non-specialized people in an interactive mode;

- It emphasizes flexibility and adaptability to accommodate changes in the environment and the decision-making approach of the user.

For Covington *et al.* (1988) it is important that a DSS provides decision makers with rapid feedback on the consequences of management alternatives. A DSS has three main components which are: a **data base**, a **model base** and a **software complex**, linking the user to the first two components (Sprague and Watson, 1986). The model base, consisting of one or many models, is the part of the DSS where the information is processed, analyzed and summarized.

The use of DSS in forest management

As in other management fields, DSS are being developed for agriculture-related fields such as the management of livestock and grazing lands (Stuth and Lyons, 1993; Gillard and Monypenny, 1988) or agricultural land (White, 1991). DSS are also used in the management of forest resources (Covington *et al.*, 1988). However, the expression DSS is not always used. Many authors in forest management and forest planning prefer to use the terms **MODEL** (even though their tools include data bases and more than one model) or **SYSTEM**. Some of these models are used to help the planning process at the national level (Seppälä *et al.*, 1983) and some are used to help managers at lower levels (management unit, concession, stand...).

The DSS used in forest management were first oriented toward timber harvesting and land allocation in even-aged forests. Some examples of such models are: FORPLAN (Johnson *et al.*, 1986); TREES (Tedder *et al.*, 1980) and MAXMILLION (Clutter *et al.*, 1978). The difference between **even-aged** stands and **uneven-aged** stands (Davis and Johnson, 1987) is that in even-aged management, stands regenerate naturally or are planted at about the same time (about the same year). The stand then grows for a number of years, is perhaps submitted to some silvicultural treatments along the way, and finally has all its stems removed in one or more regeneration cuts. Typical decisions needed in even-aged forest management concern: the rotation age, the thinning regime, species for regeneration, site preparation and regeneration, and other cultural treatments.
In uneven-aged management, however, stands have beginning nor end dates. Trees of many different sizes and ages grow in close proximity and each may need a uniquely determined time of harvest to contribute the most to the owner's objective. Illustrations of the concept of uneven-aged forest management is the *futaie jardinée* (garden forests) originally found in France and Switzerland. These are intensively managed forests in which management tries to maintain a constant ratio between number of trees in any two successive size classes. Davis and Johnson (1987) identified the following seven elements as typical issues to be decided on for uneven-aged forest management:

1. **Cutting cycle:** the number of years between two consecutive harvest entries on each hectare.
2. **Reserve growing stock level:** the residual volume or basal area per hectare of the stand immediately after harvest.

3. **Stand structure:** the number of trees per hectare by species and diameter that make up the reserve growing stock.
4. **Sustainability procedures:** constraints established on harvesting and regeneration to ensure maintenance of the stand structure, and thus perpetuation of the harvest over all future cutting cycles.
5. **Other cultural treatments.**
6. **Species for regeneration**: species and genetic stock selected for each stand type in the forest.
7. **Site preparation and regeneration method:** combination of pre- and post-harvest treatments scheduled to establish the desired species and control their early growth.

To date, almost all the DSS developed for forest management purposes require first: a data base made up of information about the current forest growing stock, growth and yield of treated and/or untreated stands, costs and prices of forest products, and constraints from laws and ecological guidelines. Second, a model base using some simulation and/or optimization techniques to process these data, generate consequences of the choices, and choose the optimal solution. Some of the most popular approaches in DSS building for uneven-aged forest management are represented by the following work:

Buongiorno and Michie (1980) developed a model (their terminology) which was to help forest managers in determining the optimum harvest level, residual stock, diameter distribution and cutting cycle for uneven-aged forest management. Their approach used a matrix model for growth prediction in undisturbed and in managed stands. Linear programming was used as a technique to select the best sustained yield management regime. Later this approach was used to design a computer-based model called UNEVEN, for assisting decision-making in the management of uneven-aged forests (Boothby and Buongiorno, 1985). Chang (1981) proposed a model to find the optimal growing stock after harvesting and the optimal cutting cycle using the forest value as a decision criterion. These two efforts were made with inventory data from uneven-aged but single-species forests. Bare and Opalach (1987) developed a model for the determination of the diameter distribution and species composition for mixed species forests using a single-tree growth model called PROGNOSIS and a nonlinear programming algorithm for optimization.

The model base of DSS in forest management
There are typically two model bases for DSS used in Forest Management: growth and yield models and economic models.

a) Growth and yield models
Growth and yield models are usually presented either in tabular forms or as equations or systems of equations. The latter is the one most used for DSS. Models presented as equations or systems of equations can be placed in one of three groups (Clutter *et al.*, 1983; Vanclay, 1994; Vanclay, 1995) depending on whether they allow prediction for whole stands, classes of trees or single trees.

i) Whole stand models. These are models for which the basic units of modeling are stand parameters. They model whole stands as portrayed by stand variables such as age, basal area per hectare or yield per hectare. Whole stand models seem to have been the first model type developed by foresters (Vuokila, 1965). They require relatively little information to simulate the growth of a stand, but consequently give rather general information about future stands. Many approaches have been developed over time but roughly these approaches can be grouped in three; growth and yield tables, growth and yield equations and detailed whole stand approaches. As Vanclay (1994) concludes: "whole stand models have been very useful for modeling plantations, but they appear of limited utility for mixed forests where the number of species and the potential for multi-modal size distributions creates difficulties in characterizing the stand with few stand level variables." Therefore, whole stands approaches are not usually retained for modeling growth and yield in tropical forests which are uneven-aged and have mixed compositions.

ii) Size class models. They use classes of trees as basic units for modeling, values for stand characteristics are rather obtained by summation of values estimated for different classes. Vanclay (1994) distinguished three principal approaches for size class models:

- ***Stand tables approaches***. These include methods and techniques such as time of passage, stand table projection, smoothed stand table models, empirical equations and process-oriented stand table models.

- ***Transition matrices***. They consist of summarizing growth characteristics summarized in a matrix. This allows growth projections to be made by simple matrix multiplication. In general, models based on transition matrices are subdivided in three: Markov chains, Leslie and Usher matrices and their generalizations.

Markov chains constitute one type of stochastic process. The system being modeled has the capability of moving from one state to another over a certain period of time. If it so moves we say that a transition has occurred. At each state i, the system has a given probability P_{ij} to another state j and this probability is called the transition probability. In Markov chains, the transitions probabilities depend only on the initial state and not on any previous state (Markov assumption) and the probabilities do not change over time (stationary assumption). Applied to forestry, the Markov assumption means, that the probability for a tree to grow up to the next diameter class depends only on the current class in which the tree is. On the other hand, the stationary assumption means that trees of a given size class have a constant probability to die, stay in the same class or move up to the next class (or classes) within one growth period. The Markov chain approach has been criticized for failing to take into account competition and suppression (Binkley, 1980; Roberts and Hruska, 1986), but as Vanclay (1994) puts it, "Provided that stand conditions remain within a narrow range similar to the development data, …predictions may be satisfactory."

Leslie and Usher matrices are modifications of Markov chains. The use of such matrices to model biological populations seems to have been initiated by Lewis (1942). However, a more important contribution came a few years later from Leslie (1945, 1948) who used the matrices on animal populations where the classes represented ages. Usher (1966) appears to be the first to use the approach for forest management purposes. The approach uses time interval and class width in such a way that a tree cannot grow more than one class during the growth period (Usher assumption) which avoids bias (Vanclay, 1994). Furthermore, Markov matrices contain only transition probabilities while in this approach, recruitment can be predicted by employing non-zero values in the top line of the matrix. The recruitment varies according to the presence of trees in various classes. Leslie and Usher matrices have been used more in forest management applications than standard Markov chains.

Generalized matrices have been introduced by Buongiorno and Michie (1980). Because of the severe restrictions imposed in matrix approaches by the Markov assumption, they avoided it and used only the stationary and Usher assumptions. Their matrix was presented as a bi-diagonal matrix with probabilities of movement to which a vector and a scalar were added to predict regeneration. A good description of the method is given by Buongiorno and Gilless (1984). They first applied the approach using hardwoods data from the North-Central region of the United States of America. Since then the approach has been used to evaluate many management strategies related to uneven-aged forests both in the temperate zone (Lu and Buongiorno, 1993; Buongiorno *et al.*, 1994; Buongiorno *et al.*, 1995, Virgilietti and Buongiorno, 1997) and in the tropical zone (Mendoza and Setyarso, 1986; Boscolo *et al.*, 1997).

An important point in transition matrix approaches is the estimation of the elements of the growth matrix or transition probabilities. Michie and Buongiorno (1984) evaluated four techniques to obtain estimates in a fixed coefficient model of a selection forest. Their conclusions suggest that, if the data set allows, it is preferable to estimate transition probabilities as simple proportions which yield unbiased estimates. Otherwise if the data set is not large enough, Vanclay (1994), drawing from Lowell and Mitchell (1987) and Vanclay (1991), suggests that "to estimate entries with greater precision and/or fewer data", logistic regression can be used. The ingrowth equations were then obtained by ordinary least squares methods.

Although criticized for the restrictions imposed by both the Markov and Matrix assumptions, the transition matrices approaches appear attractive because they are easy to implement on computers, and produce good results in many cases (Vanclay, 1994). The generalized approaches have brought improvement by avoiding the Markov assumption.

- ***Cohort models.*** In cohort models trees are not necessarily grouped by size classes of equal and predetermined size class amplitude. Instead many attributes, such as species, vigor or commercial characteristics, can be used to group trees in cohorts. This avoids having empty classes as it may be the case with the size as used in stand tables and matrix models. Various assumptions can then be made about the distribution of trees within a cohort. Some models assume that all members of a cohort are identical. Some assume a uniform distribution, and fit a distribution function across several cohorts (Vanclay, 1994). Cohort models have been used to model forest growth in plantations (Alder, 1979) and mixed forest stands (Reed, 1980; Preston and Vanclay, 1988; Vanclay, 1989). Cohort models have potentials for being used widely in modeling mixed forests but their implementation remains tedious.

iii) Individual tree models. Individual tree models simulate the growth of each individual tree in diameter, height, and crown to decide whether the tree is likely to live or die; then calculations are made to obtain volume and growth. By adding characteristics of individual trees stand characteristics are estimated. "While detailed in their accounting and often using elegant growth functions, individual tree models are logically straightforward...Only three possibilities are considered for each tree: (1) it can die, (2) it can be cut, (3) it can survive and grow. When this sequence of choices is worked out for all sample trees representing a stand, mortality, harvest growth, and the residual stand structure are summarized from the individual tree results" (Davis and Johnson, 1987). Individual tree models can be subdivided into three categories (Vanclay, 1994): a) spatial models which simulate individual trees or their components using spatial data indicating their position in the stand; b) non-spatial models which also model individual trees, but which do not require any spatial data and; c) tree list models which model small lists of trees.

Individual tree models are logically capable of yielding the most interesting results. But they are quite complicated and may require the recording of additional parameters during forest inventory related to the position and the size of neighboring trees which makes them costly. As Bruce and Wensel (1987) put it: "using a more complicated model than necessary often has at least two costs: greater computational expense and a loss in precision of estimates."

Data requirements for growth and yield modeling. The quality of the data is very important for the determination of the type of the model to be built and its quality. Ideally, modeling and the definition and collection of data should form an iterative process, starting with model formulation. In theory, the type of the model that the biometrician has in mind should orient towards data collection. In reality, this is seldom the case. Most modeling efforts commence with any data available, and the modeling approach may be dictated by limitations of the data.

In general, growth information can be obtained by stem analysis, but stem analysis does not provide reliable growth data for many tree species in tropical forests, so data must be obtained from re-measurements on permanent sample plots (PSPs). Vanclay (1994) gives a detailed account of data requirements for growth and yield modeling. His suggestions are synthesized by the following six points:

1. Ensure consistent standards,
2. sample a wide range of stand and site conditions,
3. provide both passive monitoring and experimental plots,
4. number, mark and map all trees on all plots,
5. remeasure frequently enough to enable relocation of plots, but allow enough time for growth to exceed measurement errors, and
6. check that measurement records are unambiguous and secure.

Although he insists that it is better for model predictions to be interpolations than extrapolations, Vanclay (1994) recognizes when modeling forest growth and yield in tropical forests, "the greatest problem…is that the data necessary for growth model development are not available" which in turn may lead to extrapolations from the few existing data sets.

b) Economic models

Most economic models dealing with sustainable forest management have tried to determine a target steady state which will fulfill a number of objectives. A steady state in this context means a stand structure and composition to be left after each harvest as residual growing stock. The steady state residual growing stock will grow so that at the end of every cutting cycle, the same quantity and quality of timber products may be harvested. Theoretically, the yield of forest products obtained after each cutting cycle is then equaled to the forest net growth and can be continued in perpetuity, such a yield is often referred to as the sustained yield (Davis and Johnson, 1987). A steady state with a sustained yield of timber products is characteristic of a fully regulated forest. For a given forest stand, there are many steady states which can be found each with its structure and composition, each steady state should be associated with a well defined set of harvesting rules in order to be perpetuated indefinitely. The most important of these rules are the length of the cutting cycle and the characteristics of the reserve growing stock which are linked to the characteristics of harvests. Based on the objectives of management, one of these steady states will be preferred over the others and the associated harvesting rules will be adopted. The model allows the determination of such a desired (preferred) steady state depending on the specification of management objectives.

The general solution seeking procedure consists of generating alternative steady states and using some criteria to select the desired one. Most models have used economic criteria for the evaluation of alternative steady states and associated management strategies. It is done so because, one of the most widely accepted and easy to evaluate goals is that of economic efficiency, i.e. maximization of net revenue or benefit. Some of the criteria used for that purpose are (Davis and Johnson, 1987):

i) The Present Net Worth (PNW) which is defined as the sum of discounted revenues less the sum of discounted costs over a defined planning period. Its formula reads:

$$PNV = \sum_{t=0}^{n} \frac{R_t}{(1+r)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{2.5}$$

where: R_t = revenue in year t

C_t = cost in year t

r = discount rate

n = number of years in the planning period

ii) The Benefits Costs Ratio (B/C) which indicates the amount of present value revenue per unit of present value cost. Its formula is:

$$B/C = \frac{\sum \frac{R_t}{(1+r)^t}}{\sum \frac{C_t}{(1+r)^t}} \tag{2.6}$$

iii) The Internal Rate of Return (IRR) which is a unique characteristic of a project and does not require a guiding discount rate as do the preceding criteria.

IRR = r when the following equation is solved for r:

$$\sum \frac{R_t}{(1+r)^t} = \sum \frac{C_t}{(1+r)^t} \tag{2.7}$$

The above listed criteria are mathematically interrelated. By definition, the IRR is that discount rate that makes PNW=0 and B/C=1. One drawback of the PNW and the B/C is that a prior decision about the choice of the guiding interest rate must be pre-selected, and the choice of these rates varies from one analyst to the other.

iv) The Soil Expectation Value (SEV) or Land Expectation Value (LEV), also called the Faustmann Criterion: it is defined as the present net worth of bare forest land for timber production calculated over a perpetual series of timber crops grown on that land. Its formula is:

$$LEV = \frac{\sum_{t=1}^{T} R_t (1+i)^{T-t} - \sum_{t=0}^{T} C_t (1+i)^{T-t}}{(1+i)^T - 1} \tag{2.8}$$

where T = length of the cycle

The LEV is usually preferred over the PNW if the land is definitely oriented toward forestry because it takes into account not only the first cycle, but also all the future cycles. Thus, there is no problem related to the time horizon and the cost of delaying subsequent cycles is taken into account. It accounts for the opportunity costs of capital and land of choosing a given management option especially as rotation and cutting cycles are concerned.

This criterion has been most used for estimating optimal rotation for even-aged management but the same approach has been used in the case of uneven-aged management.

Chang (1981) presented the Forest Value (FV) defined by the following formula:

$$FV = P(S-G) + \frac{P[Q(t,G) - G]}{e^{rt} - 1} \tag{2.9}$$

where: S = initial stand volume immediately before harvest

G = level of growing stock immediately after harvest
t = cutting cycle
$Q(t,G)$ = merchantable volume of an uneven-aged forest stand t years after a cut with an initial growing stock of G
P = stumpage price.
r = continuous discount rate

In such an approach, *FV* represents not only the value of the forest land but also the value of the trees currently growing that can be harvested. The optimal growing stock after harvest G and the cutting cycle t can then be found by using the derivatives of *FV*. The equations to be solved simultaneously are:

$$\frac{\delta FV}{\delta G} = 0 \qquad (2.10)$$

and

$$\frac{\delta FV}{\delta t} = 0 \qquad (2.11)$$

The interest of the *FV* comes from the facts that it can be used to derive criteria for optimality as well as to identify factors that influence it.

The use of *FV* is linked with a few problems, one of these problems is that the growing stock level is the total volume per hectares to be left after cutting irrespective of the stand structure and thus gives no rule related to the structure to be taken into account during harvesting operations. In addition it assumes that price is not related to tree sizes which is seldom the case.

Estimation of the conversion period. In most cases the forest is not fully regulated and the desire of sustainable forest management is to convert the non-regulated forest into a regulated one. The time interval between the first management operations in the non-regulated forest and the moment at which a fully regulated forest structure is reached can be called the conversion period. The conversion period poses a number of questions which forest management specialists should confront. Two of these questions to be addressed here are: how long should or will be the conversion period given the defined management objectives? What are the harvesting rules to adopt during the conversion period? The answers to these questions will be referred to as conversion strategy.

Searching for the best conversion strategy has not received the same attention by theoretical forest management analysts as the search for an optimal steady state especially as related to uneven-aged forest management. An example of an investigation of the conversion is the study by Adams and Ek (1974). The two authors made an investigation into the determination of optimal steady state structure and the optimal harvest schedule of a non-regulated stand to a predetermined target structure. They used non-linear equations and their objective was to maximize the Net Present Value (NPV) of all transitional and subsequent equilibrium yields. They found that lengthening the conversion period increased the NPV. Such a result is possible certainly because by increasing the length of the conversion period, the constraints are loosened. However, this may result in loosing the constraint of sustainability itself by degrading the forest too much during the conversion period if there is no rule that insures that the structure converges towards the desired steady state.

Michie (1985) tried to determine both the optimal steady state and the optimal conversion strategy using the land expectation value (LEV) as criterion. He found that the LEV is dependent on both the initial stand conditions and the length of the conversion period. His investigations led to the conclusion that, converting to an alternative distribution in one harvest doubled the LEV and obtained a further increase in LEV with two harvests, suggesting also that lengthening the conversion period may increase the LEV. Michie insisted in the conclusion of his study on the difficulty of solving the mathematical program if three or more harvests are considered. He suggested from his finding that, "alternative steady state distributions are tending toward the same structure regardless of the initial stand structure."

In another study, Haight and Getz (1987) determined conversion with the two approaches: the fixed endpoint problem and the equilibrium endpoint problem. In their terminology, the "fixed endpoint problems involve the determination of a target steady state and a transition regime that reaches the target after a finite transition period." Therefore the problem formulated as solved by Adams and Ek was a fixed endpoint problem. On the other hand, equilibrium endpoint problems involve the determination of transition and steady state harvests that do not require the achievement of a specific target stand structure. Michie's investigation was an equilibrium endpoint problem. Haight and Getz (1987) used a non-linear dynamic optimization model to solve both the fixed endpoint and the equilibrium endpoint problems. In their conclusions they reported that, for a given transition period length, the solution of the equilibrium endpoint problem has a higher present value than the solution to any fixed endpoint problem and that the costs of a terminal steady state constraint can be large for short transition periods but the impacts decrease as the transition period lengthens. Michie and Buongiorno (1984), and Buongiorno *et al.* (1995) have suggested a simpler approach that consists of applying the new steady state harvest repeatedly over an indefinite time period, then the desired steady state will be reached gradually. The rule in that case is: compare the number of trees in the current stand with the desired number and harvest the surplus. Such a solution is simple because it does not need non-linear investigation techniques but it can delay reaching the desired steady state. However, it should be financially interesting because studies cited previously tended to conclude that longer conversion periods have higher levels of economic return, because there are less constraints.

Mathematical programming in forest management

Mathematical programming involves the use of models to solve certain types of management science problems. The mathematical expressions that comprise a particular model may be linear or non-linear. If relationships in a mathematical model may be assumed to be known with certainty, then the model is said to be *deterministic*. If they are assumed to be subject to random variation, then the model is *probabilistic* (or *stochastic*) (Dykstra, 1984). In mathematical programming, formalized sets of instructions are used to solve problems. Mathematical programming problems usually involve a high level of computational burden. Therefore, computers are often used to solve them; however this is not necessarily so. More commonly, solutions for mathematical programming problems are obtained through the use of numerical methods. The more powerful and efficient numerical methods are referred to as *algorithmic*. An algorithm is a set of logical and mathematical operations performed in a specified sequence. Algorithms use trial-and-error approaches to search for "best" or "optimal" solutions. The procedures start by selecting and specifying a so-called *optimality criterion*. Beginning with an initial trial solution, the algorithm is used to find a new improved solution. The sequence of operations leading to this new solution is called an *iteration*. The algorithm continues to iterate until the specified optimality criterion is satisfied; then it stops. If an algorithm has been correctly designed and the mathematical programming problem to which it is applied satisfies certain conditions, then the "best" trial solution obtained during the execution of the algorithm will be the optimal solution and usually the final trial solution.

Many mathematical programming techniques have been used in forest management. These techniques are either optimization techniques or simulation techniques. The main difference between optimization techniques and simulation techniques is that: optimization techniques choose the best of all the possible solutions to the problem defined, while simulation techniques choose the best solution from only a subset of possible solutions to the problem.

The most used optimization techniques in natural resources management is certainly linear programming (LP). Dykstra (1984) presented a wide range of situations in which LP could be used or had been used to improve decision-making in forest management. The examples presented include: timber harvest scheduling, veneer production, agroforestry, wildlife management, land use planning and soil loss. For LP to be used the most important condition to be met is that all mathematical expressions in the problems must be linear (Dykstra, 1984; Hillier and Lieberman, 1989). In addition to the *linearity* requirement, further assumptions of linear programming include the *divisibility* of decision variables which means that decision variables can have any real value including both integers and fractions; *non-negativity* variables and *deterministic* meaning that all the coefficients used are constant i.e. they are known with certainty. However, as Dykstra (1984) puts it "In practice, we seldom know these values with certainty and they are commonly not fixed but subject to some kind of ... fluctuation. To some extent, uncertainties and randomness can be dealt with by means of *sensitivity analysis.*"

Other optimization techniques include: Dynamic Programming, Integer Programming, Goal Programming and Multi-objective Programming. All these techniques assume that the *linearity* condition is met; if it is not then it is better to use non-linear programming.

For simulations, one of the most used techniques in natural resources management is *binary search*. This technique can be easily used if there is only one variable which is of interest. The procedure begins by setting a starting value for the variable of interest from which the resulting consequences are simulated. If the objective is not satisfied, another value for the variable is chosen according to a predefined rule, and this will be tried again. The consequences are once more simulated and the objective checked *etcetera*. The procedure stops when a predetermined level of the objective is satisfied.

Theoretically, optimization techniques are often preferred over simulation techniques because the solution given to the formulated problem is the best of all possible solutions while with simulation, only a subset of possible solutions, is examined implying that a better solution may be left out of that subset. However, the preconditions required for the application of most optimization techniques are difficult to meet. Thus, the choice of an approach will depend on the problem confronted and the assumptions that can be reasonably made given the prior knowledge the analyst has about the problem.

2.3.4 Decision-making in tropical forestry

In tropical forestry, even-aged management applies to the management of tree plantations while natural forests are comparable to uneven-aged forests with mixed species (Eba'a, 1989). The advantages usually cited for even-aged management include: a better understanding of management techniques (Kio and Ekwebelam, 1987); ease of management operations; and greater financial returns. However, plantation forestry in the tropics is now limited only to a few species for which silvicultural techniques are well known and many hardwood species currently valued in international markets are not included. In addition, plantations simplify the ecosystem and the results obtained are most of the time interesting only if wood production is the single dominant objective. In plantations, biological diversity is lower and the forest dwellers do not always find the whole range of products they typically harvest from natural forests. Natural forests, on the other hand, are more suitable for the supply of more diversified products including timber, non-timber products, and supporting greater biological diversity. If these effects are included in the analysis, natural forest may prove to offer better economic returns than usually thought (Sedjo, 1992). However, uneven-aged management is always more difficult to carry out. The interest in the current study is mainly concentrated on natural forest management. Thus, the uneven-aged management decisions are the ones to be considered; and more and more DSS methodologies are being developed for these management strategies.

Most of the DSS were developed for temperate forests especially those of northern America and Europe. However, these approaches have also started to be used in other parts of the world (including the tropics). For example, Song (1993) has reported that a DSS was built for uneven-aged forest management in China using a matrix approach for growth modeling and a simulation technique for the search of the best solution for maximizing the net present value of the timber harvests. Few attempts have been made to model decision-making for tropical forest management. The most important efforts have concentrated on growth and yield modeling.

The best known models for the growth of natural tropical forests are from North Queensland in Australia where Vanclay (1989) reported that Higgins (1977) built a matrix model based on transition probabilities for the management of mixed tropical forests of that country. Vanclay (1989), using data from 250 Permanent Sampling Plots (PSP) developed growth equations for the same forest. These equations predicted diameter increments based on the tree diameter, the stand basal area, the site quality and soil parent material as dependent variables. To deal with the problem of diversity, the species were divided into five groups based on commercial criteria and growth habits: a) commercial species which grow rapidly to a large size, b) commercial species which grow slowly to a large size, c) commercial species which grow rapidly to small size, d) commercial species which grow slowly to small size and, e) non-commercial species. Individual tree species were assigned to one of these groups based on the prior knowledge the analyst has about each species. Two years later the same author (Vanclay, 1991b) presented a new approach to species grouping based only on growth habits. The 231 species studied gave 41 groups and the equation format retained for modeling growth was the following:

$$\log(DI + a) = \beta_1 + \beta_2 D + \beta_3 \log(D) + \beta_4 \log(D)SQ + \beta_5 \log(BA) + \beta_6 OBA \qquad (2.12)$$

Where: DI = diameter increment (cm/year)

D = diameter (cm)

SQ = site quality

BA = basal area (m^2/ha)

OBA = over-topping basal area (m^2/ha)

β_1 to β_6 are regression coefficients

In tropical Africa, three countries along the western coast have made important progress in the field of growth and yield modeling, especially concerning the establishment of Permanent Sample Plots (PSPs) which would provide data for growth and yield modeling. One of them is Ghana where a programme to establish PSP is reported to have been carried out between 1969 and 1980 (Alder, 1990). By 1980, 855 plots had been established, out of which 651 survived and were re-measured at least once by 1990. Each plot covered an area of 1 ha within which 50 trees with known commercial value were followed. Data from these PSPs were used to estimate the increments of each diameter class which in turn served in the development of the transition matrix for growth and yield modeling. This led to the development of yield tables and some prescription for managers whose dominant objective was wood production. It was concluded that a sustainable yield for redwood would be around 2 m^3/ha/yr and a cutting cycle of about 25 years was considered.

The second data set is from Côte d'Ivoire, where a forest area of 400 ha was set aside for the study in 1976 (Mengin-Lecreulx, 1976). In this area 25 PSPs of 16 ha each were established, and all trees of desirable species (73 species were considered) were identified and measured every two years in the four most central ha of each plot. The less commercial species were grouped and also measured. Plots also had some silvicultural treatments. Six years after the establishment of the PSPs, the data were analyzed to build a growth model based on the transition matrix approach. Commercial species were grouped in five categories based on assumptions regarding growth habits and on frequencies of occurrence. The average annual volume increment was found to be about 0.4 m^3/ha/yr in treated plots and 0.2 m^3/yr/ha in untreated plots.

The third network of PSPs is found in Liberia (Parren and de Graaf, 1995) where 39 plots of one hectare each were established starting from 1978. These plots were established in four stations a few years after conventional logging operations. Silvicultural treatments were conducted in some of the stations.

Most of the analyses of data collected from the above mentioned African countries have focused on estimating average diameter increments for different tree species. In general, only a few attempts have been made to suggest management options. The few management options proposed concentrate on ecological aspects and the sustainability of wood productions. No economic information on wood products was utilized which may be a serious omission when trying to assist forest management. Indeed, as Gong (1990) puts it: "expectations on future timber prices affect forest owner's current management decisions" and thus, these expectations on future timber prices should be integrated in all forest resources management models as is already the case in temperate forestry. Furthermore, multiple objective forest management was not considered of interest in the analysis of PSP data from African countries.

2.3.5 Integration of non-timber aspects in forest management strategies

The non-timber aspects include not only products and commodities but also conservation of biological diversity and non-material advantages derived from the forests. Integrating these aspects in forests resources management means that all of them are taken into account simultaneously (Holtrop, 1988).

a) Biological diversity and conservation

Biological diversity is of interest because by integrating it into the model we take into account nature conservation concerns. A model that is constrained to have a certain level of diversity in the forest insures the protection of endangered species. In addition, ensuring biological diversity indirectly guarantees the supply of local populations in NTFP because species that produce other products are preserved.

Usually, three levels of biological diversity are distinguished: ecosystem diversity, species diversity and genetic diversity. In the current context, because the analysis is being conducted at stand level, our interest is on species diversity and more precisely on plant species diversity, which is illustrated by the number of tree species represented in the stand. It is assumed that biological diversity at the other levels is also enhanced in the wake of species diversity. The higher the number of species, the more diverse is the stand. Another important notion used here is tree size diversity meaning the number of diameter classes represented in the stand. If two stands are compared on that basis the most diverse will be the one in which more diameter classes contain trees. Species and tree size diversity can be combined to look for the stand where not only the most species are represented, but also trees are present in all diameter classes. The lowest species-size diversity will be obtained where all the trees are of the same species and belong to the same diameter class, while the highest species-size diversity will be reached in stands where all the species are represented and for each species, trees are evenly distributed over all diameter classes. Both aspects of diversity are important. It is known that forests with trees of diverse age and species are not only more resistant to natural hazards (Hunter, 1990) but they also provide a rich variety of habitats for wildlife (MacArthur and MacArthur, 1961; Rice *et al.*, 1984).

To integrate biological diversity in the model, a quantitative method should be used to express it. Many quantitative expressions have been developed in the course of this century for species diversity. Magurran (1998) and Huston (1994) give a detailed account of these expressions that are mostly composite statistics based on the number of species and the relative abundance. However, the most used of these statistics appears to be the Shannon Index and the Simpson Index (Huston, 1994).

The Shannon Index is expressed as:

$$H' = -\sum \left(p_j \ln p_j \right) \tag{2.13}$$

where p_j is the proportion of the total number of individuals composed of species j (or group of species) in the sample. The Shannon Index is equal to zero when all trees are of the same species. Similarly, the Simpson Index is expressed as:

$$\lambda = \sum p_j^2 \tag{2.14}$$

The Simpson Index is rather seen as a dominance index. This has led to a new expression derived from it and referred to as Simpson's D. Its formula is:

$$D = 1 - \lambda \tag{2.15}$$

In an analysis of Ghana's forests, Hawthorne (1990) has also used a number of indices including: a Pioneer Index which reveals the balance of "regeneration guilds", a Genetic Heat Index based mainly on the rarity value and an Economic Index based on the concentration of common species threatened by exploitation. All these indices require some kind of prior classification of species according either to ecological behavior or to the threats they are subjected to. For this reason, it is difficult to use these indices in a model that already comprises a classification based on different criteria like in this case.

In an effort to combine economic efficiency and biological diversity concerns in one optimization model, Buongiorno *et al.* (1994) used the Shannon Index and the Soil Expectation Value as diversity and economic criteria respectively. Because the Shannon

Index involves logarithms, they used nonlinear optimization techniques. An interesting feature of their approach was that they took into account not only species diversity, but also size diversity. One of their main conclusion was that: "...*it is taken for granted that economic* goals are always in direct conflict with ecological concerns, the results also suggested that lengthening the cutting cycle could increase tree size diversity and be economically attractive". Their conclusions were criticized by Önal (1995) who stated that: "the results by Buongiorno *et al.* are derived from improper models, namely nonlinear models with improper convexity". He went on to warn analysts who are dealing with optimization that "...nonlinear constraints can be critical even when convexity requirements are satisfied."

But Buongiorno *et al.* (1995) suggested an alternative to the Shannon Index, which is the minimum number of trees in any species-size class. This is expressed as:

$$N_{\min} = \min_{i,j}(y_{ij}) \tag{2.16}$$

In this way, if different stand structures are compared, the one with the largest number of trees in the least represented species-size class would be the most diverse. Of course, such an approach favors species and size classes which are the least represented in the stand but has the advantage of being linear and easy to understand. It can be used in the design of a "safe minimum standard of conservation" strategy which tends to minimize maximum possible environmental losses (Ciriacy-Wantrup, 1968). In any case, it is advantageous to threatened species.

b) Integrating wildlife in forest management

Examples of the integration of wildlife concerns along with timber production into forest management are rather scarce, especially in the tropical region. Most strategies and regulations have been developed and implemented separately for either wildlife (Especially in national parks and other wildlife reserves) or timber production. Attempts to derive optimal strategies for integrated management of these resources are even more scarce. Where these attempts have been made, decisions were based on spatial analysis of socio-economic, cultural and natural resource information. Caldecott (1988) presented some of the socio-economic data needed about wildlife for sound hunting and wildlife management. These include: hunting patterns (Techniques and fire power, special influences on hunting and species affected by hunting), wildlife trade, wild meat in human nutrition, scale of the wildlife harvest and value of wildlife harvest. In addition, data on the resource should be gathered including:

- estimation of animal populations and trends,
- a large-scale habitat and wildlife survey,
- behavioral and ecological studies of animal population and,
- effects of logging on forest habitats and wildlife communities,

Getting these data has not been an easy task. Winter (1984) identified some problems of wildlife management peculiar to the tropical forests. These include:

- seasonal effects,

- complexity and high species diversity (It is generally recognized that the tropical rainforest is the most complex and diverse of terrestrial ecosystems),
- insular nature of rainforest (the structure of the rainforest is radically different from that of more open forests. Consequently much of the wildlife occurring in rainforest is restricted to that habitat and does not extend beyond it. The knowledge of the minimum area of rainforest required to support a species community becomes more critical than that of open forests),
- importance of zoo-geographical distribution patterns of species,
- assessment of the effects of disturbance to the rainforest and,
- traditional use of wildlife.

The lack of prior knowledge of all these elements makes it very difficult to use quantitative techniques when designing integrated management strategies for both timber and wildlife resources.

c) Integrating local use of the forest

The involvement of local people in forest management implies that their needs and the ways they utilize the forests should be integrated into the design and implementation of management plans. An important part of the utilization of the forest by local populations is the gathering and harvesting of plant products for food, shelter, fuel, medicine *etcetera* (Botkin and Talbot, 1992). In general, the needs of the local populations are often summarized by the umbrella term Non-Timber Forest Products (NTFPs). A definition of NTFPs is proposed by Wickens (1991) as "...all the biological material (other than industrial roundwood and derived sawn timber, wood chips, wood-based panels and pulp) that may be extracted from natural ecosystems, managed plantations, etc., and be utilized within the household, be marketed, or have social, cultural or religious significance."

In order to make the integration effective and to combine harvesting and gathering of these products with timber production, the planner needs to list the species of interest in the area for both utilization patterns. Additional socio-economic information needed for these products concern their trade, their role in human nutrition and welfare, as well as the trends of their relative importance over time. In addition to socio-economic information, ecological information is also needed to determine the relationships of these species with the rest of the plant community as well as the animal community and their basic ecological requirements.

The consideration of NTFP in management strategies is unavoidable for sustainable tropical forest management because the utilization of the forest by the local population cannot be overlooked. The main concern is however, about the development of appropriate methodologies that takes into account these products. Because of the large amount of specific quantified information needed to incorporate these items in mathematically formulated management models, it is at this moment impossible to use an endogenous formulation to integrate them. However, with minimal data input, the continuous supply of these products can be guaranteed by means of constraints to timber harvesting and by policy formulation.

2.4 Conclusion: research orientation

The preceding literature survey has shown some gaps in the knowledge about uneven age management systems in general and particularly as applied to tropical forests. In general, models for optimal decision-making in uneven-aged forest management have been mostly used outside the tropical region. Criteria for decision-making identified (Bare and Opalach, 1988) include: 1) the optimal sustainable diameter distribution, 2) the optimal species mix, 3) the optimal cutting cycle, 4) the optimal conversion strategy and length, and 5) the optimal schedule of treatments for all stands to best meet forest level objectives and constraints. Unfortunately, the various research projects undertaken have had an unbalanced attention of these aspects even in temperate countries. For example, the question of optimal species mix has received less attention than the development of silvicultural techniques. The development of decision support tools has received even less attention. The lag in DSS development for use in tropical forest management seems to be tied to two major problems. The first is related to the fact that the few efforts made focused only on wood production without incorporating financial data to asses at least the profitability of management operations. The second problem is that of the difficulty of modeling growth in diverse forests where little if any data are available. It is recommended to use data from PSPs (Vanclay *et al.*, 1993) which unfortunately are scarce or usually not old enough or not consistently re-measured.

For the growing number of research projects that are now underway in tropical countries for natural forest management, the focus has been mostly on developing silvicultural systems and more recently predicting the growth and yield. Almost no attempt has been made to combine results from growth and yield studies research in silviculture and economic data to derive management strategies. Management criteria such as cutting cycles, appropriate forest stocking levels and structure, and the need to incorporate silvicultural treatments have been by and large based on the subjective experience of decision-makers or at best on fragmented scientific knowledge in each sub-discipline. For example, in some cases, growth information was used to deduct the cutting cycle as the time needed after logging to reach a given diameter limit but the setting of such a limit has not been justified scientifically and technically. The study presented here tries to narrow the gap in this area. In Cameroon diameter limits are also used by the forestry administration to control logging activities; but no scientific approach was used to set those limits. Furthermore, if there are more and more claims as for the need for management systems to provide multiple outputs, investigations are not done on the possible co-existence of timber harvesting and production of other outputs from the forest to meet the need of the local population. The study proposed here will make a primary attempt to identify conditions for such a co-existence.

Chapter 3

Research objectives and conceptual approach

3.1 Synopsis of research gaps

The presentation of the status of forest management in Cameroon done in chapter 1 and the review in chapter 2 lead to the observation that: some scientific and technical knowledge exists even though it is not enough to feel secure about the success of sustainable forest management in the tropical zone. This is especially true when uneven-aged forest management is foreseen, which is the case in natural tropical forests. But even more lacking are tools to support decision-making as applied to tropical forest management. Tools are needed that can assist forest management by not only generating alternative management options, but also allowing the analysis of different options to capture their consequences and trade off between objectives. In other words, this research confronts the problem of how to assist decision-making in tropical forest management using the best available scientific information gathered in different disciplines.

3.2 Research objectives

In Cameroon, like elsewhere, decision-making in forest management centres around a few key management attributes especially when timber production is one of the objectives. These attributes concern the steady state definition and the conversion strategy. These concepts are the focal decision items considered in this research.

3.2.1 General objective

The overall objective of the research proposed here is to design a system that can support decision-making for the management of natural tropical forests.

The system should provide insights into the critical factors that affect the sustainability of management strategies of the tropical moist forests of southern Cameroon. To obtain such insights an adequate methodology is needed, which is capable of: (i) generating information about short-term and long-term economic consequences of management options, and (ii) providing information about the future structure of forest stands and of key forest products utilised by both the local population and the industrial partner in the concession. The emphasis of the research is on designing a methodological tool which may be used to help in decision-making and monitoring of the forest that is being managed and might have potentials for utilisation in other tropical countries.

3.2.2 Specific objectives

The specific objectives to be reached by this research are the following:
1. To design a system for supporting decision-making with respect to the management of tropical forests.
2. To assess the effects of different management options on the economic returns of the logging enterprise as well as on the structure of the forest at steady state.
3. To provide insights into the trade offs between income generation through sustainable timber harvesting and the use of the forest by the local population on the one hand, and between income generation through sustainable timber production and nature conservation on the other hand.
4. To derive recommendations for conversion of the current forest at the TCP research site into a steady state forest.
5. To evaluate and suggest adaptations of existing strategies aimed at sustainable management of the tropical moist forest of south Cameroon.

3.3 Conceptual framework

The main underlying assumptions of the research and the development of the methodology in particular are that:
a) The goal of sustainability in forest management can be attained only if ecological, economic and sociological constraints are taken into account within any management strategy developed and implemented.
b) There are ways to reconcile forest conservation (maintenance of forest cover and some biological diversity) with some levels of both industrial timber harvesting and forest utilization by the local population.

As evoked in sections 2.2.3 and 2.4, most research previously done for the development of management options in tropical forestry have used growth and yield information and silvicultural systems with little reference to socio-economic considerations. Even more scarce are efforts to combine many of these aspects in one decision-making approach in order to obtain simultaneous quantitative figures to support tropical forest management. Knowledge about dynamics of treated or untreated forest stands has been used separately from socio-economic information to support decision-making in forest management. Even though all attempts are usually made to use the best available knowledge, using stand characteristics separately from the socio-economic environment may lead to missing the interactions that exist between bio-ecological aspects of forest management on one hand and the socio-economic environment on the other. Such disintegrated approaches may lead to solutions which are far from optimal as it is known that, by aggregating optimal solutions developed on parts of a problem, one does not necessarily get an optimal solution.
The idea in the development of the current system is to combine growth and yield modeling with an economic analysis to design a tool that supports decision-making in forest management and satisfies social needs and ecological constraints. It should, however, be noted that the methodology developed here does not intend to include all possible details on the social, economic, physical and ecological dimensions of the tropical forest environment.

An attempt is made to take into consideration these four broad aspects, but within each aspect the levels of detail examined depend on available information and on the necessity to have a usable tool. The general conceptual approach may be illustrated by Figure 3.1.

3.4 Research questions

The general objective of the research presented here can be translated into the following overall question:

Can a system be developed, which is capable of supporting decision-making for the sustainable management of tropical forests in south Cameroon, taking into account both the diversity of forest stand characteristics and the complexity of the external management environment?

To meet the stated specific objectives, the following questions need to be addressed:

a) What methodological approaches can be used to design a system, which supports decision-making for the management of tropical forests of south Cameroon? What are the components of such a system and how can they be related?
b) What coefficients and parameters need to be included in a system which is designed to support decision-making in south Cameroon and how can these coefficients and parameters be estimated given the current availability of information?
c) What outcomes does the system designed provide concerning optimal steady state forest stand structure, harvest and financial returns of logging? How are these outcomes affected by changes in management parameters and objectives?
d) How do the outcomes of the system developed compare with the structure of the current forest at the Tropenbos Cameroon research site and which guidelines can be derived for the sustainable management of this forest?
e) What insights can be obtained from the outcomes of the system developed concerning the trade off between alternative management objectives?
f) What can be recommended for the improvement of forest management strategies in south Cameroon on the basis of the insights obtained from the system designed?

Questions a and b relate to specific research objective 1, which deals with the development of a system capable of supporting decision-making for the sustainable management of tropical forest in south Cameroon. Questions c, d, e and f relate to specific objectives 2, 3, 4 and 5 respectively.

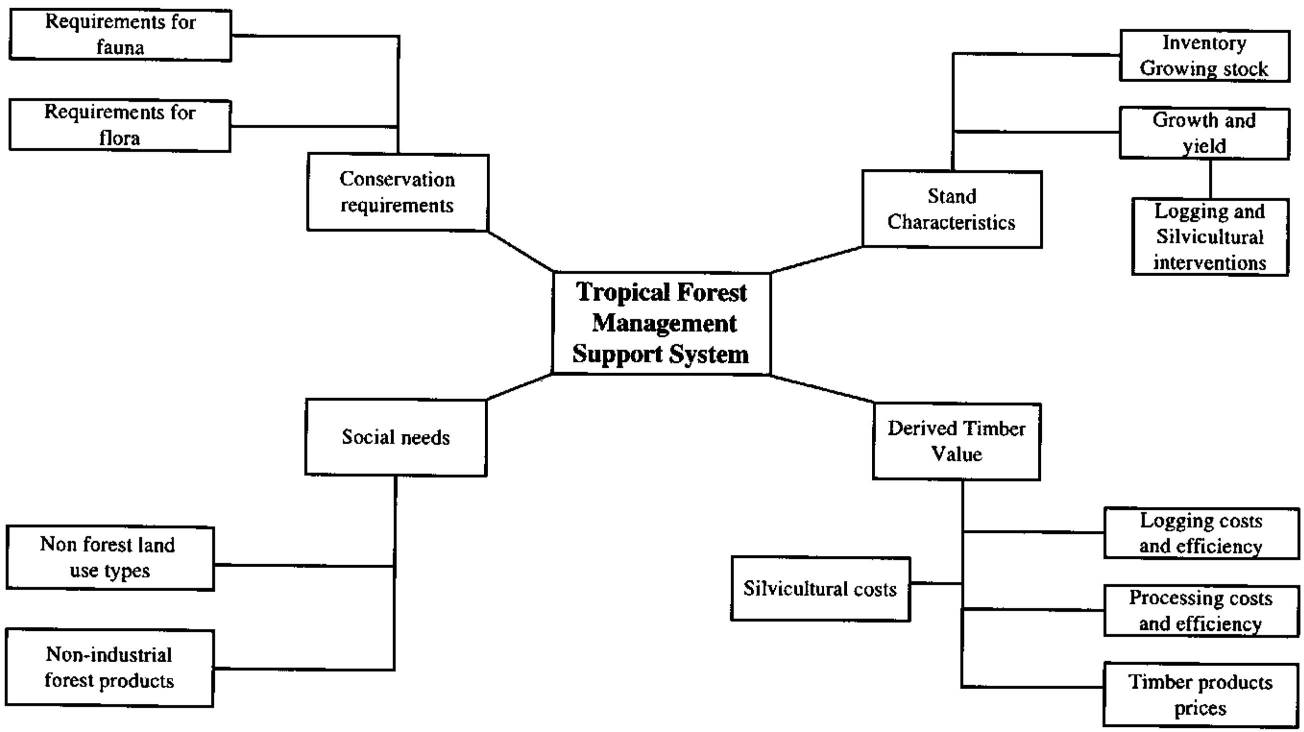

Figure 3.1: Conceptual framework for integrated decision-making in tropical forest management

3.5 The research process

The research is to develop a methodology, which is presented as a model. The idea is to design a tool that uses numerical methods to seek for optimal solutions to a forest management problem formulated in mathematical programming terms. To achieve this, a logical **iterative process** is followed, which addresses research questions and objectives systematically, but also interrelates different steps of research to constitute a coherent approach. Thus, the model is framed on Operations Research procedures. Figure 3.2. illustrates the main phases of the research process.

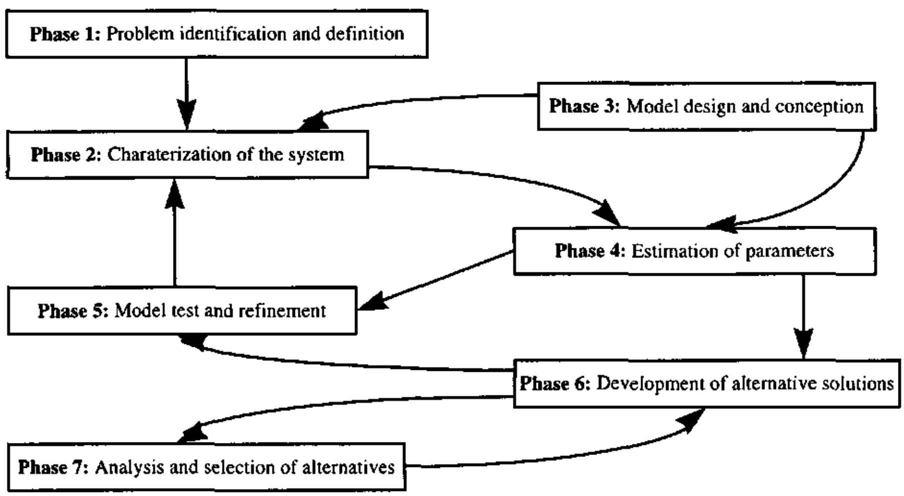

Figure 3.2: Phases of the research process

Phase 1: Problem identification and definition
This phase consists of the identification and definition of the management problems to be solved. The problem of the research has been stated in section 3.1. However, this problem should be related to the objectives of management and the decisions which are to be supported by the model. In the case of this study, an important objective is sustained timber production. The decisions addressed are classical for uneven-aged forest management and include: a) the optimal sustainable diameter distribution, b) the optimal species mix, c) the optimal cutting cycle, d) the allowable cut and e) the optimal conversion strategy. In addition to sustained timber production, two other objectives are the sustained production of other forest products utilised by the local population and nature conservation.

Phase 2: Characterization of the system
Knowledge of the main components of the decision environment, their functioning and their interactions is gathered. For the purpose of managing the tropical forests, these components

relate to the characteristics of the forest ecosystem (growth and yield of forest stands, forest composition and stocking level and biodiversity), or to the managerial environment (forest utilization by the local population, industrial exploitation of timber and the administrative and legal setup).

Phase 3: Model design and conception
In this phase, the model (an idealized representation of the system) is conceived and mathematical techniques to be used in the model are chosen and the chronological procedures of the model are determined.

Phase 4: Estimation of model parameters
Data are collected in the field and used to estimate the values of parameters and coefficients needed for model specification. For the development of the current model the data concerned are the result of periodic measurements on permanent sample plots, market prices for timber products, logging costs, silvicultural costs, information about the utilization of the forest by the local population and ecological constraints.

Phase 5: Model runs and refinement
The parameters and coefficients developed are to be inserted into the theoretical model as designed in phase 3 and test-runs are conducted in an iterative process to determine how well the model fits reality. By confronting the theoretical model with the observed reality, it also becomes possible to refine and improve the predictive and explanatory attributes of the model.

Phase 6: Development of alternative solutions
Once the model is judged satisfactory, data collected on forest stands are used with different management assumptions and alternative management options are developed.

Phase 7: Analysis and selection of alternatives
The options developed are in the last stage analyzed and discussed, and the trade off between management objectives are examined in order to assist in the selection of options which meet the objectives best.

3.6 Synopsis of the research methods

Phase 1 was completed through a literature survey as shown in chapter 2 (Section 2.4), and has led to the definition of objectives presented in section 3.2. Phases 2 and 3 address research question a) and were also conducted through literature survey and characterization of the management environment by descriptions. Phases 4 and 5 address research question b) and are conducted by statistical analysis after acquisition of growth data. The statistical analysis methods used include cluster analysis for species aggregation, logistic regression for the estimation of transition probabilities needed in growth and yield modeling and regression analysis for the development of bole volume equations. In addition, the stumpage prices are derived using the residual approach. Phase 6 relates to research question c) and involves mathematical programming and implementation and running of the system with a computer.

Finally research question d), e) and f) are addressed in phases 6 and 7. It should be emphasized that this process is iterative and although ordered, it is not completely hierarchical Table 3.1 gives a summary of linkages between research objectives, questions, processes and methods. The research methods are described in more detail in chapter 5.

Table 3.1: Summary of linkages between research objectives, questions and methods

Specific research objective	Research questions	Research process phase	Research methods
1 - To design a system for supporting decision-making in tropical forest management	a) What methodological approaches can be used to design a system, which supports decision-making in forest management in south Cameroon? What are the components of such a system and how can they be related?	Phase 1: Problem identification and definition. Phase 2: Observation of the decision environment Phase 3: Model design and mathematical formulation	• Literature survey • Characterization of the • management environment
	b) What coefficients and parameters need to be included in a system, which is designed to support decision-making in south Cameroon and how can these coefficients and parameters be estimated given the current availability of information?	Phase 4: Estimation of Model parameters	• Growth data acquisition • Cluster analysis • Logistic regression analysis • Stumpage price derivation
2 - To assess the effects of different management options on the economic returns of the logging enterprise as well as the structure of the forest	c) What outcomes does the designed system provide concerning optimal steady state forest stand structure, harvest and financial returns of logging? How are these outcomes affected by changes in management parameters and objectives?	Phase 5: Model runs and refinement Phase 6: Development of alternative solutions	• Mathematical programming
3 - To provide insight into the trade off between income generation trough timber harvesting and forest use by the local population and nature conservation respectively	d) What insights can be obtained from the outcomes of the developed system concerning the trade off between alternative management options?	Phase 7: Analysis and selection of alternatives	• Mathematical programming • Interpretation of outcomes
4 - To apply the system to develop the management of the TCP research site.	e) How do the outcomes of the developed system compare with the structure of the current forest in the Tropenbos Cameroon research site and which guidelines can be derived for the sustainable management of this forest?	Phase 7: Analysis and selection of alternatives	• Mathematical programming • Simulations • Interpretation of outcomes
5 - To evaluate and suggest adaptations of existing strategies aimed at sustainable management of the tropical moist forest of south Cameroon	f) What can be recommended for the improvement of forest management strategies in south Cameroon on the basis of the insights obtained from the designed system?	Phase 7: Analysis and selection of alternatives	• Mathematical programming • Simulations • Interpretation of outcomes

Chapter 4

TROPFOMS: Architecture, procedures and theoretical approaches in the model

The previous chapters, and especially sections 2.4 and 3.1, have highlighted the need to develop appropriate tools to assist decision making for the sustainable management of tropical forests. The central idea of the research presented here is to design such a methodological tool which can support decision making for the sustainable management of natural tropical forests of south Cameroon using modeling techniques (See general objective and specific objective 1 in section 3.2).

In Cameroon, there is a general setting at the national level within which forest management is conducted. This general setting includes a forestry law and a zoning plan which define the national approach for forest management (See section 1.1.3a) including the distinction between different forest types according to their ownership and their leading management objectives. Some forest types are: research forest for which the leading objective is scientific research and development of technologies for sustainable forest management, protection forests whose leading objective is nature conservation and production forests with income generation through timber production as the main objective. The system designed in this research focuses on the production forests. However, it should be noted that even though income generation through timber production is the leading objective in production forests, there are other objectives recognized by the general setting of forest management in Cameroon as well as the wider international community. Therefore, the aspects related to these other objectives are also recognized by the system designed in this research. More specifically, two other objectives are taken into account. These are: nature conservation and the improvement of living conditions of the local populations through the production of NTFPs.

The system designed in this study is referred to with the acronym TROPFOMS (TROPical FOrest Management support System).

4.1 Expected outputs from TROPFOMS

TROPFOMS focuses on the management of natural tropical forests which is an uneven-aged forest (See section 2.3.3) where many trees of different species, size and age coexist in a small tract of land (Buongiorno and Gilless, 1987). Therefore, the decisions to be addressed by TROPFOMS are part of the typical decisions made in uneven-aged forest management (See section 2.3.3).

Given that TROPFOMS focuses on production forests, one aspect of sustainability in which it has interest is the achievement of sustained yield of timber as a management guiding principle. Sustained yield of timber in this context means a quantity of wood harvested at the end of each cutting cycle, which is equal to the net growth of the forest stand and can be continued in perpetuity. Such a sustained yield is produced from a theoretical fully regulated forest, which in an uneven-aged management system is characterized by its structure, its growing stock and related management rules. The structure is defined as the number of trees per species and size class to be left after each harvest. The growing stock is the timber resource left after harvesting. It can be expressed as a volume or number of trees per unit area. When the forest is fully regulated, the growing stock becomes a steady state growing stock, because it represents a theoretical equilibrium where the resource left after harvest produces the same yield of wood from one cutting cycle to the other.

To attain a steady state forest and maintain it, management should follow a number of rules. Two of the most important of these rules are the periodicity of harvests (cutting cycle) and the amount of timber to be taken at each harvest entry (Davis and Johnson, 1987). Although there are many more important decisions to be made in forest management, with sustainable timber production as a wish, decisions on the cutting cycle and the level of harvest are critical. Inadequate choice of cutting cycle and level of harvest can lead either to depleting the resource (cutting cycle too short or harvest too heavy) or under-supply of needed timber products to the society (cutting cycle too long or harvest too light). A given forest stand has many steady states, each with a defined set of characteristics, but only one can best meet the objectives of management. Therefore, management should be able to select among alternative steady states the one that satisfies its objectives best.

However, forests are almost never fully regulated, and the steady state is rather a target that provides guidance for management operations in the current forest. The desire of sustainable forest management is to convert a non-regulated forest into a regulated one characterized by its target steady state structure. It is then important to determine this target structure. The time interval between the first management operations in the non-regulated forest and the moment at which a fully regulated forest structure is reached is called the conversion period. The conversion period poses a number of questions which forest management planning should confront. Two of these questions are: how long should or will be the conversion period given the defined management objectives? What are the harvesting rules to adopt during the conversion period? The answers to these questions are often referred to as the conversion strategy.

TROPFOMS intends to support forest management decisions that relate to the characteristics of the steady state. It is designed to assist decision making in defining the target steady state growing stock and related management guidelines. However, it should also help in investigating the conversion strategy since the forest is not fully regulated. More precisely, TROPFOMS intends to support decision making for sustainable forest management by providing outputs on the following points given a set of management objectives and parameters:

1) The target steady state growing stock characteristics, mainly the structure in terms of number of trees per size class to be found both before and after harvest and the composition of the stand,
2) The appropriate cutting cycle for timber harvest,

3) The amount of wood to be harvested at the end of each cutting cycle,
4) The expected length of the conversion period and expected levels of harvest during that period,
5) The multiple use of the forest through an analysis of the trade-off between alternative land use types and especially between timber production, nature conservation and forest utilization by the local population and,
6) Consequences in changes in management parameters.

The design of TROPFOMS involves defining its architecture, the procedure of its functioning and the theoretical approaches to be included in it.

4.2 The architecture of TROPFOMS

The model architecture as understood in this section consists of the exhibition of the different components of the model and the linkages that exist between these components.

TROPFOMS is designed based on the conceptual framework presented in section 3.3. In Figure 3.1 it was shown that four main aspects should be taken into account under the underlying assumptions to achieve sustainable forest management. These aspects are: forest stand characteristics, market value of timber, social needs of the local population and conservation requirement. These main aspects serve as the basis for building TROPFOMS.

The definitions of sustained yield and steady state given in section 4.1. show how critical the knowledge of stand growth is for the definition of forest management guidelines. In fact the idea is to harvest periodically the growth of a forest stand and leave a constant growing stock at steady state. The steady state growing stock constitutes a capital which grows for one cutting cycle and the growth is harvested at the end of the cutting cycle. Therefore, a system such as TROPFOMS which intends to provide information about steady characteristics growing stock, harvest level and cutting cycle must have an ability to estimate forest growth and yield and make projections of future stand structure. For this purpose, a growth and yield module is included in TROPFOMS as shown in Figure 4.1.
The ability to estimate growth and yield would be enough if wood production was the ultimate objective of forest management. It would be sufficient then to estimate the cutting cycle which gives the highest Mean Annual Increment (MAI) in volume in the case of even-aged forest management or the highest Periodic Annual Increment (PAI) in the case of an uneven-aged management system, and related growing stocks using the knowledge on growth and yield (Leuschner, 1984). MAI is the total volume per unit area divided by the age of the stand at the time of measurement, while PAI is the change in volume between two different points in time divided by the number of years separating the two points in time. In uneven-aged forest management it seems more reasonable to refer to the PAI because forest stands have no beginning or end in time.

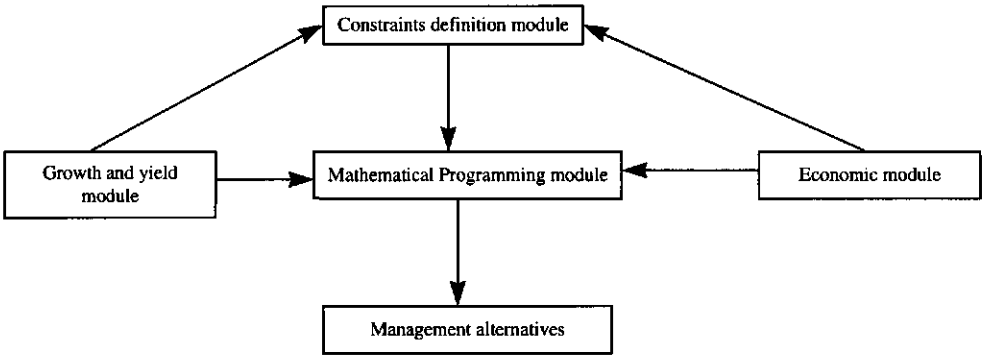

Figure 4.1: Main components of TROPFOMS

However, the objective of management is not often wood production but income generation through timber production. The PAI increment does not necessarily consider the value of the products harvested from the forest. Therefore, to define a target steady state, information from the market of timber products should be incorporated in the decision support tool in addition to growth and yield information. This explains why one of the components of TROPFOMS is an economic module, which provides market information in the system.

Income generation through sustainable timber production is a leading objective in production forests, but it is not the only one. In fact, traditionally, forest management has concentrated on timber production and sustained yield of timber appeared to be the only concern. This has changed and other non-timber aspects may be integrated in the management alongside timber production (See section 2.3.5). TROPFOMS recognized two other aspects: forest utilization by the local populations and nature conservation. These aspects limit the leading role of timber production and are incorporated in the constraints definition module.

The growth and yield module, the economic module and the constraint definition module bring information to the mathematical programming module which then processes it and produces the expected outputs as described in section 4.1 and shown by Figure 4.1.

4.3 The procedural design of TROPFOMS

The development of management options using the methodology of TROPFOMS involves going through the procedures pictured in Figure 4.2 and described by the following steps:

Step 1: Derive the timber value with the economic module. The results of this module are given in the format of a monetary value of an average tree belonging to a given diameter class and of a given species group.

Step 2: Use the growth and yield module to estimate for each species group and each diameter class the up-growth[1] and stability[2] ratios as well as the in-growth into the smallest diameter class for every species group.

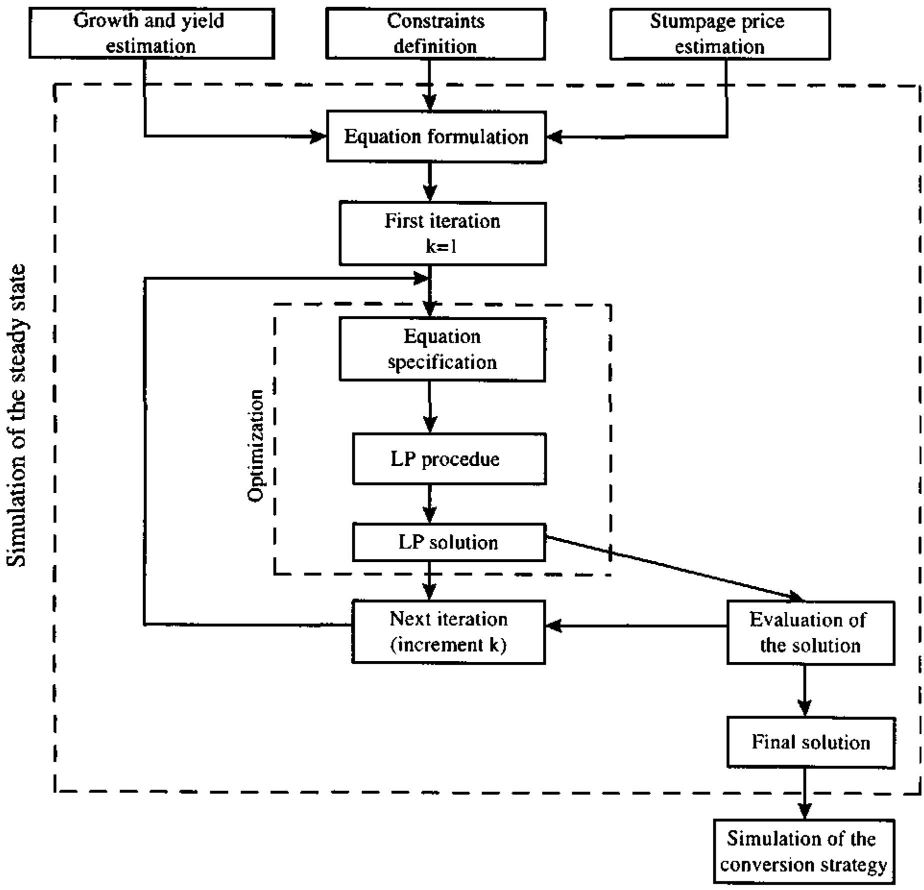

Figure 4.2: The architecture of TROPFOMS

Step3: The available information on resources limitations, existing regulations and local utilization of forest products are used to define the constraints.

[1] Number of trees that grow out of their initial diameter class between two successive measurements on a network of PSPs.

[2] The stability ratio is seen as the number of trees that stay alive but do not change diameter classes between two successive measurements on a network of PSPs.

Step 4: All the information developed in the previous steps is used to formulate the problem within the mathematical module. However, due to growth period that resulted from PSP mensuration campaigns, the cutting cycle is supposed to be a multiple of 5 years, thus the cutting cycle is noted as $5k$ years (k is a constant). In a simulation loop, the mathematical procedure first sets k=1. At the end of this step, the problem is entirely specified in algebraic terms but the cutting cycle is supposed to be equal to 5 years.

Step 5: The problem is solved within an optimization loop which uses Linear Programming (LP). The solution is given as optimal forest structure, harvest strategy and a value for the decision criterion. It should be noted that the optimization loops have their own imbedded set of iterations which are different from the one describe above. The problem becomes solvable by techniques only after the above step has been completed, the objective and the constraints then become linear.

Step 6: The routine goes back to step 4, increments k by one and moves to step 5. A new value is found for the decision criterion.

Step 7: Different values of the decision criterion obtained by the steps above are compared and the highest one is retained.

Step 8: The solution retained gives the characteristics of the desired steady state including the structure in terms of the number of trees per species and diameter class to be left after each harvest. The conversion strategy is estimated for the solution retained.

4.4 The theoretical approaches in TROPFOMS

4.4.1 The approach in growth and yield modeling

TROPFOMS is designed for uneven-aged tropical natural forests where the decision to harvest is made for each individual tree or for a category of trees but not the whole stand as is the case with the even-aged management system. It is therefore better to adopt a modeling approach that provides information with some details about distribution of trees in size classes instead of general information about future stands as provided by whole stand models (Vanclay, 1994). The approach adopted for TROPFOMS is a size class approach with the diameter at breast height (DBH) as the size characteristic and an arrangement of growth describing elements in a transition matrix.

a) The growth model for a single tree species

TROPFOMS uses the approach of transition matrices. The genesis of this approach is presented in section 2.3.3. The model uses the following theoretical reasoning that is inspired by the example of Buongiorno and Gilless (1987).

Say trees in a forest stand are grouped in three diameter classes. At any given time t, three variables can be defined as $y_{1,t}$, $y_{2,t}$, $y_{3,t}$, where $y_{i,t}$ is the number of live trees per hectare in diameter class i at time t. A growth model is then a set of equations 4.1 that gives the state of the stand at time $t+1$, given the current state. The three equations in the set for this simplified case are:

$$\begin{aligned} y_{1,t+\theta} &= a_1 y_{1,t} + I_t \\ y_{2,t+\theta} &= b_1 y_{1,t} + a_2 y_{2,t} \\ y_{3,t+\theta} &= b_2 y_{2,t} + a_3 y_{3,t} \end{aligned} \tag{4.1}$$

In this set of equations, a_i is the estimated fraction of live trees inventoried in diameter class i at time t that are still alive and in this same diameter class after θ years. The fraction of trees b_i denotes those which were in diameter class i at time t and are still alive after θ years but have grown up to the diameter class $i+1$; a_i and b_i are called transition probabilities (b_i is often referred to as upgrowth), I_t denotes the ingrowth into the smallest diameter class after θ years. The fraction of trees that died during the time interval θ can be estimated as $1\text{-}a_i\text{-}b_i$. Equation set 4.1 allows us to make a projection of the stand structure after θ years.

b) ***Modelling steady state and harvest***

From such an approach, a steady state stand structure can be estimated. By definition, steady state means that the forest has reached an equilibrium and regardless of the time when the stand is observed, it has always the same number of trees in each diameter class. The distribution of trees in diameter classes as observed at time t is the same at time $t+\theta$. The set of equations 4.1 can therefore be written as:

$$\begin{aligned} y_1 &= a_1 y_1 + I \\ y_2 &= b_1 y_1 + a_2 y_2 \\ y_3 &= b_2 y_2 + a_3 y_3 \end{aligned} \tag{4.2}$$

If the stand is left without harvesting, the equilibrium results from compensations between ingrowth and mortality, and the set of equations 4.2 has a unique solution. Only knowledge about growth is needed to determine the steady state structure.

If the forest stand is managed for timber production, the achievement of sustained yield still means that a steady state is searched in which the amount cut is equal to the amount by which the stand has grown since the last time it was cut. This should be true for each diameter class.

Let y_i be the number of trees in diameter class i before harvest and h_i the number of trees cut in the steady state. Then for the successive harvesting campaign, the following should be true in order to achieve sustained yield:

$$y_{i,t+1} = y_{i,t} = y_i \quad \text{and} \quad h_{i,t+1} = h_{i,t} = h_i \quad \text{for } i = 1,2,3$$

The harvests can be introduced in equation set 4.2 to give equation set 4.3 as follows:

$$\begin{aligned} y_1 &= a_1(y_1 - h_1) + I \\ y_2 &= b_1(y_1 - h_1) + a_2(y_2 - h_2) \\ y_3 &= b_2(y_2 - h_2) + a_3(y_3 - h_3) \end{aligned} \tag{4.3}$$

The system of equations 4.3 has three equations and six unknowns, thus there are many solutions (or many steady states) and there is a need to select only one solution, which requires to have a decision criterion. However, because the number of trees cut cannot exceed what is available, the only meaningful solutions are the ones where:

$$h_i \le y_i \tag{4.4}$$

c) Introducing the matrix notation

The notation in the equation sets 4.1 to 4.4 can become tedious to handle when the number of diameter classes increases and multiple species are introduced. Therefore it may seem better to use a matrix notation for these systems of equations. To introduce such a notation, the system of equation 4.3 can be rewritten in such a way that all the variables are present in each equation. This writes as follows:

$$\begin{aligned} y_1 &= a_1(y_1 - h_1) + 0(y_2 - h_2) + 0(y_3 - h_3) + I \\ y_2 &= a_1(y_1 - h_1) + a_2(y_2 - h_2) + 0(y_3 - h_3) + 0 \\ y_3 &= 0(y_1 - h_1) + b_2(y_2 - h_2) + a_3(y_3 - h_3) + 0 \end{aligned} \tag{4.3'}$$

The system of equations 4.3 is equivalent in matrix terms to (4.5):

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} a_1 & 0 & 0 \\ b_1 & a_2 & 0 \\ 0 & b_2 & a_3 \end{bmatrix} \begin{bmatrix} y_1 - h_1 \\ y_2 - h_2 \\ y_3 - h_3 \end{bmatrix} + \begin{bmatrix} I \\ 0 \\ 0 \end{bmatrix} \tag{4.5}$$

A more compact notation of 4.5 is:

$$Y = G(Y - H) + I \tag{4.6}$$

Where: Y = column vector with elements y_i, being the number of trees in diameter class *i* just before harvest,

G = square matrix of growth elements a_i and b_i defined as above

H = column vector of elements h_i defined as above

I = column vector of ingrowth into the smallest diameter class

d) Recognising multiple species

Until this point, the considered stand has only one tree species and three diameter classes. In tropical natural forests this is not the case, there are many species as described in section 2.2.2. Therefore, modelling growth and yield should have a way to consider multiple species.

Still as an example, let us assume that the stand has three species (or species groups). We can now define three different sub-sets of equations using the matrix notation as follows:

For species group 1:

$$\begin{bmatrix} y_{11} \\ y_{21} \\ y_{31} \end{bmatrix} = \begin{bmatrix} a_{11} & 0 & 0 \\ b_{11} & a_{21} & 0 \\ 0 & b_{21} & a_{31} \end{bmatrix} \begin{bmatrix} y_{11} - h_{11} \\ y_{21} - h_{21} \\ y_{31} - h_{31} \end{bmatrix} + \begin{bmatrix} I_1 \\ 0 \\ 0 \end{bmatrix} \tag{4.7}$$

For species group 2:

$$\begin{bmatrix} y_{12} \\ y_{22} \\ y_{32} \end{bmatrix} = \begin{bmatrix} a_{12} & 0 & 0 \\ b_{12} & a_{22} & 0 \\ 0 & b_{22} & a_{32} \end{bmatrix} \begin{bmatrix} y_{12} - h_{12} \\ y_{22} - h_{22} \\ y_{32} - h_{32} \end{bmatrix} + \begin{bmatrix} I_2 \\ 0 \\ 0 \end{bmatrix} \tag{4.8}$$

And for species group 3:

$$\begin{bmatrix} y_{13} \\ y_{23} \\ y_{33} \end{bmatrix} = \begin{bmatrix} a_{13} & 0 & 0 \\ b_{13} & a_{23} & 0 \\ 0 & b_{23} & a_{33} \end{bmatrix} \begin{bmatrix} y_{13} - h_{13} \\ y_{23} - h_{23} \\ y_{33} - h_{33} \end{bmatrix} + \begin{bmatrix} I_3 \\ 0 \\ 0 \end{bmatrix} \tag{4.9}$$

In the sets of matrix equations 4.7 to 4.9 the following specifications apply:

y_{ij} = number of trees of species group j diameter class i before harvest

h_{ij} = number of trees of species group j harvested in diameter class i

a_{ij} = fraction of trees of species group j and diameter class i which stays in the same diameter class after θ years

b_{ij} = fraction of trees of species group j and in diameter class i which grows into the next diameter class after θ years

I_j = ingrowth into the smallest diameter class for species group j

The compact matrix notation for each species group is:

$$Y_j = G_j(Y_j - H_j) + I_j \tag{4.10}$$

where: Y_j = column vector with elements y_{ij}

G_j = square matrix of growth elements a_{ij} and b_{ij} defined as above

H_j = column vector with elements h_{ij}

I_j = column vector of ingrowth into the smallest diameter class for species j

An extended matrix formulation can be written to include the three groups as:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix} = \begin{bmatrix} G_1 & 0 & 0 \\ 0 & G_2 & 0 \\ 0 & 0 & G_3 \end{bmatrix} \begin{bmatrix} Y_1 - H_1 \\ Y_2 - H_2 \\ Y_3 - H_3 \end{bmatrix} + \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

e) Multiple growth periods

Growth data are often collected with a periodicity of one to five years, while the cutting cycles can encompass longer time periods, usually a few decades. The time interval between two successive plot measurements is called a growth period. There is a need to model stand growth for many periods. The estimation of the stand structure after two growth periods can easily be found in the following way:

$$Y_{t+2\theta} = G(Y_{t+\theta}) + I = G(GY_t + I) + I = G^2Y + GI + I \tag{4.11}$$

Equation 4.11 can be used for making projections for k growth periods as:

$$Y_{t+k\theta} = G^k Y_t + \sum_{u=o}^{u=k-1} G^u I \tag{4.12}$$

At the steady state and when the harvest occurs every $k\theta$ years, the following will apply:

$$Y = G^k (Y - H) + \sum_{u=o}^{u=k-1} G^u I \tag{4.13}$$

4.4.2 The economic objective function

At the end of section 4.4.1b, the need for a decision criterion to select one solution among many was pointed out. The objective function provides a criterion for selecting a solution. TROPFOMS is designed to support decisions in the case of forests oriented towards sustainable timber production for which economic returns constitute a high priority for logging companies. Therefore, it is logical that one of the bases for evaluating alternative management options be economical. More reasons for using an economic approach in the formulation of objectives in natural resources management are given by FAO (1993) when stating that: "The strength of economics whether conventional or based on such ideas of sustainability, is that it provides a method for examining the range of costs and benefits associated with the choices open to the society. Costs and benefits may be distributed in space or in time, and may be seen as differently by those with different perspectives (the state, the private owner, the logger, the local communities, environmental groups, ...). Benefits may be obtained as marketable goods or as public services, or even as other human values. Economic analysis permits an objective comparison of the overall costs and benefits from various view points".

One of the most used criteria is the Land Expectation Value (LEV) (Chang, 1981) also called the Faustmann criterion from the name of the author who presented it first (Gregory, 1972). Its general formula is presented in chapter 2 (section 2.3.3).

Although the LEV has been most used for even-aged management, some authors have also used it for uneven-age management. Buongiorno and Michie (1980), followed by Michie (1985) for example utilized the same line of reasoning when looking for the best harvest strategy in uneven-aged forests and determining the stand structure. The importance of the Faustmann criterion comes from the fact that it includes not only revenues but also the opportunity costs of land and capital due to investments in the growing stock. The objective function (called Z) to be maximized under a certain number of constraints is:

$$Z = \frac{PH'y^*}{(1+r)^{k\theta}} - P(y^* - H'y^*) \tag{4.14}$$

where: P = vector of prices with elements representing the value of trees in each diameter class
r = real rate of discount
k = number of growth periods between two cuttings
H' = matrix with 1's in diagonal elements corresponding to harvested classes and 0's elsewhere
y^* = vector of the steady state diameter distribution resulting from the cutting strategy defined by H'
θ = length of the growth period in years

In this equation, the first term on the right hand side is the present value of the harvest occurring every $k\theta$ years and the second (which is subtracted from the first) is the opportunity cost of capital of the residual stock left after harvest. This formulation of the objective function relates to the economic stocking rule in uneven-aged forest management first proposed by Duerr and Bond (1952) and reviewed later by authors such as Buongiorno and Teeguarden (1973) and Adams (1976).

Within TROPFOMS, the decision criterion is called the sustainable timber value (STV) and it is formulated as:

$$STV = \frac{PH' - \Sigma C_t (1+r)^{k\theta - t}}{(1+r)^{k\theta} - 1} - P(Y - H') \tag{4.15}$$

Where C_t is the cost of silvicultural treatments per hectare at time t. Herewith it is possible to conduct silvicultural operations between two harvests, such as thinning or climber cutting, to boost the growth or reduce logging damage. This criterion is used to choose among alternative harvesting strategies and forest structures.

4.4.3 Constraints

Constraints and the objective function are related. The manager is confronted with many objectives. An objective can alternatively be formulated in the mathematical program in the objective function or as a constraint. The use of linear programming allows the definition of only one management objective in the objective function. The other ones then have to be formulated as constraints. In TROPFOMS, in addition to the economic efficiency concerns there are two other major concerns, one is sustainability of timber production and the other one is biological diversity.

a) The sustained yield constraints. These constraints state that harvests should be equal or less than the growth from a certain steady state structure. There is a desired regulated steady state to be found from which some growth is recorded during $k\theta$ years (One cutting cycle). The harvest should then be equal to the growth after deduction of mortality. Since the growth and yield module makes predictions based on the numbers of trees, these constraints reflect also the fact that sustainability of timber production requires that the maximum number of trees harvested will be at most equal to the in-growth into the smallest diameter class. The sustained yield constraints are in fact introduced by equation 4.13.

b) Diversity constraints. Two major concerns of sustainable forest management are nature conservation and supply of non-timber forest products. Sustaining the highest level of biological diversity contributes to the satisfaction of these concerns in a simultaneous way. It enhances nature conservation by preserving a large number of species, but it also logically ensures the supply of non-timber forest products to local populations because these products are collected from a large number of tree species whose continued existence is guaranteed if a high level of diversity is maintained. TROPFOMS tries to maintain both species and size diversity. The model imposes constraints to maximize the number of trees in the least represented diameter class and the least represented species group (See section 2.3.5, sub section a), but allows also to be more flexible by just keeping track of the species groups.

c) Other constraints. These are mainly constraints limiting variables to positive values. However, a number of management parameters can be introduced for analysis as it will be done in chapter 7.

4.4.4 The conversion strategy

The sections 4.4.1 to 4.4.3 have presented the approach used in TROPFOMS to obtain the expected outputs that relate to the steady state (section 4.1). There is a need to estimate the conversion strategy of the current forest towards the steady state. The conversion strategy includes not only the conversion period (See section 2.3.3b) but also the cuts to be made during that period and an estimation of the expected revenues.

The conversion strategy is basically derived from the comparison of the current forest stand and the design of a harvest schedule and/or silvicultural prescription, which gradually leads the stand to the target steady state structure. In principle, two possible situations can be brought up by the inventory of the current forest. First, the current forest may have more trees than the target steady state structure in all size classes and for all species groups. Then, it is easy to reach the steady state structure by harvesting and/or killing all trees in excess. The steady state structure is reached immediately after removing trees. Second, some or all species-size classes have less trees than the target structure, then it takes one or more cutting cycles to reach the target structure.

4.5 Conclusion on the design of TROPFOMS

TROPFOMS is designed to support decision making in tropical forest management through three different types of outputs as it can be seen in the list provided in section 4.1. The three types of outputs are: the outputs which relate to the steady state (Outputs 1, 2, 3), one which relates to the conversion period (Output 4) and the ones which result from sensitivity analysis of both the steady state and the conversion period (Outputs 5 and 6).

The outputs concerning the steady state are obtained by solving the equations set 4.13 for Y and H mainly on the basis of growth and yield information (Matrix G) and market information (Price vector P). As for growth and yield information, the modeling approach in section 4.4.1 shows that there is a need to have essentially the estimates of transition probabilities and those of ingrowth. For the market information, it can be seen from section 4.4.2 that the most important need is the estimate of timber prices represented by the vector P in equation 4.15. However, a value of the discount rate should also be adopted. The growth matrix, the ingrowth estimates and the price vector constitute the basic coefficients needed by TROPFOMS.

Concerning the conversion strategy, inventory data of the current forest stand constitute the basic data input needed. However, forest utilization patterns at the local level and knowledge of other possible management objectives are needed to formulate constraints.

Chapters 5 and 6 present the methods used to estimate the needed coefficients and management parameters and the estimates obtained and used in later chapters.

Chapter 5

Research methods

At the end of the preceding chapter, the basic information needed for the implementation of TROPFOMS was identified. This basic information has to include the growth matrix (called *G* in chapter 4) and the vector of tree prices (called *P* in chapter 4). Stand growth data and data from the market of timber products are used to estimate the matrix *G* and the vector *P* that both provide the coefficients for TROPFOMS. This chapter presents the methods used to estimate these coefficients. However, it also gives a brief overview of the forest inventory that later allows the description of the conversion period and includes a short characterization of the utilization of forest plant products by the local population. Finally, this chapter reviews the mathematical programming technique adopted in TROPFOMS.

5.1 Methods for the estimation of growth and yield parameters

The aim of the analysis is to estimate the transition probabilities and the ingrowth introduced in section 4.4.1a. However, tropical forests are very heterogeneous as described in chapter 2 (Section 2.2.2a) and it is difficult to develop a model concerning growth and yield on the basis of individual tree species. It appears necessary to aggregate first the individual tree species in groups, and to estimate later the transition probabilities on the basis of this grouping.

5.1.1 Species aggregation

Tropical forests are considered to be the most complex forest ecosystems on earth. Walter (1979) noted that: "When considering different ecological types, it should be emphasized that the greatest variety of plant forms is found in the tropical rain-forest". Describing the extent and variation of tropical forests, Palmer and Synnott (1992) noted that, in comparison with temperate forests, tropical forests often display complex structures, marked variations from one hectare to the next, relatively unpredictable growth rates and besides they are uneven-aged.

These attributes give tropical forests a special priority in all attempts to preserve biological diversity at the global level, but it also makes the development of management strategies for tropical forests difficult especially if sustainable timber production is one of the objectives. In fact, tropical forests are both ecologically rich (large number of species per unit area) and diverse. As a consequence, the number of individuals for any species is often small (National Research Council, 1982). This further complicates attempts to develop management methods and techniques, especially models such as growth models based on statistical analysis of sample data. Working with individual tree species becomes rather impractical not only because it will require too many coefficients and/or functions, but also because of the paucity of data for many species which may inhibit the development of reliable relationships (Vanclay, 1991b).

These facts have encouraged forest management specialists to group species based on more or less objective criteria. For example, Vanclay (1991b) working on data from tropical forests of North Queensland used a regression analysis to form 41 species groups out of the 237 tree species based on diameter increment. But he avoided "imposing any limit on the number of groups" which gives his work a high theoretical value. However, field implementation of these results remains difficult; 41 groups still being difficult to handle. In Cameroon, species are usually aggregated in three main groups, according to their current commercial status in the market (commercial, potentially commercial and non-commercial). Such a grouping certainly provides a practical tool when evaluating the current growing stock of forest resources, however it is almost useless when making growth and yield projections because species belonging to the same group do not necessarily have the same growth habits. Therefore, it would be desirable having only a few groups, in order to decrease the computation burden and to facilitate the handling of the growth and yield model, and to have an aggregation that is based on an objective criterion allowing growth and yield prediction as well as prediction of future stand structure and composition.

The purpose of this analysis is to contribute to the search of methods to form few groups from the multitude of species found in tropical forests on the basis of growth habits. It contributes to the achievement of research objective 1 (Section 3.2.2).

a) Principle of analysis.
Cluster analysis is a method for detecting natural groupings in data. The analysis was mainly concentrated on four variables: the average diameter increment (DI), the average dbh recorded at the beginning of the growth period (d_1), the commercial status (CS), and the minimum diameter for felling (DME).

Diameter increment was chosen because it has almost always been considered as one of the best variables when trying to model the growth of mixed tropical forest. For example, Alder (1983), in a review of growth and yield of mixed tropical forests noted that: "Mixed tropical forest growth information from permanent plots...has mostly been analyzed in terms of individual tree increment". He went on to identify diameter increment as "a basis for species grouping". In fact, Vanclay (1991b), in his important work on species grouping in tropical forests based his analysis mainly on diameter increment, but he preferred to use regression analysis rather than cluster analysis. Logically, if tree growth can be defined for forest management purposes as a change in a selected tree attribute over some specified time (Davis and Johnson, 1987), diameter increment - a change in tree diameter over a specified period of time - should necessarily be one of the best variables to portray tree growth.

In addition to diameter increment, which is a variable representing growth, it appeared important to have at least an additional variable which characterizes the initial stand at the beginning of the growth period. For this, the average DBH per species at the first round of measurement was chosen. Many authors such as Rollet (1974) and Jonkers (1987), have shown or used the relationship between average diameter of a species and the distribution of stems of the same species among size classes in the stand. The average diameter can thus be reasonably seen as a stand characteristic.

As for the DME, it is the minimum diameter allowed for logging according to current regulations. The DME varies by species. It was chosen because it gives an idea of the maximum size that a tree of a given species can reach. The DME illustrates the idea that a tree of a given species at maturity will be larger or smaller than a tree of another species also at maturity. For example: say there two trees one of species A and the other of species B. Suppose that a mature tree of species A can reach a maximum DBH of 150 cm on that site while a mature tree of species B can reach only 90 cm. If both trees have an equal actual DBH of 85cm, one would expect their growth rate to be different because the tree of species B is almost at the end of the growing phase of its life. Thus, the DME of species A will be larger than the one of species B and is different from the actual mean DBH. This illustrates the fact that trees of the same species on different sites with different mean DBH can grow at different rates (all other things being equal).

Each tree species j could thus form a single statistical case characterized by the average diameter of the species at the beginning of the growth period d_{1j}, the average diameter increment for that species DI_j, its commercial status CS_j and DME_j. These statistical cases which correspond to species are then aggregated.
These averages were simply computed as follows: let d_{1ij} be the value of the DBH measured for tree i of species j at the beginning of the growth period and d_{2ij} the DBH recorded at the end of the growth period for the same tree. DI_{ij} the diameter increment for tree i could be computed as:

$$DI_{ij} = d_{2ij} - d_{1ij} \tag{5.1}$$

d_{1j} and DI_j were found as:

$$d_{1j} = \frac{\Sigma d_{1ij}}{n_j} \tag{5.2}$$

$$DI_j = \frac{\Sigma DI_{ij}}{n_j} \tag{5.3}$$

Where n_j is the number of trees of species j.

The four values d_{1j}, DI_j, CS_j and DME_j are used as coordinates to locate each tree species on a four-dimensional plan. The principle of the clustering procedure consists of calculating the distance from the location of a randomly chosen species to the location of its nearest neighbor (Newnham, 1991; Kent and Coker, 1992). The measures of distance used in this study are the

Squared Euclidean distance and the Euclidean distance. The Squared Euclidean distance is the sum of the squared differences between the values of the clustering variables. If the starting species is j and its neighbor species $j+1$, $E_{j,j+1}$ the Euclidean distance between the two is:

$$E_{j,j+1} = \sqrt{(d_j - d_{j+1})^2 + (DI_j - DI_{j+1})^2 + (CS_j - CS_{j+1})^2 + (DME_j - DME_{j+1})^2} \tag{5.4}$$

$E_{j,j+1}$ can be squared to obtain the Squared Euclidean distance.

Similarly the distance from $j+1$ to its nearest neighbor can be calculated. If the nearest neighbor of $j+1$ is j, then a potential cluster has been formed. Otherwise, the aggregation continues by choosing another species that is not in the previous cluster and then trying to form a new cluster until all trees have been considered.

Some measure of the central location of each cluster can be calculated, and further, clusters themselves may be clustered. One of the commonly used central points in the cluster analysis is the center of gravity of the cluster also called the centroïd (Eriksson, 1993). Say a cluster has m species, each species j is located on the plan by its coordinates d_{1j} and DI_j, CS_j and DME_j the centroïd of the cluster noted C can also be characterized by coordinates d_{1c}, DI_c,

$$d_{1c} = \frac{1}{m} \Sigma d_{1j} \tag{5.5}$$

$$DI_c = \frac{1}{m} \Sigma DIj \tag{5.6}$$

CS_c and DME_c defined as:

$$CS_c = \frac{1}{m} \sum CS_j \tag{5.7}$$

$$DME_c = \frac{1}{m} \sum DME_j \tag{5.8}$$

The process yields a hierarchy of cluster solutions, ranging from one overall cluster to as many clusters as there are cases. A cluster at a higher level can contain several lower-level clusters, but within each level the clusters are disjoint. Depending on the objective of the analysis (for example a predetermined number of groups), an appropriate level is chosen as the final solution.

The aggregation of species was done using the Hierarchical Cluster Analysis procedure of SPSS (SPSS Inc, 1993). The centroïd clustering method was used based on Euclidean distances. The variables chosen were different in magnitude and ranges, for example DME varies from 50 to 100 while the diameter increment varies mostly between zero and five. For that reason, all variables were standardized within the range of 0 to 1. A single solution of four clusters was retained.

b) The data set

The data analyzed here were collected in Liberia, West Africa. Starting from 1978, several pilot projects were installed in the country with the cooperation of German institutions, the general objective being to determine the silvicultural potentials of logged-over forests (Parren and de Graaf, 1995). Within the framework of these projects, about 39 one-hectare Permanent Sample Plots (PSPs) were established in four stations: Cavalla (12 plots), Grebo (20 plots), Gola (three plots) and Kpelle (four plots) with different specific research objectives. In Grebo, the objective was to monitor the development of the stand after logging without any treatment. At the three other stations, studies aimed at testing the effects of different silvicultural treatments after logging.

Within each PSP, trees with a diameter at breast height (DBH) larger or equal to 10 cm were numbered and their species determined. For each numbered tree, measurements were taken including: dbh, total height, bole height, crown diameter and exposure to light. Each tree was also located on the map using rectangular coordinates. A total of more than 15,000 trees of 245 species were thus monitored.

Because of variations among silvicultural treatments that were tried from one station to the other, and due to the inconsistency in re-measurement dates, only the 20 plots of Grebo were used. The plots of Grebo represent a data set of 7664 re-measured trees. The analysis focused mainly on species met in both Cameroon and Liberia. Annex 1 gives a list of the tree species concerned with their scientific and pilot names. All together, these plots provided a data set of 3735 trees of 46 species re-measured five years apart (growth period). Annex 1 gives a summary of the data set used for species aggregation.

It should be noted that it would have been better to avoid using data from Liberia out of their physical context and use data collected in South Cameroon instead. Unfortunately, as it is the case in most tropical countries, a network of PSPs that could provide such data was not yet established in Cameroon when this study was conducted. At least five years are needed to obtain data on which such an analysis can be conducted. Thus, we used data from a different tropical country of Africa to estimate the growth rates. However, even though the bio-physical conditions are not exactly the same, there is a great similarly in species composition between the forests in both countries.

5.1.2 Estimation of growth and yield

a) Principle of analysis

The methods utilized here contribute to the achievement of research objective 1. As already described in chapter 3 (Section 3.2.4: theoretical approaches in TROPFOMS), the matrix approach was chosen to model growth and yield. The methods here are designed to estimate coefficients of the growth matrix meaning the ingrowth into the smallest diameter class per species group and the transition probabilities (a_{ij} and b_{ij}).

Ingrowth equation is estimated by ordinary least square regression as a function of both the basal area of the stand and the number of trees per species group in the stand. The basal area of the whole stand expresses the competition which occurs in the stand. As one can imagine, a tree of a given size and a given species competes not only with trees of the same species, but also with trees of other species. If the equation for ingrowth can be written as:

$$I_{jt} = \beta_o + \beta_1 B_t + \beta_2 N_{jt} + \beta_3 N \tag{5.9}$$

Where: I_{jt} = the ingrowth

B_t = the basal area at the beginning of the growth period

N_{jt} = the number of trees of species group j in the stand

N = the total number of trees in the plot and

β_0, β_1, β_2 and β_3 are regression coefficients

β_1 is expected to be negative, meaning that for a constant number of trees, ingrowth will be smaller in stands where trees are larger since in such stands the canopy of the larger trees tends to suppress the growth of smaller ones. On the other hand, β_2 is expected to be positive because at a constant basal area, stands with more trees per unit area are younger and the ingrowth should be more active (Buongiorno and Gilless, 1987). In mixed stands, a larger number of stems for a given species group should also mean more chance for seed production and better regeneration.

The probabilities a_{ij} - the probability for a tree of species group j and diameter i to stay alive and in the same diameter class after one growth period - and b_{ij} - the probability for a tree of species group j and diameter i to move to the next diameter class after one growth period - were estimated using logistic regression. The general form of the logistic equation used was:

$$\Pr(e) = \frac{1}{1 + \exp X} \tag{5.10}$$

where: *Pr(e)* = probability of the event *e*. The event in this case is changing a diameter class for a given tree during one growth period, in the reverse event the tree is staying in the same diameter class during one growth period.

X = a function of the diameter class in which the tree was registered at the beginning of the growth period, the basal area of the stand and the number of trees per ha.

Mortality was taken into account in the process using estimates from prior observations.

The smallest diameter class of interest was 20 cm to 30 cm. The diameter classes were defined as shown in table 5.1.

Table 5.1: Definition of diameter classes

Diameter class	Values (cm)
1	[10,20[
2	[20,30[
3	[30,40[
4	[40,50[
5	[50,60[
6	[60,70[
7	[70,80[
8	[80,90[
9	[90,100[
10	≥100

b) The data set

The data set described in section 5.1.1 was used to estimate the transition probabilities. It allowed for each individual tree to know whether it stayed in the same diameter class or grew up or died.

5.2 Stumpage derivation

a) Principle of analysis

Stumpage price derivation was designed to contribute to research objective 1. The purpose of the analysis is to estimate the value of a standing tree of a given species and of a given diameter class based on market prices of timber products. The general principle for the derivation of the stumpage price is that stumpage price at a specific location will equal the log price at the mill minus the cost of availability (Gregory, 1972). The approach adopted is the so-called residual approach for which the starting point for determining stumpage price is the selling price of the product or products that are to be produced from the raw material. By subtracting all costs from the product's sale price one derives a residual value. As industrial logging is especially oriented towards the export market in Cameroon, the Free On Board (FOB) price for logs was used in place of the price at the mill.

The first step of the derivation of the stumpage price was the estimation of FOB prices for logs of each species group. This was done by gathering information from timber exporting companies, the forestry administration and the Société Générale de Surveillance (SGS). The price to be assigned to the unit volume of a log belonging to a given species group was estimated by averaging available FOB prices of all species in the group.

Next the cost of availability is estimated. The costs of availability include different taxes, transport costs (from the forest landing to the seaport log yard), all logging costs and all overhead costs. These costs are expressed per unit volume of log (CFA Franc (FCFA)/ m^3 of log) [3].

Then the value of a unit volume of stumpage can be estimated. It can be anticipated that a cubic meter of marketable logs represents more than one cubic meter of stumpage because of logging waste. The stumpage value is derived as:

$$P_j = cc_j(FOB_j - AC_j) \tag{5.11}$$

Where: P_j = value for a cubic meter of stumpage of species group j
cc_j = commercialization coefficient for species group j
FOB_j = FOB price for a cubic meter of log of species j and
AC_j = cost of availability for species group j

The commercialization coefficient cc is the ratio of the volume of marketable logs over the volume of stumpage as estimated before logging and during the forest inventory; cc can be expressed as:

$$cc = \frac{V_L}{V_S} \tag{5.12}$$

where: V_L = log volume and
V_S = stumpage volume

The commercialization coefficient cc should be less than 1. The cc is developed by measuring standing trees to estimate their stumpage volume (V_S) using mainly the DBH and bole volume equations. DBH is measured directly in the field and the stumpage volume is found using pre-developed equations of which the implicit formula is:

$$V_S = f(DBH) \tag{5.13}$$

The trees are subsequently felled, limbed and then skidded to the forest landing. Once at the forest landing, the trees are bucked which reduces them into marketable logs. Logs are then measured to obtain the v_L (the volume of individual logs obtained from bucking a given tree). The v_L for individual logs was estimated by subdividing the log into 2 m bolts[4] and

[3] 1 Euro=656 FCFA

[4] A bolt here means a subdivision of a bole measuring 2 meters of length (See also Fonweban, 1997)

measuring sectional diameters with a caliper. The volumes of bolts were next calculated using Smalian's formula as:

$$v_B = \pi(dh^2 + ds^2)L/8 \qquad (5.14)$$

v_B = volume of a bolt in m^3
dh = diameter at the large end of the log
ds = diameter at the small end of the log and
L = length of the bolt (2 m)

Bolt volumes are later summed to give the volume of the log v_L. The method has been considered by many forest inventory specialists as one of the least biased, the most accurate and the most precise (Cailliez, 1980; Pardé and Bouchon, 1988; Fonweban, 1997). The volumes of all individual logs bucked from the same tree are further summed to obtain the log volume of the corresponding tree V_L.

Finally, calculations can be made to estimate the value of a tree of a given species j belonging to a given diameter class i. Let p_{ij} be that value, it can be estimated as:

$$p_{ij} = P_j * v_{ij} \qquad (5.15)$$

where: v_{ij} = volume of a tree of diameter class i and of species group j.

Bole volume equations are developed for the estimation of volumes of standing trees (v_{ij}). They predict stumpage volume based on one, two or more dependent variables (one, two or more entries). Usually single entry equations use the DBH as dependent variable while double entries equations use both the DBH and the bole length. In standard forest management, single entry equations with the DBH are preferred because the diameter is the easiest variable that can be recorded at low costs. This type of equation was chosen for the development of bole volume equations used for the development of TROPFOMS.

The development of single entry equations required the DBH of a number of trees measured in the field and the corresponding volume estimated as accurately as possible. Two techniques were used to estimate these variables, one with standing trees the other with felled trees.

On standing trees, the DBH was taken with a diameter tape, then the bole was optically sectioned in four bolts using the mirror relascope. The diameters at the small and large ends of each of the bolts was also estimated optically as well as the lengths of the bolt in order to use the Smalian's formula (described above).

Of felled trees, the DBH was taken before felling. After felling, the same technique was used to estimate the volume of individual logs above to obtain the volume of the tree. It should be noted that, in both cases, only the trunk was measured (up to the first big branch). A problem then appeared to know whether or not the data collected on standing trees could be mixed with data collected on felled trees. In other words, are the volumes estimated with one technique different from the volumes estimated with the other? A test of hypotheses was conducted (Paired t-test) with a number of trees on which the measurement was made with the two techniques. Each of these trees was measured optically and a second round of measurement was made after felling so that one could have for each tree: the DBH, the volume estimated with the mirror relascope and the volume estimated by direct measurements after felling. For each tree in the sample v_R the volume estimated with the relascope was recorded as well as v_f the volume estimated after felling (Mfou'ou, 1996). The difference $DIFF = v_s - v_R$ was also calculated. The hypotheses tested were:

H_0: $\overline{DIFF} = 0$, the mean difference is not significantly different from 0

H_1: $\overline{DIFF} \neq 0$, the mean difference is significantly different from 0

Based on previous experiences found in the literature (Medeng, 1988; Nkie 1994, Mfou'ou, 1996) three different types of regression equations were tested for each species group. These are:

$$V = b_0 + b_1(DBH) \text{ (Linear)} \tag{5.16}$$

$$V = b_0 + b_1 \ln(DBH) \text{ (Logarithmic)} \tag{5.17}$$

$$V = b_0 + b_1(DBH) + b_2(DBH)^2 \text{ (Quadratic)} \tag{5.18}$$

$$V = b_0(DBH)^{b_1} \text{ (Power)} \tag{5.19}$$

Where: V= average tree volume for a given diameter

b_o = a constant

b_n = regression coefficient

DBH = tree diameter at breast height

ln = the natural log base

One of these types was selected, based on the coefficient of determination and the standard error.

b) Data set

Four types of data were needed for the analysis: prices and costs, data for the estimation of the commercialization coefficients, data to test for differences between volume estimation techniques and data for the development of bole volume equations:

- **Prices and costs**. The FOB prices collected for 30 species from *Société Générale de Surveillance* (SGS) are presented in table 5.2. SGS is a multinational inspection company which monitors international timber trade in Cameroon. These are average prices from Cameroon seaports and for all destinations. As for the costs, they were provided by the records of the industrial logging company operating on the TCP research site. The records allowed to have the total volume of logs produced per year, the yearly overhead costs including equipment, traveling, maintenance, insurance, personnel and taxes. Detailed costs per cubic meter were available for inventory, felling, skidding, road construction, felling taxes, concession fees, equipment, insurance and miscellaneous.

Table 5.2: FOB prices (per m^3) for log exports from Cameroon in 1997 (1FF = 100 FCFA)

Species	Price (FF)	Species	Price (FF)
Assamela	262.3	Padouk	130.6
Bubinga	232.3	Teak	130.0
Doussie	280.0	Aiele	108.2
Sapelli	193.3	Amouk	95.6
Sipo	193.6	Andoung	73.1
Acajou	145.7	Azobé	104.9
Pachyloba	175.0	Bilinga	97.8
Ayous	120.8	Fromager	76.1
Bibolo	115.0	Ekop	98.9
Bosse	133.0	Eyong	88.9
Framire	103.3	Faro	74.4
Iroko	158.7	Fraké	106.6
Bete	153.3	Koto	99.1
Moabi	151.5	Niove	76.1
Movingui	129.0	Tali	91.9

Source: SGS Forestry (1997)

- **Data for the test of the difference between volume estimation techniques.** A total of 27 trees were measured both standing (with the mirror relascope) and after felling following the selection of the logging company. Table 5.3 gives more details on the trees measured.

- **Data for development of bole volume equations.** These data were collected at the TCP research site. In total, 500 trees of 32 species were measured, of which 103 were felled and 397 were standing. Annex 4 summarizes the data set.

- **Data for the development of commercialization coefficients.** Data were collected in and around the Tropenbos Cameroon research site. The collection was done in collaboration with the field crews of GWZ, the industrial logging company that was operating at the site. The logging company selected the trees based on their market demand and current regulations, they also used their logging equipment and technique on the trees on which measures were taken. All groups of species were not equally represented in the data set, because of the selection by the logging company and because the plot could not normally have the desired species. In total 360 trees were monitored.

Table 5.3: Data used for the test of difference for volume estimation techniques

Tree	V^1_s	V^2f	DIFF[3]	Tree	V_s	V_f	DIFF
1	14.532	14.580	-0.048	15	7.933	8.090	-0.157
2	10.270	10.010	0.260	16	12.809	13.325	-0.516
3	12.940	12.600	0.340	17	8.574	8.928	-0.354
4	11.840	12.040	-0.200	18	11.443	13.325	-1.882
5	33.130	33.440	-0.310	19	9.390	8.497	0.893
6	14.076	13.490	0.586	20	14.030	13.545	0.485
7	17.636	17.500	0.136	21	14.095	14.640	-0.545
8	9.956	10.007	-0.051	22	14.657	13.960	0.697
9	8.858	9.196	-0.338	23	13.708	14.240	-0.532
10	15.550	14.642	0.908	24	8.134	5.046	1.088
11	16.070	15.280	0.790	25	18.490	18.274	0.216
12	8.610	8.620	-0.010	26	20.990	19.765	1.225
13	36.100	37.174	-1.074	27	14.630	14.250	0.380
14	11.443	11.238	0.392				

[1] Volume (m^3) of the tree measured while still standing (with the relascope)
[2] Volume (m^3) measured after felling (with tape and caliper)
[3] Difference between the two volumes

5.3 Analysis of inventory results

a) Principle of analysis201

The analysis of inventory results was made to achieve research objective 2. The purpose was to have a quantitative assessment of forest stands in the TCP research site and to summarize the current stocking so that it can be utilized to feed TROPFOMS. The inventory results should be presented in terms of number of trees per species group and per diameter class for every forest type within the production forest of the TCP research site.

b) The data set

Due to financial limitations an inventory of the whole production forest at a rate of about 1 % as wished was not made. However, the inventory made for the establishment of PSPs in the site could provide enough information to feed the model. The inventory concerned a forest area of about 165 ha divided into 18 plots of nine to ten ha each (Bibani, 1996). In each plot, all trees of 10 centimeters on DBH or more were identified in botanical terms and their DBH recorded.

5.4 Analysis of forestry sector organization and regulations

a) Principle of analysis

The analysis contributes to the achievement of research objective 3. The purpose was to briefly describe the organization of the Cameroon forestry sector and highlight the existing regulations that are designed to ensure the sustainable management of forest resources. This should allow the evaluation of these strategies in the light of the results of the application of TROPFOMS methodology on the production forest of the TCP research area.

b) Information source

The main sources of information consisted of official documents of the forestry administration of Cameroon. These included the Forestry Law (Government of Cameroon, 1994), The decree of application of the Forestry Law (Government of Cameroon, 1995), The forest policy statement (Government of Cameroon, 1993) and the Zoning Plan (Côté, 1993). Additional information was obtained through personal communications with different people interested in the management of Cameroon forests.

5.5 Forest utilization by local populations

a) Principle of analysis

The analysis contributes to the research objective 4. It aims at determining critical tree species that are covered by industrial logging as well as the local populations. This will allow later developing and examining scenarios and options on the utilization of those resources.

b) Data source

A detailed inventory of names and functions of non-timber forest product species was conducted in and around the TCP research site (van Dijk, in press). The inventory results give a comprehensive list of plant species that are utilized by the local population and their respective relative importance.

5.6 Mathematical programming methods

The main need for a mathematical programming method in TROPFOMS is for optimization. The optimization method adopted is linear programming.

Linear programming appears to be one of the most widely used mathematical programming method, and it has been the most broadly applied of all management sciences techniques in natural resource management and related disciplines. Dykstra (1984) gives an account of published applications of linear programming relating to natural resources until the beginning of the 1980s. Since then many more applications of these techniques have been made, boosted by new developments in computer science.

Linear programming seems to have been developed by an American mathematician called Dantzig (Winston, 1987; Dykstra, 1984). A typical linear programming problem can be summarized by the following three characteristics (Winston, 1987):

1. An attempt to maximize (or minimize) a linear function of the decision variables. The function that is to be maximized or minimized is called the objective function.
2. The values of the decision variables must satisfy a set of constraints. Each constraint should be a linear equation or a linear inequality.
3. A sign restriction is associated with each variable

These characteristics of linear programming match in general with a part of the problem to be solved with TROPFOMS as described in sections 4.4.2 and 4.4.3. The decision variables here are the elements of the vectors Y_j and H_j which define the composition and structure of the forest stand and the harvest strategy respectively at steady state. The linear function to be maximized is the objective function introduced in section 4.4.2 while the constraints are presented in section 4.4.3.

Linear programming problems have many solutions which satisfy the equations, but only one solution is optimal and provides the best satisfaction of the objective function. The simplex algorithm that is described in all references on linear programming is an efficient way to select the optimal solution among a host of solutions to a linear programming problem. However, the use of linear programming implies that certain underlying assumptions are satisfied. These assumptions are: linearity in objective function and constraints (included in characteristics 1 and 2 above); divisibility that implies that each decision variable can assume any real value including both integers and fractions; non negativity of decision variables (characteristic 3 above) and; deterministic or certainty assumption that means that all coefficients and parameters are known with certainty. Of all these assumptions, the certainty assumption is the most difficult to satisfy in natural resources management. However, to some extent uncertainties and randomness can be dealt with by means of sensitivity analysis.

In addition to linear programming, TROPFOMS uses simulation. Simulation here consists of describing the real system (forest stand) in a simplified and abstract way by equations that represent the behavior of the real system simulated. Simulation helps in making projections and depicts long-term effects of a course of action. In TROPFOMS simulation is used for checking alternative cutting cycles and in the description of the conversion period.

Chapter 6

Parameters and coefficients used in TROPFOMS

Chapter 5 has presented the methods used for the estimation of the coefficients to be included in TROPFOMS. The coefficients needed relate to growth and yield, tree prices, the inventory of the current forest at the TCP research site and the use of forest products by the local populations as already identified in section 4.5. In this chapter, the results obtained from the analysis are given. These results, however, do not include those of mathematical programming which will be shown as outcomes of the model in chapter 7 and 8.

6.1 Growth and yield coefficients

The methods used for developing growth and yield coefficients were presented in section 5.1. The basic aim is to obtain transition probabilities and ingrowth estimation. However, as shown in section 5.1.1, there is a need to first aggregate tree species in groups and subsequently develop coefficients for species groups instead of individual tree species.

6.1.1 Species groups

The analysis yielded four species groups (or clusters) as presented in table 6.1. These groups were numbered automatically by the cluster procedure of SPSS. Annex 3 shows the SPSS outputs on Clusters Membership and Dendrogram.

Group 1 contains four species that can be characterized as fast growing as their average diameter increment is the highest of the four groups. Judging from their DME (80 cm), which is the second highest, it can be concluded that the species in this group can reach large sizes and their average price indicates that they are well appreciated by the market. In fact, Ayous is the most exported timber species from Cameroon (Eba'a, 1998b) and it is found in large quantities in both primary and secondary forests. The average diameter of this group at first mensuration is also the highest. This should result from the high diameter increment, suggesting that these species are the first commercial species to take advantage of the light influx that was increased by logging. The group is quite homogenous because, apart from Ayous, the other three species are from the same botanical family; the Meliaceae, also called mahogany family (Hawthorne, 1990) which includes many of Africa's most valuable timber species, but the family is also quite diversified.

Group 2 consists of 12 species that appear to be mostly comparatively small sized trees given that they have the lowest DME (all the 12 species have a DME of 50cm). Hawthorne qualifies the botanical family (Annonaceae) to which one of the species (Odjobi) of this group belongs as "small to medium-sized trees common in the lower stories of forest." This explains why the average diameter at first mensuration is the lowest. Species of this group are also the least demanded in the market and all these species are listed as "*essences de promotion*" by the forestry administration in Cameroon which means that they are typical lesser known species whose marketing is being promoted.

Group 3 has 22 species that generally grow to medium sizes. The DME varies between 50 and 60 cm (average 56.3 cm). This group is the most diversified and contains eight species that are regularly commercialized and exported (Azobé, Bilinga, Koto, Fraké, Faro, Aiele, Kotibe and Tali) but they are classified by the Forestry administration as "*essences à faibles valeurs*", meaning that the market price is low. The fairly high average diameter (55.1 cm) is explained by the fact that all mature trees of the group were not harvested during the logging operations which occurred before because of their low market demand. In addition the average diameter increment is also quite important and that also contributes to an increase of the average diameter a few years after logging. The market demand is low and species of this group are considered as "*essences de promotion*".

Group 4 consists of five species, three of which belong to the same botanical family (Meliaceae) and are of the same genus (*Entandrophragma).* These are Kossipo, Sipo and Sapelli. The group is thus fairly homogenous and contains the most valuable timber species of the data set. The market demand for these species is high and logging companies harvest them systematically. The average diameter of the group is low because these species were certainly the main target of the selective logging that occurred in roughly 15 years before the beginning of the experiment. The average DME of this group is the highest. In fact, species of this group are typical shade-tolerant species that gradually grow into the main canopy and finally, they become large emergent trees. Their life-spans are long (FAO, 1978). The diameter increment is the lowest both because they are slow growing species and because in this particular case they are part of the understorey, and thus they receive a limited quantity of light.

In general, the analysis has yielded interesting and plausible results. The grouping seems to be done in a logical way since each species has been assigned to a group which reflects its commercial value and growth habit. Group 1 aggregates fast growing commercial timber species of which the trees grow to medium to large sizes. Group 2 contains smaller trees with a low market demand. Group 3 is a mix of timber species some of which are well known by the market but have low prices and some are still being promoted, trees of this group grow to small to medium sizes with fair growth rates. Finally, group 4 contains slow growing and the most valuable timber species whose trees have large sizes at maturity. Nevertheless, it should be noted that the number of groups was set in a subjective manner. The intent was to keep the number of groups manageable and to avoid too many groups with only a few trees per group, which would have made statistical analysis less meaningful.

6.1.2 Transition probability estimates

The transition probabilities a_{ij} and b_{ij} (See section 4.4.1d) were estimated as indicated in section 5.1.2, the upgrowth probabilities were estimated by logistic regression analysis. The form of the logistic function considered was:

$$P(g) = \frac{1}{1 + e^{-f(D_i, BA, NT)}} \quad (6.1)$$

$P(g)$ = probability of a growth event
BA = basal area of the stand in m^2/ha
NT = number of trees per ha
D_i = center of the diameter class (m)
e = base of the natural logarithm

Table 6.1: Species groups

	Group 1	Group 2	Group 3	Group 4
Species	Acajou, Ayous, Bibolo, Tiama	Adjouaba, Afane, Andock, Babang, Essia, Kiasose, Kumbi, Nom-atui, Ngobisolbo, Odjobi, Tola	Aiele, Azobé, Bilinga, Bongo, Bongo H, Dabema, Ezang, Faro, Fraké, Fromager, Ilomba, Kibekoko, Kotibe, Koto, Landa, Mubala, Mutondo, Oboto, Parkia, Rikio, Sougue, Tali	Assamela, Ebene, Kossipo, Sapelli, Sipo
Average DBH (cm)	56.3	20.4	55.1	21.1
Average increment (cm)	3.3	1.1	2.46	0.9
Average DME (cm)	80	50	56.3	88
Average price (FCFA/m^3)	127,880	49,660	74,130	202,440

Note: Increment was observed over a five-year growth period

To estimate the coefficients of the equation, a dichotomous variable was defined in such a way that it took the value 1 if the tree considered grew up to the next diameter class during the growth period and the value 0 if it stayed in the same class. The above regression model was estimated, with a variable selection procedure using forward stepwise techniques. The results (See annex 7) showed that for the available data the basal area and the number of trees were not significant for predicting the upgrowth probabilities. This may result from the fact that the range of variation in basal area was not wide enough. About 80% of the plots have their basal area between 20 and 26 m^2/ha. It is common to reduce the basal area of stands by 10 m^2/ha or more in tropical forest silviculture to obtain the needed growth response (de Graaf *et al.*, 1998). It should be recalled that the plots that provided these figures were only selectively logged without further silvicultural treatment. Table 6.2 gives the different coefficients for significant variables (Significance level: 0.05).

Table 6.2: Coefficients for the estimation of upgrowth with logistic regression analysis.

Species Group	Constant	Diameter class center (m)	Square diameter class center (m)
1	-1.8497	8.0583	-6.9702
	(0.0903)	(2.1255)	(1.6763)
2	-2.3089	8.0671	-7.2771
	(0.2030)	(1.1180)	(1.0611)
3	-4.3875	14.4358	-12.1631
	(0.8060)	(2.5854)	(1.9022)
4	-3.2181	5.3605	not significant
	(0.3478)	(1.0119)	

Note: standard error in parenthesis

Upgrowth probabilities estimated from the logistic regression equations are given in Table 6.3. Except for Group 4, D_i^2 was a significant variable, which means that the upgrowth probability has a parabolic evolution. The upgrowth probability increases up to a certain diameter class and then starts to decrease.

Table 6.3: Upgrowth probabilities per species group and diameter class

Dclass	Clcenter	Group1	Group2	Group3	Group4
1	0.15	0.31	0.14	0.08	0.08
2	0.25	0.43	0.22	0.20	0.13
3	0.35	0.53	0.29	0.36	0.21
4	0.45	0.59	0.34	0.52	0.31
5	0.55	0.62	0.35	0.62	0.43
6	0.65	0.61	0.34	0.67	0.57
7	0.75	0.57	0.29	0.68	0.69
8	0.85	0.49	0.22	0.64	0.78
9	0.95	0.38	0.15	0.55	0.87
10	1.25	0.00	0.00	0.0	0.00

Note: Dclass = conventional diameter class number
Clcenter = value of the diameter class center in meters

Difficulties arose with species group 4 because trees larger than class 7 were not met. This is certainly due to the fact that this group contains the most valuable species that are systematically harvested by logging companies. The area in which the PSPs are located which provided the data was exploited about 15 years before data collection. All mature trees of that group were then harvested and the growth has not been fast enough to have trees in classes above class 7 during the first round of measurements. Therefore, the probabilities in classes greater than 7 are extrapolations using the logistic regression equation of that group. This may explain why group 4 was the only one for which the upgrowth probability was not sensitive to

D_i^2. In fact, it is possible that group 4 being constituted by species of big but slow growing trees (See section 6.1.1), the diameter class at which the upgrowth probabilities reach the maximum is higher than 7. Therefore, the data analyzed included only diameter classes where the upgrowth still increases which led to a positive linear relationship. In addition, the upgrowth probabilities of class 10 were put at zero given that class 10 is the highest class considered.

Another problem was the one of estimating mortality. Mortality data were so sporadic that statistical modeling became meaningless especially when the few available data had to be distributed among species groups and diameter classes. For this reason of insufficient mortality data, it appeared better to use figures found in the literature referring to African tropical forests. Experience gathered in West Africa (Alder, 1990; Alder, 1995; Mengin-Lecreulx, 1990) led to an estimate of mortality of 2% per annum on average if all tree species and all diameter classes are taken into account. The mortality rate for a five year growth period can then simply be estimated by compounding:

$$m_5 = 1 - (1 - m_1)^5 \tag{6.2}$$

where: m_5 = mortality rate for a five year growth period
m_1 = annual mortality rate

Such an estimation method yields an average mortality rate of 9.6% for a growth period of five years. This mortality is incorporated in the growth module of TROPFOMS by subtracting one tenth of it from the non-growth probabilities a. The respective values of the non-growth probabilities are calculated as in equation 6.3. The results obtained are shown in table 6.4.

$$a_{ij} = 1 - b_{ij} - 0.1 \tag{6.3}$$

Table 6.4: Transition probabilities used in TROPFOMS

Dclass	Clcenter (m)	a.1	b.1	a.2	b.2	a.3	b.3	a.4	b.4
1	0.15	0.59	0.31	0.76	0.14	0.82	0.08	0.82	0.08
2	0.25	0.47	0.43	0.68	0.22	0.70	0.20	0.77	0.13
3	0.35	0.37	0.53	0.61	0.29	0.54	0.36	0.69	0.21
4	0.45	0.31	0.59	0.56	0.34	0.38	0.52	0.59	0.31
5	0.55	0.28	0.62	0.55	0.35	0.28	0.62	0.47	0.43
6	0.65	0.29	0.61	0.56	0.34	0.23	0.67	0.33	0.57
7	0.75	0.33	0.57	0.61	0.29	0.22	0.68	0.21	0.69
8	0.85	0.41	0.49	0.68	0.22	0.26	0.64	0.11	0.79
9	0.95	0.62	0.38	0.75	0.15	0.35	0.55	0.03	0.87
10	1.25	0.90	0.00	0.90	0.00	0.90	0.00	0.90	0.00

Note: a.*j* = column of non-growth probabilities for species group *j*
b.*j*= column of upgrowth probabilities for species group *j*
Dclass= conventional diameter class number
Clcenter= center of the diameter class

6.1.3 Ingrowth equations

Multiple regression analysis was conducted as described in section 5.1.2 (Equation 5.9). Annex 6 gives a summary of plot data on ingrowth and number of trees per species group. The analysis produced the following regression equations for the four groups while their statistics are given in table 6.5.

Table 6.5: Statistics for the ingrowth equations

Species groups	Constant	BA	N_j	N	R^2	SE	I
1	-3.7878	0.0719	0.0147	0.0047	0.2009	0.9728	0.6
	(2.6608)	(0.0975)	(0.0358)	(0.0067)			
2	-26.5236	2.2253	0.2232	0.0913	0.1946	17.5762	28.6
	(44.4394)	(1.7018)	(0.1394)	(0.1033)			
3	28.2032	-0.1955	0.1295	0.0102	0.0740	8.9683	9.9
	(22.4508)	(0.8651)	(0.1874)	(0.0479)			
4	-0.2777	0.1400	0.0467	0.0467	0.2484	1.7093	1.3
	(4.1912)	(0.1646)	(0.0235)	(0.0236)			

Note: I = average ingrowth
BA = basal area of the stand in m^2/ha
N_j = number of trees of species group *j* per ha
N = total number of trees per ha
R^2= coefficient of determination of the model
SE= standard error of the model
I= average ingrowth for the species group

The statistics shown in table 6.5 indicate that the relationships between the ingrowth and the stand variables studied are weak. All coefficients of determination (R^2) are below 0.3 while in general if the relationships were good, the R^2 would be expected to be greater than 0.5. However, many previous studies such as the ones by Michie and Buongiorno (1980), Solomon *et al.* (1986), Lu and Buongiorno (1993) and Buongiorno *et al.* (1995) have yielded similar coefficients of determination although working with data from more homogenous forests. In addition, the standard errors are large compared to the averages shown in table 6.4. Thus these regression equations appeared unreliable. To select between the three variables that one may be more appropriate, a backward elimination procedure (SPSS Inc., 1993) was conducted, but it resulted in the elimination of all the three variables for all the four groups.

Moreover, signs of coefficients are not consistent. For example, for group 1, 2, and 3 the coefficients for the basal area are negative which appears normal because a high basal area means more competition and therefore less ingrowth but the coefficient for group 4 is positive which contradicts the expectations even though the group consists of slow growing shade tolerant species. The regression statistics suggest that little would be lost by modeling ingrowth as a constant. To that end the average ingrowth per species group (table 6.5) can be used. It is suggested that some other important variables (for example the site quality) may influence ingrowth more than the available variables. Unfortunately, no information had been gathered on such a variable.

6.2 Stumpage prices

6.2.1 FOB prices per species group

Table 6.6 summarizes the FOB prices per species group that resulted from the survey of prices as described in section 4.3.1. The prices from logging companies and the Cameroon government were collected in CFA Francs (FCFA), which is the regional currency used in Cameroon, while SGS Forestry provided its information in French Francs (FF). As already observed, the most expensive timber species are in group 4 followed by group 1and the least expensive are in group 2.

Table 6.6: Average FOB unit prices for different timber species groups (1997)

Species group	Average Price (FCFA/m^3)
1	127,880
2	49,660
3	74,130
4	202,440

a) Test of data homogeneity. Bole volume equations are needed for the estimation of the stumpage volume. One of the first problems met when trying to specify these equations was to decide whether or not data gathered from measurements on standing trees could be mixed with data collected of felled trees without severe risk. To decide on that, a test was conducted as described in section 4.3.1. On 27 trees of different species (the number was dependent on the choice of the logging company which felled trees to meet the market demand) measures were taken both before felling and after felling. The volume was estimated optically before felling and by hand measurement after felling. Annex 8 shows the data used to test the homogeneity of measurements. The paired t-test gave the results shown in table 6.7.

Table 6.7. Results of the paired t-test on differences between measurements on standing and felled trees

Variable	Mean	Standard deviation of mean	Standard error of mean
Felled volume	14.3876	6.819	1.312
Standing volume	14.4474	6.697	1.289
Difference (m^3)	-0.0598	0.720	0.139
DF[1]: 26	Corr[2]: 0.994	t-value[3]: -0.43	2-tail sig[4]: 0.67

[1] Degrees of freedom

[2] Correlation coefficient

[3] Observed t-value

[4] Tabulated t-value

These results indicate that there is a strong correlation between measurements made on standing trees with optical tools and measurement made on felled trees with hand instruments, the correlation coefficient equals to 0.994. Furthermore, the t-value as observed (-0.43) is far below the tabulated t-value (0.67) at the 0.95% confidence level, meaning that there is insufficient evidence to reject the hypothesis H_0; measurements made on standing trees are equivalent to measurements made on felled trees. Data from the two types of measurements tend to differ little and can therefore be mixed safely for subsequent analyses.

b) Development of bole volume equations. As indicated in chapter 4, four types of regression models were fitted for each species group, and one was chosen on the basis of both the coefficient of determination (R^2) and the standard error. The four regression models chosen were the linear, the logarithmic, the quadratic and the power. Annex 5 presents extracts of the SPSS outputs of the analysis for each species group while table 6.8 gives the coefficients of determination and standard errors of regression models for different species groups.

The highest coefficients of determination for the four species groups are obtained with the power curve regression model. Similarly, the lowest standard errors result from the same type of regression model. Thus the bole volume equations retained for the four groups are the power equations. The coefficients of determination are quite high, as they are above 90% for three groups and 88.6% for the lowest. The lowest value corresponds to species group 3 which may be explained by the fact that the group is the most heterogeneous (Section 5.1).

Table 6.8: Coefficients of determination (R^2) and standard errors (*E*) of different equation models and different species groups

Model	Species group 1		Species group 2		Species group 3		Species group 4	
Method	R^2	E	R^2	E	R^2	E	R^2	E
Power	0.932	0.267	0.910	0.255	0.886	0.413	0.946	0.326
Linear	0.896	1.442	0.864	0.936	0.816	2.768	0.911	3.338
Logarithmic	0.811	1.948	0.744	1.283	0.680	3.653	0.708	6.067
Quadratic	0.915	1.320	0.898	0.813	0.842	2.572	0.944	2.671

The four retained bole volume equations are:

Group 1 : $V = 9.891(DBH)^{2.247}$ (6.4)

Group 2: $V = 8.872(DBH)^{2.270}$ (6.5)

Group 3: $V = 8.683(DBH)^{2.196}$ (6.6)

Group 4: $V = 9.576(DBH)^{2.264}$ (6.7)

Table 6.9: Average stem volume (m^3) per diameter class for different species groups

Diameter (cm)	Class center (m)	Stem volume group 1	Stem volume group 2	Stem volume group 3	Stem volume group 4
10 - 20	0.15	0.139	0.120	0.135	0.131
20 - 30	0.25	0.439	0.381	0.414	0.415
30 - 40	0.35	0.935	0.819	0.866	0.889
40 - 50	0.45	1.644	1.448	1.504	1.571
50 - 60	0.55	2.581	2.284	2.336	2.474
60 - 70	0.65	3.757	3.337	3.372	3.611
70 - 80	0.75	5.182	4.618	4.616	4.993
80 - 90	0.85	6.865	6.135	6.077	6.628
90 - 100	0.95	8.814	7.897	7.758	8.526
> 100	1.25	16.330	14.723	14.174	15.870

Note: The last diameter class is wider than other diameter classes and most trees have their DBH between 1 and 1.5 m (although a few trees are bigger). For this reason the center was chosen to be 1.25 m.

These results permit the estimation of average stumpage volumes for different species groups and different diameter classes. The average volume is found by applying the bole volume equations to the center of the diameter class. Table 6.9 shows the estimates of stumpage volumes for each diameter class and each species group. As expected, there are some differences in stem volumes between species at the same diameter class resulting from differences in tapers. Group 1 has the highest volume in any diameter class.

6.2.3 Commercialization coefficients

The commercialization coefficients were estimated as indicated in section 5.2a (Equation 5.12). In total, 360 trees were used for the analysis and all species groups were not equally represented. Table 6.10 summarizes the distribution of trees among species groups. As already mentioned in section 5.2b, these trees were harvested by the industrial logging company during the time of data collection of this part of the study. It can be seen that, species group 3 had the biggest number of trees. This certainly results from the fact that this group also includes the largest number of species that are regularly demanded by the market. Group 3 is followed by group 1 and 4 which contain a smaller number of species than group 2 (the least represented). Groups 1 and 4 consist also of species of high market demand and are therefore attractive to loggers.

Table 6.10: Distribution of trees among species groups

Group 1	66
Group 2	36
Group 3	194
Group 4	64
Total	**360**

The monitoring of harvested trees gave the results presented in table 6.11. This table reports on volume losses at different logging stages both in absolute and relative terms for each species group. The most important losses occur in the forest at the felling site. The percentages given in the last column are the commercialization coefficients. The two highest coefficients are respectively for group 4 and 1, which can be explained by the fact that these species groups have a high market demand and loggers try to minimize waste on them during

Table 6.11: Volume losses at different stages of logging and commercialization coefficients for each species group

Species Group	Stumpage volume		Abandoned on the site		Abandoned on the forest landing		Commercial logs	
	m^3	%	m^3	%	m^3	%	m^3	cc (%)
1	1030.52	100	245.30	23.80	76.75	7.45	708.47	*68.75*
2	293.85	100	37.06	12.61	74.43	25.33	182.36	*62.06*
3	2814.04	100	682.17	24.24	469.67	16.69	1662.20	*59.07*
4	1127.08	100	27.45	2.43	188.20	16.70	911.43	*80.87*
Total	**5265.49**	**100**	**991.98**	**18.83**	**809.05**	**15.37**	**3464.46**	***65.80***

Note: cc = commercialization coefficient

logging operations. In addition, these species groups have higher DMEs (Table 6.1) suggesting that there is a positive relationship between the diameter of trees harvested and the commercialization coefficient. In other words, the larger is the harvested tree, the smaller is the relative waste and the higher is the commercialization coefficient. This positive relationship has already been demonstrated by some authors in past studies (CTFT, 1972; Fournier-Djimbi and Fouquet, 1998). The smallest coefficient corresponds to species group 3 which may result from both the heterogeneity of species in this group and their low market value.

6.2.4 Costs of availability

The average costs paid by the logging company for the production of 25,000 m^3 of logs are presented in table 6.12. The company has three main types of profit bearing activities: logging, the sawmill and trade (dealing). The column labeled: 'Logging' gives costs that are

Table 6.12: Average logging costs in thousand FCFA

	Logging	General Management
Operational costs	156,636.804	87,554.389
Transport	781,063.691	307,202.808
Maintenance	147,567.387	128,217.486
Insurance	28,479.689	21,382.115
Personnel	138,852.688	158,462.190
Taxes	45,730.014	267,984.429
Bank fees and interests		84,782.835
Total	**595,372.952**	**1055,586.252**

directly related to logging operations, while the column labeled: 'General Management' reports on overhead costs for the whole enterprise. A problem is the allocation of these costs to the three main activities. The total logging costs are estimated by adding one third of the general management costs to direct logging costs. The general management costs are divided by three because the company has three main activities. The total costs are therefore 947,235,036 FCFA, which corresponds to 37,890 FCFA/m^3. The available information did not allow to differentiate the costs between diameter classes. Therefore, the costs per cubic meter in this section are assumed to be the same for all diameter classes.

6.2.5 Stumpage price

The prices per m^3 of stumpage for each species group were estimated as explained in section 5.2a (Equation 5.11) and the results are presented in table 6.13.

Table 6.13: Stumpage price (1000 FCFA/m^3) per species group

Group	FOB price	Commercialization coefficient	Stumpage price
1	127.9	0.6875	61.87
2	49.7	0.6206	7.30
3	74.1	0.5907	21.41
4	202.4	0.8087	133.07

Similarly, the prices per tree were computed based on equation 5.15 and the average stem volumes per species group and per diameter class given in table 6.10. The resulting estimates are given in table 6.14.

Table 6.14: Tree prices (1000 FCFA/tree) per species group and diameter class

Diameter class	Group 1	Group 2	Group 3	Group 4
1	8.60	0.88	2.89	17.43
2	27.16	2.78	8.86	55.23
3	57.85	5.98	18.54	118.30
4	101.71	10.58	32.20	209.06
5	159.68	16.68	50.01	329.22
6	232.44	24.37	72.18	480.52
7	320.60	33.73	98.82	664.43
8	424.72	44.81	130.09	882.00
9	545.31	57.68	166.08	1134.57
10	1010.30	107.54	303.42	2111.85

6.3 Forest inventory

The inventory was conducted for silvicultural purposes in an experiment within the TCP research area. In total, 18 plots covering about nine ha each were inventoried which adds up to about 162 ha (Bibani, 1996). In each plot all trees with a DBH of 10 cm or more were identified and their DBH recorded. The area had not been logged before, but signs of human disturbance were present. The results of the inventory are summarized in table 6.15. On average, one ha contained 467 trees representing 291.5 m^3 of raw bole volume which is equivalent to 0.62 m^3 per tree. The two most demanded species groups by the timber product market (groups 1 and 4) account only for about 3% both in terms of number of trees and volume while the least demanded group alone (group 2) has about 58% of the stems and 41% of the volume. This fact illustrates how selectively logging still is practiced in tropical Africa in general and in Cameroon more specifically. Figure 6.1 illustrates the current structure of the forest as a distribution of trees per diameter classes. For all species groups the figures resemble the theoretical negative exponential distribution typical of uneven-aged forests (Davis and Johnson, 1987). Bibani (1996) working with the same set of data obtained less regular distributions by using individual tree species. The similarity with the theoretical distribution observed when species are grouped suggests that management systems based on species groups may reduce worries about regeneration and future harvests.

Table 6.15 Summary of forest inventory results in the Tropenbos Cameroon research site

Diameter class		**Group 1**		**Group 2**		**Group 3**		**Group 4**	
No	center	Trees/ha	Volume	Trees/ha	Volume	Trees/ha	Volume	Trees/ha	Volume
1	0.15	3.1	0.3	171.1	9.1	107.8	14.5	6.7	0.9
2	0.25	1.2	0.3	51.4	10.8	36.3	15.0	1.4	0.6
3	0.35	0.3	0.2	24.4	12.7	13.0	11.3	0.3	0.3
4	0.45	0.1	0.1	9.6	9.9	7.2	10.8	0.2	0.3
5	0.55	0.2	0.4	4.2	7.4	5.6	13.1	0.3	0.7
6	0.65	0.1	0.3	2.9	8.0	3.7	12.5	0.2	0.7
7	0.75	0.1	0.4	2.4	9.8	2.0	9.2	0.0	0.0
8	0.85	0.1	0.6	0.8	4.6	1.1	6.7	0.1	0.7
9	0.95	0.0	0.0	0.6	4.6	1.1	8.5	0.0	0.0
10	1.25	0.0	0.0	2.6	42.1	4.4	62.4	0.1	1.6
Total		**5.2**	**2.7**	**270.0**	**119.0**	**182.2**	**164.0**	**9.3**	**5.8**

Note: Volume in m^3/ha

6.4 Forest utilization by the local population

To sort out forest product utilization by the local population in the TCP research area, a study was conducted by a TCP researcher (van Dijk, 1994). The study included three Bantu villages and one Bakola (Pygmies) settlement. It dealt not only with tree species, but also with other plant species and animal species. Many tree species were identified as used by the local populations either on the basis of observed frequency of utilization or on the basis of statements by the local populations. The difference between frequency of use and statement

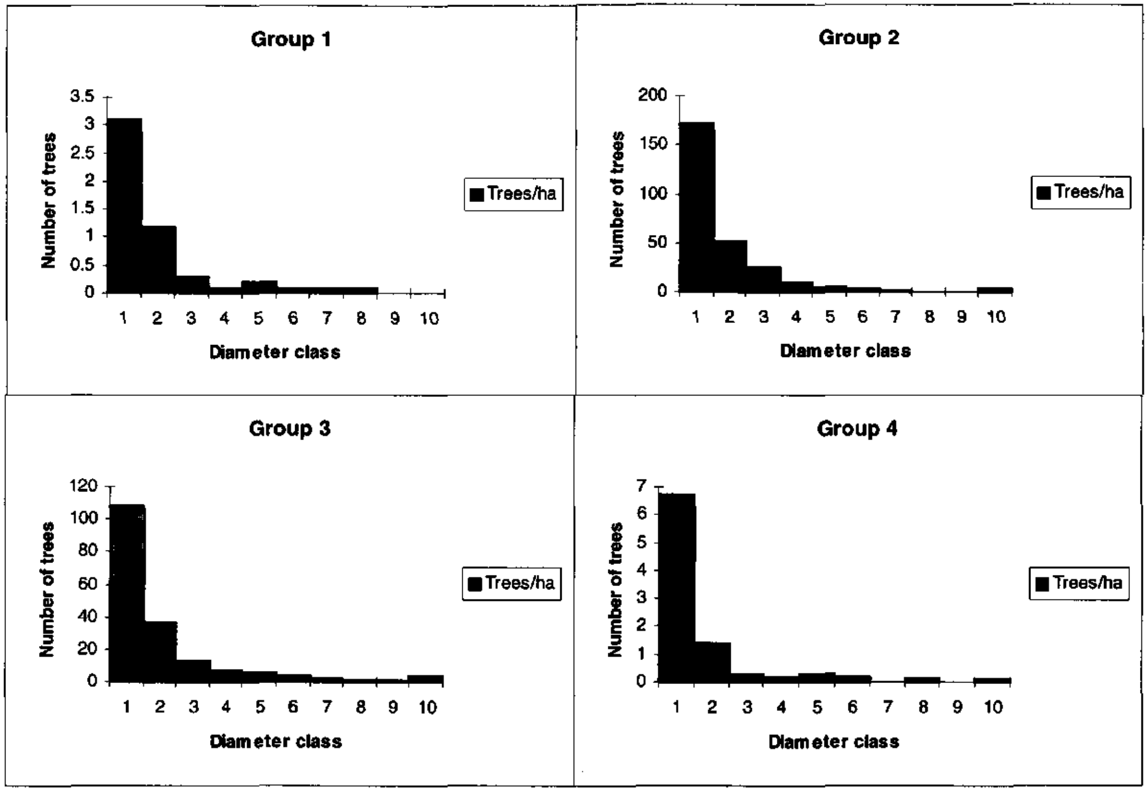

Figure 6.1: Diameter class distribution per hectare for different species groups at the TCP research site
Source: based on Bibani (1996)

allowed to identify the tree species which are important for both the local population and the logging company in the area. These species are seen as critical for forest management strategies. Table 6.16 gives a list of critical tree species and their corresponding groups. The number of critical tree species in different groups decreases gradually from species group 3 to 4 and to 1, which relates mainly to the number of species contained in each of these groups (Section 6.1.1). None of the critical species is in group 2, which can be explained by the fact that tree species of this group are the least demanded in the timber market.

By matching these data with the above described forest inventory results, it was found that on average, there are about 31 trees per hectare of interest to the local population which represents 6.7% of the total number of trees per ha. It is not clear whether all trees of these species are actually used by the population or whether they use only a few of them which are close to the village, for example.

Table 6.16: Important tree species used by the local population as well as the logging company at the TCP research site

Pilot name	Group	Pilot name	Group
Acajou	1	Padouk	3
Bibolo	1	Azobé	3
Angongui	3	Bahia	3
Aiele	3	Niove	3
Movingui	3	Bilinga	3
Eyong	3	Sapelli	4
Tali	3	Bubinga	4
Bongo	3	Iroko	4
Bilinga	3	Moabi	4
Dabema	3		

Source: adapted from van Dijk (1994)

6.5 Conclusion on the coefficients used by TROPFOMS

The previous sections of this chapter have presented the results obtained in each step of the estimation of coefficients for TROPFOMS. The main figures to be used in the next chapters are those shown in tables 6.1, 6.4, 6.5 and 6.14 for the production of steady state related outputs, while the numbers in table 6.15 will be used for the simulation of the conversion period. Table 6.16 and related comments contain the figures used to incorporate the objective of improving living conditions for the local populations.

Chapter 7

Outcomes of TROPFOMS for the steady state forest

The general objective of this research as presented in chapter 2 is to design a system that can support decision-making for the management of natural tropical forests. The system designed intends to provide information on key forest management parameters, the impact of different management objectives on these parameters and the economic consequences of chosen management options. The management parameters of interest are the cutting cycle of the timber harvest and the structure of forest stands at steady state, but also characteristics of the conversion period. This chapter focuses on the steady state. The steady state in this case refers to a fully regulated forest stand capable of yielding the same harvest of the forest product of interest (timber for example) at the end of every cycle. Such a fully regulated forest is characterized by a stable stand structure (steady state structure) in terms of distribution of trees per species and size classes which guarantees enough growth to obtain a stable harvest at the end of each cutting cycle. The three most important characteristics of the steady state forest are then: the cutting cycle, the structure of forest stands and the expected harvest. The interest of these parameters is that they have a synthetic attribute, meaning that a change in one of them can be translated in a change in the extent to which the forest under management is capable of meeting multiple objectives.

The main forest management objectives considered are: the generation of income through industrial timber production, the improvement of living conditions for local populations through non-timber forest products and nature conservation. The system designed should help in assessing the trade off between these objectives. The key point in the design of such a system is the development of the methodology to be used by the system when performing the needed analysis. This is related to specific research objective 1 of the current research.

The chapters 4 to 6 present the design of the system that was given the acronym of TROPFOMS (TROPical FOrest Management support System). After presenting the conceptual framework, that identifies factors contributing to the sustainability of forest management strategies, these chapters present TROPFOMS including its main components, its procedural design, the theoretical approaches used in it and the scientific methods used to develop its coefficients and parameters (description of the data set and principles of analysis). The current chapter shows different outcomes of running the system with a computer. These outcomes are obtained based on the growth coefficients and stumpage prices developed according to the methods described in chapter 5 and whose resulting values are given in chapter 6. The outcomes relate to the steady state characteristics mentioned in specific research objectives two and three and in the analysis of critical factors that affect the management of natural forest in south Cameroon.

The outcomes produced and analyzed in the current chapter concern the three management objectives stated above. However, all three objectives do not come to expression in the objective function of TROPFOMS that uses linear programming techniques in its optimization routine; linear programming accepts only one management objective in the objective function[3]. The management objective that is expressed in the objective function is income generation through sustainable timber production. Sustained timber production is viewed as the need to maximize financial returns from timber harvesting for an infinite number of cutting cycles. The quantitative measure of sustained timber production is the sustained timber value (Chapter 5). Nature conservation is expressed as the need to maximize species and tree size diversity (See also section 2.3.5a. and 5.3.3b). Forest utilization by the local population is dealt with as a constraint to preserve a certain proportion of NTFPs (See section 2.3.5c for a definition of NTFPs) producing trees, which has appeared to be the best way to include it given the nature of the information at hand. However, another implicit way of considering NTFPs is through conservation. In fact, it seems to be a reasonable assumption to state that the higher the diversity of the forest is, the better is its ability to produce NTFPs. Thus, a high level of species and size diversity also yields a high level of NTFPs.

TROPFOMS is to be run under different assumptions and each run results in a steady state with a related guiding cutting cycle, stand structure to be left after harvest for sustained yield, the level of harvest to be expected once the forest is regulated, a measure of diversity and the level of financial returns obtained. Comparisons between several runs provide information for trade off analysis. It should be emphasized that the characteristics obtained describe the desired steady state which forest management may target for the future. Therefore the volume and number of trees harvested should not be expected from the actual forest if the structure and the composition are different from that in the steady state. Before the characteristics of the steady state under different management options can be presented, it appears important to recapitulate the basic constraints of TROPFOMS.

7.1 Recapitulation of basic constraints specifications

This section refers the mathematical programming approaches already presented in section 5.6. In addition, the specific values used in some constraints when running the model with the computer are given as well as the reasons for choosing these values. The constraints specified here were basic for all the runs to obtain characteristics of the steady states.

The first set of basic constraints relates to sustainability of the forest in the sense of its continued existence and the continuity of the timber harvest at the level and periodicity determined. This set of constraints is formulated as (See also section 4.4.1 for the details of this notation):

$$Y = G^{k\theta}(Y - H) + \sum_{u=0}^{k\theta-1} G^{u} I \tag{4.13}$$

[3] In Goal Programming (GP), more than one management objective can be included in the objective function through the minimization of deviations from a prior specified level of achievement of these objectives. However, GP has not been used here because of the various difficulties inherent to it (See Dykstra, 1984).

Y = column vector of elements y_{ij} representing the number of trees before cutting in diameter class i and species group j.
H = matrix of harvest elements h_{ij} representing the number of trees to be harvested at the end of every cutting cycle in diameter class i for species group j at the steady state
k = number of growth periods in the cutting cycle
G = growth matrix of transition probabilities
I = column vector of ingrowth

Equation 4.13 generates 40 constraints: one for each diameter class in every species group. It expresses the fact that the harvest in each diameter class can not exceed growth in terms of number of trees. Another constraint is introduced to keep the cut less or equal to the number of trees that entered the stand during a cutting cycle of k growth periods. The formulation of such a constraint is:

$$\sum_j h_{ij} \leq kI_j \tag{7.1}$$

I_j = average number of ingrowth trees for species group j

Equation 7.1 generates a set of 4 constraints one for each species group.
Preliminary phenological observations of tree species at the TCP research site (Bibani *et al.*, 1998) have shown that many species do not fructify for DBH less than 30 cm. Given that TROPFOMS examines sustainable management options based on natural regeneration, it should therefore not be allowed to harvest trees which are smaller than 40 cm to allow each tree to have some reproduction time before it is harvested. This corresponds to diameter classes 1, 2 and 3. One of the easiest ways to incorporate such a regeneration concern is to give no market values to trees smaller than 40 cm, but that does not guarantee that trees of these diameter classes will not be cut. This will only further their priority in harvesting. However, this constraint can also be explicitly written as:

$$\sum_{i=1}^{i=3}\sum_{j=1}^{j=4} h_{ij} = 0 \tag{7.2}$$

Another constraint included in all runs is a resource limitation constraint. Because the data did not allow us to establish a good relationship between growth and basal area, which was expected to be a negative one, it seemed necessary to limit the basal area that a stand can reach in order to reach an equilibrium at one point. The inventory results from undisturbed forests in the research site and discussions with specialists in silviculture have led to set the maximum basal area of a forest stand at 40 m^2/ha before harvest. In this constraint, average basal areas for each diameter class are used (Table 7.1). The constraint is formulated as:

$$\sum_j \sum_i ba_i y_{ij} \leq 40 \tag{7.3}$$

ba_i = average basal area (m^2) of diameter class i

The level of 40 m^2/ha is considered to be a climax level and not an optimal one. It restricts the model from growing trees without limit. Such a restriction is of special importance because the data did not allow to establish a good relationship between stand density and growth. Without this relationship, the model may grow trees limitlessly. However, the practice of sustainable management imposes also other conditions related to the basal area to avoid irreversible damage of the stand. A study of harvesting intensity in relation with sustainability conducted in Indonesia by Sist *et al.* (1998) emphasizes the need to restrict harvest intensity to avoid irreversible ecological problems in the stand. The way this is done is by limiting the proportion of the total basal area that can be removed at the end of each cutting cycle. Equation 7.4 formulates the constraint related to such a restriction in basal area removal.

$$\sum_j \sum_i ba_i h_{ij} \leq \alpha \sum_j \sum_j ba_i (y_{ij} + h_{ij}) \tag{7.4}$$

α = maximum proportion of the basal area permitted to be removed

Table 7.1: Basal area of an individual tree per diameter class

Diameter class	1	2	3	4	5	6	7	8	9	10
Diameter class center (m)	0.150	0.250	0.350	0.450	0.550	0.650	0.750	0.850	0.950	1.250
ba (m^2)	0.018	0.050	0.097	0.160	0.238	0.332	0.442	0.568	0.709	1.228

Note: $ba = \frac{3.14 * d_i^2}{4} + e$; d_i = center of diameter class i; e= correction for bias

There is a bias when estimating the average basal area of a class by using the center value of the class. This bias comes from the fact that the basal area is a quadratic function of the diameter. By using the center of the class the average basal area of the class is underestimated. The correction term is $e = \frac{\pi}{48} w^2$ with w = the width of the class (Jansen, 1999).

7.2 Steady state characteristics under economic objective

One of the management objectives considered in this research is the generation of income through timber production. This section shows the outcomes of running TROPFOMS with such an objective and various management options in relation to specific research objective two (Section 3.2.2). The outcomes consist of the characteristics of the desired target steady state structure. But, before retaining one final target structure, the effects of management factors on the steady state characteristics are examined.

The objective function related to the economic objective is stated as to maximize the Sustained Timber Value (STV), referring to the terminology defined in section 5.3.2. The mathematical expression of that objective is (See also section 4.4.2):

$$\text{Maximize } STV(h,y) = \frac{PH - \sum C_t (1+r)^{k\theta - t}}{(1+r)^{k\theta} - 1} - P(Y-H) \tag{4.15}$$

P = row vector with elements p_{ij} representing prices of trees in diameter class i and species group j

C_t = costs of silvicultural treatments conducted in year t.

r = discount rate

In most runs the costs of silvicultural operations are considered equal to zero as there is currently no practice of silviculture in natural forest management in Cameroon. The vector of prices P uses the figures presented in section 6.2.1 for tree prices per species and diameter class. The growth period θ is equal to five years. In linear format, equation 4.15 can be written as:

$$STV = \frac{1}{(1+r)^{k\theta} - 1}\left[\sum\sum p_{ij}h_{ij} - \sum C_t(1+r)^{k\theta - t}\right] + \sum\sum p_{ij}h_{ij} - \sum\sum p_{ij}y_{ij} \tag{7.5}$$

The optimization problem defined by equations 4.13, 4.15 and 7.1 to 7.5 was solved using AIMMS 5 (Paragon Decision Technology, Faculty version).

A forest growing under a set of defined ecological conditions and with given biological characteristics has many steady states whose characteristics vary with management conditions. The management conditions include management options and management parameters. Management options are based on the management objectives. Management parameters, such as discount rate, market prices and harvesting techniques, are mostly imposed by the technical and the socio-economic environment. Management options can be included in a model with the help of constraints or in the objective function, while management parameters may be defined as constraints or just as coefficients in a model. Given a set of management options and parameters, one steady state will be preferred to the others. This is the target steady state. Section 7.2.1 below analyses the impact of key management parameters on the target steady state, while sections 7.2.3 and 7.2.4 show the changes in the target steady state as result of some management options. All this relates to steps 6 and 7 of the research process (Section 4.3).

a) Impact of the discount rate

In section 6.2, the prices for trees to be used in equation 7.5 were given, but until now the discount rate has not been chosen. The choice of the discount rate for project analysis is an issue of continuing debate among economists. The debate is even more engaged when analyzing projects that are related with renewable resources such as the tropical forest. One of the most important features of the discount rate is that it tries to measure the time preference. The assumption is that economic actors prefer to enjoy benefits of their operations as soon as possible and delay the payment of the costs. Thus, a project that provides the same benefits sooner is preferred to one that provides them later. Many authors in environmental economics, such as Hueting (1991), have opposed the idea of using the same discount rate for both commercial and environmental costs and benefits. Such an idea may go against the idea of sustainability for which future benefits are seen as important as present ones. As Markandya and Pearce (1988) put it: "One important feature of the literature on environment, natural resources and development is its requestioning of the fundamental argument for discounting. This reanalysis arises partly because of the alleged discrimination of conventional discount rates against the interest of the environment and partly because concern for natural environments is often associated with an ethical stance on intergene-rational justice." However, Markandya and Pearce advocated for the policy of the World Bank to use the same discount rate for environmental projects as for other projects and to impose policy constraints for the conservation of the environment. According to these two authors, the discount rate should be chosen between 8% and 12% when analyzing projects in developing countries.

In a later, and more detailed analysis, the OCDE (1995) advocated to use a much lower discount rate for environmental projects in developing countries. Their estimates are in the range of 3% to 5%. Lescuyer (1998), using the approach put forth by OCDE obtained a discount rate of 3.8% for Cameroon.

Table 7.2: Impact of the cutting cycle and the discount rate on the sustainable timber value (STV 1000 FCFA) (maximum permitted basal area removal of 35%)

Cutting Cycle (years)	STV (1000 FCFA) at discount rate 3%	5%	10%
10	55738.8*	35628.4*	20934.7*
15	35616.1	23327.7	14633.5
20	19243.9	12897.4	8606.5
25	14069.8	9236.9	6141.9
30	10759.2	7127.2	4955.9
35	6827.8	4305.8	2899.6
40	2954.7	1357.4	536.6

Note: (*) indicates the highest STV

In this study, a discount rate of 5% is adopted, which is in the range of OCDE but at the upper end. However, before choosing a discount rate, an analysis was conducted to evaluate the impact of the discount rate on the steady state characteristics of the forest. Results are shown in table 7.2. Three values were chosen for the analysis, the borders of the interval proposed by OCDE (3% and 5%) and 10% which is at the middle of the range of the World Bank. The maximum basal area removal allowed was 35% of the basal area before harvesting.

From this table, it can be seen that the highest STV is found at a cutting cycle of 10 years for all discount rates, making the choice of the discount rate in this respect less important. Timber harvesting seems to be very attractive for financial returns, although the STV decreases as the discount rate increases. Table 7.3 shows the stand structure before harvest and the expected harvest for the cutting cycle of 10 years. It should be noted that of the 17.07 m^3/ha harvested the species groups 1 and 4, which are currently the most commercialized, represent only about 1.88 m^3/ha which is far below the current harvest of 6 m^3/ha at the TCP research site (van der Hout and van Leersum, 1998). Therefore, if the stumpage price per cubic meter is the same for every diameter class as computed in section 6.2.5 and used here, TROPFOMS advises to have frequent but light harvests.

Table 7.3: Stand structure before harvest and harvest (trees/ha) for a cutting cycle of 10 years (discount rate 5%) and a maximum permitted basal area removal of 35% (uncorrected prices).

Diameter class	Species group 1	Species group 2	Species group 3	Species group 4
		Stand structure before cut (trees/ha)		
1	1.46	119.00	54.90	7.20
2	0.86	52.20	14.70	2.47
3	0.58	29.50	6.39	1.04
4	0.41	17.0	3.17	0.36
5	0.18	10.5	1.19	0.07
6	0.00	8.02	0.00	0.00
7	0.00	7.06	0.00	0.00
8	0.00	6.30	0.00	0.00
9	0.00	5.40	0.00	0.00
10	0.00	8.11	0.00	0.00
Total	**3.49**	**263.09**	**80.35**	**11.14**
		Cut (trees/ha)		
1-3	0.00	0.00	0.00	0.00
4	0.41	5.28	3.17	0.36
5	0.18	0.00	1.19	0.07
6-10	0.00	0.00	0.00	0.00
Total	**0.59**	**5.28**	**4.36**	**0.43**
STV: 35 620 400 FCFA		Pre-harvest basal area: 40 m^2/ha		
Trees cut: 10.66 trees/ha		Post-harvest basal area: 35.04 m^2/ha		
Volume cut: 17.07 m^3/ha		Number of trees after cut: 347.41		

One implication of the harvest shown in table 7.3 is that, to obtain such a harvest every 10 years, some trees of species groups 2 and 3 should be removed even if they are not commercialized. The removal of such trees will make space for more increment under the assumptions of the model, thus silvicultural operations are needed. In any case, the prices used (See section 6.2.5) assume that all trees cut are commercialized because they can improve the profit margin. Such an assumption is certainly too optimistic. The resource limitation constraint that restricts the basal area to less than 40 m^2/ha is binding while the limitation imposed to harvest no more than 35% of the initial basal area is not. Furthermore, it can be noted that for species groups 1, 3 and 4 there are no trees in diameter classes 6 to 10 before harvest at steady state. A cutting cycle of 10 years will have a serious impact on size diversity.

b) Recognition of a diameter related price difference

The prices of trees used until now are those calculated in chapter 6 (Section 6.2). The price differences among trees of different size classes stem only from a difference in volume. This source of difference is not enough and does not explain behaviors such as the one of the logging company of the TCP research site. This logging company does not harvest Azobé trees of less than 80 cm even though the regulations allow to go down to 60 cm. On the other hand, forestry officers in charge of the enforcement of logging regulations usually report many infractions by logging companies which tend to harvest smaller trees of species groups 1 and 4 at smaller DBH than the official DME (See also section 5.2.2 and table 6.1). The real stumpage prices have more sources of differences than just the volume per tree as estimated in section 6.2. Unlike the results shown in table 6.14 in which trees in all diameter classes and all species groups have positive stumpage prices, there are diameter classes for which tree prices are equal to zero or negative and for which logging is not profitable.
Therefore, there are other sources of price differences between trees of successive diameter classes than just the differences in volume. These other sources of difference in stumpage price were not quantified in this research due to the lack of information. The minimum diameter for which logging operations become profitable depend on species groups, and it is possible that the logging company's estimation is that harvesting trees of species group 3 becomes profitable only around diameter class 8.

In addition to difference in volume, two more sources of price variation may be thought of. One of these sources of price difference is related to logging waste. It is generally known that the logging waste decreases as the diameter of the tree harvested increases, resulting in different commercialization coefficients (See section 6.2.3) for different diameter classes (CTFT, 1972; Fourier-Djimbi and Fouquet, 1998). Therefore, for species of low unit volume price such as Azobé, the volume extracted from a small tree may be too small to offset the costs of harvesting. Another source of variation relates to the decrease of harvesting costs per unit volume as the diameter increases (FAO, 1977; FAO, 1992). This is due to the fact that some logging costs remain constant per tree no matter the size of the trees. Examples of these costs are the costs of prospecting and the cost for the felling crew to move from one tree to the next.

To correct stumpage prices estimated in section 6.2.5, two proportions can be defined. Let w be a proportion by which the commercialization coefficient decreases from one diameter class to the next smallest and c the proportion by which the logging costs increase following the same gradient. New tree prices can be estimated by trying different values of w and c to obtain a value 0 for trees of diameter class 7 in species group 3. The diameter classes for which the tree prices start being equal to 0 will be smaller for groups 1 and 4 and higher for group 2 which is even less valuable than species group 3. The proportions w and c can be inserted in equation 5.11 to give equation 5.11', which expresses stumpage prices per cubic meter at different diameter classes. Similarly, equation 5.12 which allows the estimation of stumpage prices per tree will change to equation 5.12'. The two equations are (terminology defined in section 5.2a):

$$P_{ij} = [(1-w)cc_{i+1,j}][FOB_j - (1+c)AC_{i+1,j}] \quad (5.11')$$

$$p_{ij} = P_{ij} * v_{ij} \quad (5.12')$$

Such a result is approached when both w and c are 0.3. Diameter class 10 is considered to be the reference class from which the prices of the other classes are deducted. Table 7.4 gives the new tree prices corrected in this way. Some of the prices are negative which means that, if trees of the corresponding diameter classes are harvested, the logging company will loose money because the revenues received from selling wood will not compensate logging costs.

Table 7.4: Stumpage prices (1000 FCFA) by species group and size class corrected for differences in logging waste and costs between diameter classes

	Price per cubic meter				Price per tree			
Diameter class	Species group 1	Species group 2	Species group 3	Species group 4	Species group 1	Species group 2	Species group 3	Species group 4
1	-7.60	-9.82	-8.81	-6.51	-1.06	-1.06	-1.05	-0.85
2	-7.18	-9.28	-8.00	-4.97	-3.15	-3.54	-3.31	-2.06
3	-6.22	-9.61	-7.96	-2.35	-5.82	-7.87	-6.89	-2.09
4	-4.45	-9.73	-7.56	1.86	-7.31	-14.09	-11.37	2.92
5	-1.48	-9.49	-6.61	8.39	-3.82	-21.68	-15.43	20.77
6	3.25	-8.73	-4.83	18.30	12.19	-29.12	-16.30	66.06
7	10.53	-7.15	-1.85	33.06	54.54	-33.01	-8.52	165.08
8	21.51	-4.37	2.92	54.85	147.65	-26.82	17.76	363.51
9	37.84	0.18	10.28	86.72	333.50	1.38	79.79	739.34
10	61.87	7.30	21.41	133.07	1010.31	107.54	303.42	2111.85

As expected, the prices per cubic meter increase with the diameter class. However, the price per tree, which is obtained by multiplying the price per cubic meter by the average tree volume of each diameter class (Table 6.10), decreases as the diameter increases for negative values and increases with the diameter for positive values. The evolution of prices per tree can be explained by the increase in tree volume that is faster than the increase in stumpage value per cubic meter. Thus, if the price per cubic meter is negative, harvesting will result in more important financial losses as trees grow bigger. The result of the correction is that it does only become useful to harvest trees in certain diameter classes, but also that the price differences between consecutive diameter classes have increased, and that even higher preference will be given to bigger trees. The effects on STV and optimal cutting cycle of applying the corrected prices in comparison to the initial ones are shown in table 7.5.

Table 7.5 shows that correcting stumpage prices results in lower values for the STV and the optimal cutting cycle has shifted from 10 years to 25 years. The shift in the optimal cutting cycle is due to the fact that by lengthening the cutting cycle, there is more chance to have a larger number of big trees that have higher values. The increase in tree values because of lengthening of the cutting cycle from 10 to 25 years is obviously more important than the increase of the opportunity cost of capital because of delaying the harvest.

Table 7.5: Effects of corrected tree prices on the STV (1000 FCFA), discount rate 5%, maximum permitted basal area reduction of 35%

Cutting cycle (years)	STV initial prices (1000 FCFA)	STV corrected prices (1000 FCFA)
10	35628.4*	3418.92
15	23327.7	3611.04
20	12897.4	3848.01
25	9236.9	3919.05*
30	7127.2	3856.10
35	4305.8	3789.34
40	1357.4	2928.96

Note: * indicates highest STV

Table 7.6 shows the stand structure that is associated with the new optimal cutting cycle of 25 years. The expected total timber cut is 137.03 m^3/ha. It can be considered that this volume consists of a non-commercial[4] volume cut in diameter classes where the stumpage price is negative and a commercial volume cut in classes with positive stumpage value. The non-commercial volume to be cut is equal to 32.33 m^3/ha or 23.6% of the total volume cut. Of the total commercial volume, the most commercialized species groups represent 14.52 m^3/ha or 13.9 %. It should be observed that, although diameter classes 4 and 5 of species group 2 do not contribute to the objective function in a positive way, the model still recommends to cut trees in these classes. This can be explained by the need to open the stand for an increase of growth in subsequent cycles. The interest of removing trees in small diameter classes is that the number of trees of higher diameter classes of the same species is at the same time decreased for the future. Thus, there will be more room for growth of valuable species. It appears better to sacrifice younger trees in the least valuable species group to allow growth in the other groups. Thus, it can be said that silvicultural interventions are necessary at the end of each cutting cycle to stimulate growth of remaining trees[5]. Except for species group 2, timber harvest now concentrates on diameter class 10 only. The analyses in the next sections will use only corrected prices and a discount rate of 5%. The cut recommended represents 12.4 m^2/ha of the basal area, which is 31% of the total basal area before harvest. Thus, the constraints on the proportion of basal area allowed for reduction is not binding.

[4] The distinction between commercial and non-commercial volumes is not straight forward because timber from classes with positive values may not be sold although selling will allow to cover all the costs of harvesting.

[5] These silvicultural interventions are entail with costs. The negative prices of removing some trees can be considered as silvicultural costs.

Table 7.6: Stand structure before harvest and harvest for a cutting cycle of 25 years (discount rate of 5%, maximum permitted basal area reduction of 35%, corrected prices)

Diameter class	Species group 1	Species group 2	Species group 3	Species group 4
		Stand structure before cut (trees/ha)		
1	1.46	119.10	54.90	7.22
2	0.86	25.10	15.00	2.51
3	0.59	29.40	6.25	1.07
4	0.46	18.30	3.70	0.55
5	0.36	11.20	2.75	0.31
6	0.32	6.19	2.17	0.21
7	0.29	4.50	1.93	0.14
8	0.28	4.25	1.68	0.11
9	0.36	3.80	1.68	0.09
10	0.57	3.31	3.82	0.33
Total	**5.55**	**251.15**	**93.88**	**12.54**
		Cut (trees/ha)		
1-3	0.00	0.00	0.00	0.00
4	0.00	18.30	0.00	0.00
5	0.00	3.43	0.00	0.00
6-9	0.00	0.00	0.00	0.00
10	0.57	2.31	3.82	0.33
Total	**0.57**	**24.04**	**3.82**	**0.33**

STV: 3,919,050 FCFA	Pre-harvest basal area: 40 m^2/ha
Trees cut: 28.76 trees/ha	Post-harvest basal area: 27.6 m^2/ha
Volume cut: 137.03 m^3/ha	Number of trees after harvest: 335.52 trees/ha
Commercial volume cut: 104.70 m^3/ha	Commercial harvest: 7.03 trees/ha

c) Changing the residual basal area

As mentioned in section a, the analysis until now has been conducted with the restriction to avoid a reduction of more than 35% of the total pre-harvest basal area. In many tropical forestry situations, the basal area has been reduced at higher and/or lower levels either by logging (Sist *et al.*, 1998) or silvicultural treatments or a combination of both (Jonkers, 1987; de Graaf *et al.*, 1998). However, it has been avoided in most cases to reduce the initial basal area by more than 50%. For that reason, it is of interest to study the effects of changing the maximum level of reduction in basal area on the structure of the growing stock as well as the harvest policy. In the following sections, two additional levels of reduction constraints are modeled, these are 25% and 50%.

Table 7.7 shows the results of constraining the basal area removal to the level of 25% of the basal area before harvest. Unlike the results shown in table 7.6 the constraint on basal area reduction has become binding, which means that the growth characteristics of the species groups which constitute the stand can recover from heavier basal area reduction. To adjust for the constraint level of 25% the model has to increase the cut of marketable trees in group 3 and the cut of small trees in group 2 compared to the situation of table 7.6.

Table 7.7: Stand structure before harvest and harvest for a cutting cycle of 25 years (discount rate 5%, maximum permitted basal area reduction of 25%, corrected prices)

Diameter class	Species group 1	Species group 2	Species group 3	Species group 4
		Stand structure before cut (trees/ha)		
1	1.46	119.10	52.80	7.22
2	0.86	52.10	14.00	2.51
3	0.59	29.40	3.80	1.07
4	0.46	18.30	3.43	0.55
5	0.36	11.02	2.55	0.31
6	0.32	5.56	2.01	0.21
7	0.29	3.49	1.79	0.14
8	0.28	3.26	1.55	0.11
9	0.36	2.97	1.56	0.09
10	0.57	4.50	3.54	0.33
Total	**5.55**	**249.70**	**87.03**	**12.54**
		Cut (trees/ha)		
1-3	0.00	0.00	0.00	0.00
4	0.00	18.30	0.00	0.00
5	0.00	6.83	0.00	0.00
6-9	0.00	0.00	0.00	0.00
10	0.57	0.00	3.54	0.33
Total	**0.57**	**25.13**	**3.54**	**0.33**
STV: 3,335,590 FCFA		Pre-harvest basal area: 40 m^2/ha		
Trees cut: 29.57 trees/ha		Post-harvest basal area: 30 m^2/ha		
Volume cut: 106.7 m^3/ha		Number of trees after cut: 325.25 trees/ha		
Commercial volume cut: 66.6 m^3/ha		Commercial harvest: 4.44 trees/ha		

The model so avoids any harvest reduction in the most valuable groups (1 and 4), but can not avoid a lower STV because of the higher cost of the cut of small trees of group 2 and less marketable trees of group 3.

When the permitted basal area reduction is increased to 50%, the model gives exactly the same outcomes as in table 7.6, reinforcing the idea that it is not necessary to reduce the basal area before harvest by more than 31% because the forest cannot recover such a removal within 25 years and thus such a harvest cannot be sustained.

d) Including logging damage on residual stand

Until now the model has included only growth and mortality for stand structure projections. In a production forest where logging occurs with heavy equipment, an important factor that affects the number of trees in a stand is the damage inflicted upon the residual stand by logging operations. At the TCP research site a study conducted on logging damage shows that on average 1.8 trees are destroyed per hectare logged (van Leersum, 1998) for a harvesting intensity of about 10 m^3/ha. This figure corresponds to 0.18 trees per m^3 harvested. Logging damage can be recognized in this model by including a new column vector D with elements d_{ij} representing the number of trees damaged in diameter class i for species group j. Such a vector can be included in equation 4.13 to give equation 7.6 as follows:

$$Y = G^{k\theta}(Y - H - D) + \sum_{p=0}^{k\theta-1} G^p I \tag{7.6}$$

Because the damaged trees do not contribute to the objective function but rather tend to reduce it, the model may set the number of these trees equal to zero for all diameter classes and all species groups if there is no constraint. An additional constraint which binds the system to recognize the damage should be included. Such a constraint can be written as:

$$\sum_i \sum_j d_{ij} \geq \delta \sum_i \sum_j h_{ij} v_{ij} \tag{7.7}$$

d_{ij} = number of damaged trees of diameter class i and species group j
v_{ij} = volume of a tree in diameter class i and of species group j
δ = number of trees damaged per unit volume harvested

Another tendency expected from an optimization technique in this situation is to include damage on only the species group that contributes less to the objective function, meaning species group with lowest stumpage prices. In reality, trees of all species groups are damaged by logging operations irrespective of their commercial value. However, it appears logical to assume that the number of trees damaged in each species group is a function of the total number of trees of that species group in the stand. The formulation of a constraint that includes this function is difficult because it requires that variables be used as denominators in proportions, thus making the constraint non-linear. To overcome that, it is possible to rather use the ingrowth because it obviously has a strong link with the number of trees found in the stand for each group. Let λ_j be the ratio of the average ingrowth of species group j to the total ingrowth, equation 7.8 formulated below divides the damage on residual stand between all the species groups proportionally to the ingrowth. It is also logical to assume that the damage to smaller trees is more substantial than to bigger trees (Jonkers, 1987). This fact is recognized by setting damage to trees of a given diameter class at most as important as the damage to the preceding diameter class (Equation 7.9).

$$\sum_j d_{ij} \geq \lambda_j \sum_j \sum_i d_{ij} \tag{7.8}$$

$$d_{ij} \geq d_{(i+1)j} \tag{7.9}$$

The result of including modifications related to the logging damage on the residual stand in the model for different cutting cycles is shown in tables 7.8 and 7.9. Including logging damage results in lengthening the cutting cycle from 25 to 30 years. Compared to the previous optimal cutting cycle of 25 years with the same permitted basal area removal of 35%

(Table 7.6), the STV has decreased by about 14% due to logging damage. Table 7.9 shows the structure of the pre-harvest stand which is associated which the 30-year cutting cycle. The 30-year cutting cycle appears to be the one which is to be chosen for timber production because ignoring logging damage is unrealistic. Lengthening of the cutting cycle is profitable because also young trees with a high commercial value are damaged. This means that a damaged stand needs more time to produce the same value as a less damaged stand. Table 7.9 shows, however, that a deviation of five years from the optimum cutting cycle does not have a substantial influence on STV.

Table 7.8: Cutting cycle and the STV (1000 FCFA) at 5% discount rate and maximum permitted basal area reduction of 35%, with corrected prices and logging damage

Cutting cycle (years)	STV (1000 FCFA)
10	2952.50
15	3155.02
20	3314.76
25	3335.59
30	*3360.39
35	3296.56
40	3202.72

Note: * indicates the highest STV

e) Incorporating costs of management planning

In the previous sections, the analysis has recognized only the costs related to logging operations. However, there are costs such as management planning costs or the costs of silvicultural interventions, which can be included in forest management practices especially as it relates with the quest of sustainability. In Africa, silvicultural interventions have been confined to research situations and costs and gains of such interventions are still unknown. For these reasons, silvicultural costs - except those resulting from the cut of trees with a negative stumpage price - and gains are not incorporated in the current analysis.

However, management planning is now widely accepted as a requirement for sustainability. For example, the criteria and indicators for sustainable forest management of ITTO consider the existence of a forest management plan as one of the key indicators of sustainable forest management practices (ITTO, 1998).

Similarly, the Forest Stewardship Council (FSC), which has developed criteria and indicators for forest certification, as well as the African Timber Organization (ATO) in its set of criteria and indicators for sustainable forest management, have included a forest management plan as a criterion or an indicator of sustainable forest management. In Cameroon, a panel of experts who conducted the CIFOR test of criteria and indicators for sustainable forest management also identified the forest management plan as a criterion for sustainable forest management (Prabhu *et al.*, 1998). The current forestry law in Cameroon makes it mandatory to draw a management plan for every forest concession. The plan should be written twice, at the beginning of the cycle and in the middle. The costs of drawing a management plan in the

Cameroon context were estimated recently to amount to 2,800 CFA/ha (Durrieu de Madron *et al.*, 1998). For a cutting cycle of 30 years, these costs will be due at year 0 and at year 15. This can be included in the objective function shown in equation 4.15 with *t* given the value 0 and 15.

Table 7.9: Steady state stand structure before harvest and harvest for a cutting cycle of 30 years (discount rate of 5%, maximum permitted basal area reduction of 35% with corrected prices and logging damage)

Diameter class	Species group 1	Species group 2	Species group 3	Species group 4
		Stand structure before cut (trees/ha)		
1	1.43	117.50	50.60	6.64
2	0.80	49.70	12.62	2.14
3	0.51	26.55	5.33	0.87
4	0.37	15.92	3.04	0.45
5	0.29	10.21	2.23	0.26
6	0.27	6.80	1.78	0.17
7	0.25	5.49	1.54	0.12
8	0.23	5.19	1.42	0.09
9	0.30	4.63	1.39	0.07
10	0.53	3.21	3.58	0.30
Total	**4.98**	**245.20**	**83.53**	**11.11**
		Damage (trees/ha)		
1	0.62	7.28	10.10	1.32
2	0.00	7.28	0.00	0.00
3	0.00	7.28	0.00	0.00
4	0.00	7.28	0.00	0.00
Total	**0.62**	**29.12**	**10.10**	**1.32**
		Cut (trees/ha)		
1-3	0.00	0.00	0.00	0.00
4	0.00	3.80	0.00	0.00
5-9	0.00	0.00	0.00	0.00
10	0.53	3.21	3.58	0.30
Total	**0.53**	**7.01**	**3.58**	**0.30**

STV: 3,360,390 FCFA	Pre-harvest basal area: 40 m^2/ha
Trees cut: 11.42 trees/ha	Post-harvest basal area: 27.44 m^2/ha
Volume cut: 117 m^3/ha	Number of trees after cut: 292.17 trees/ha
Commercial volume: 111.5 m^3/ha	Commercial harvest: 7.62 trees/ha

Incorporating the costs of management planning in the analysis resulted in a decline of the STV from 3,360,390 FCFA to 3,355,014 FCFA which represents a decline of 0.16%. However, including these costs into the model has not led to a change in the cutting cycle or the stand structure. This is certainly because the costs of management planning are relatively small.

7.3 Constraining TROPFOMS for alternative forest management objectives

The outcomes shown in the preceding section relate to one management objective which is the economic efficiency in industrial timber production. The constraints are formulated to achieve sustained yield of timber production and to recognize technical limitations. In this section, constraints are formulated to include the other management objectives, that are nature conservation and improvement of living conditions for the local population.

7.3.1 Including constraints for species-size diversity

In production forests, income generation through sustained timber production is an important objective. However, in the framework of multiple objectives, an additional concern may be to include nature conservation. As already discussed in section 2.3.5a, two aspects of biological diversity are considered in this research: species diversity and size diversity. Species diversity refers here to the number of species groups represented in the steady state growing stock while size diversity relates to the number of trees in each diameter class of each species group.

One way to measure diversity in both senses is the smallest number of trees left in each species-size class in the steady state growing stock. For example, for the steady state growing stock of table 7.7 the smallest number of trees in any species-size class is 0.09 before harvest while in table 7.9 this number is 0.07. Let the smallest number of trees in the least represented species-size class be called μ. In all the steady state optimal solutions provided by TROPFOMS until now the highest value of μ is 0.01. The value 0.01 means that all the species-size classes will only be represented with one tree within an area of 100 hectares. A constraint can be included to look for a solution where all the species-size classes are represented with at least one tree within an area of 10 hectares (μ=0.1) or within an area of 1 hectare (μ=1) after harvest. Such a constraint is simply formulated as:

$$y_{ij} - h_{ij} \geq \mu \qquad (7.10)$$

μ takes the value of 0.1 or 1 as needed. The outcomes of running TROPFOMS after setting μ=0.01, 0.05, 0.1 alternatively are shown in table 7.10.

It appears to be impossible to have a steady state with all species groups represented in all diameter classes after harvest in an area of 10 ha. However it is possible to arrive at such a representation starting from an area of 50 ha. The 30-year cutting cycle is still the best one, but the STV has decreased from 3,360,390 FCFA in table 7.9 to 3,335,970 FCFA and 3,238,270 FCFA for the levels of diversity of 0.01 and 0.05 respectively. The relative decreases are 0.7% and 3.6% for both levels. These results could already be foreseen from those of table 7.9, because before harvest all size classes had at least 0.07 trees. By only reducing the harvest in class 10 for different groups the required results can be obtained easily for the levels of 0.01 and 0.07, but not for 0.1. Table 7.11 shows the structure of the stand at 30 years under the constraint of 0.05 trees to be left at least in each size-species class.

Table 7.10: Effect of the diversity constraint on the cutting cycle and the STV (discount rate of 5%, maximum permitted basal area reduction of 35%, corrected prices, damage included)

Cutting cycle (years)	μ =0.01	μ =0.05	μ =0.1
		STV/ha (1000 FCFA)	
10	2935.42	2867.00	Infeasible
15	3136.16	3059.00	Infeasible
20	3295.53	3218.58	Infeasible
25	3313.76	3226.43	Infeasible
30	3335.97*	3238.27*	Infeasible
35	3323.30	3180.24	Infeasible
40	2679.33	2577.07	Infeasible

Note: * denotes highest STV

Table 7.11: Steady state stand structure before harvest and cut for a cutting cycle of 30 years (discount rate 5%, maximum permitted basal area reduction of 35%, minimal 0.05 trees per species-size class, corrected prices, damage included).

Diameter class	Species group 1	Species group 2	Species group 3	Species group 4
		Stand structure before harvest (trees/ha)		
1	1.43	117.50	50.60	6.63
2	0.80	49.70	12.61	2.14
3	0.51	26.53	5.32	0.86
4	0.37	15.89	3.03	0.45
5	0.29	10.17	2.23	0.26
6	0.27	6.75	1.77	0.17
7	0.25	5.44	1.54	0.12
8	0.23	5.14	1.42	0.09
9	0.30	4.59	1.39	0.07
10	0.56	3.20	3.61	0.34
Total	**5.01**	**244.91**	**83.52**	**11.13**
		Cut (trees/ha)		
1-3	0.00	0.00	0.00	0.00
4	0.00	3.80	0.00	0.00
5-9	0.00	0.00	0.00	0.00
10	0.51	3.15	3.56	0.30
Total	**0.51**	**6.95**	**3.56**	**0.30**

STV: 3,311,140 FCFA	Pre-harvest basal area: 40 m^2/ha
Trees harvested: 11.31 trees/ha	Post-harvest basal area: 27.71 m^2/ha
Volume cut: 116 m^3/ha	Number of trees after harvest: 295.04 trees/ha
Commercial volume cut: 109.77 m^3/ha	Commercial harvest: 7.52 trees/ha

7.3.2 Restrictions related to the local population

As mentioned in the introductory statement of this chapter, one management objective often associated with tropical forest management is the improvement of the living conditions of the population living nearby the forest being managed. One aspect of this management objective is to guarantee the continued supply of non-timber forests products (NTFPs) for the population. A special interest is devoted to tree species that are of interest for both the local populations and the logging company. Management may wish to be ensured that these species are not used only for logging but that enough stems are maintained for the supply of NTFPs. Such a concern can lead to a ban of a certain proportion of trees of these species from logging activities. Let τ_j be the proportion of critical trees of a given species that management intends to cut. All the trees of these species represent a proportion Γ_j of a species group; τ_j is a proportion of Γ_j. For each diameter class eligible for cutting a new harvest amount $h_{ij}^{'}$ can be defined as:

$$h_{ij}^{'} \leq (1-(\Gamma_j - \Gamma_j * \tau_j))h_{ij} \tag{7.11}$$

Table 7.12: Steady state stand structure before harvest and harvest for a cutting cycle of 30 years (discount rate 5%, maximum permitted basal area reduction of 35%, corrected prices, logging damage included and a ban on logging of all NTFP trees)

Diameter class	Species group 1	Species group 2	Species group 3	Species group 4
		Stand structure before harvest (trees/ha)		
1	1.43	117.50	50.60	6.64
2	0.80	49.70	12.62	2.14
3	0.51	26.55	5.33	0.87
4	0.37	15.92	3.04	0.45
5	0.29	10.21	2.23	0.26
6	0.27	6.80	1.78	0.17
7	0.25	5.49	1.54	0.12
8	0.23	5.19	1.42	0.09
9	0.30	4.63	1.39	0.07
10	0.53	3.21	3.58	0.30
Total	**4.98**	**245.20**	**83.53**	**11.11**
		Cut (trees/ha)		
1-3	0.00	0.00	0.00	0.00
4	0.00	3.80	0.00	0.00
5-9	0.00	0.00	0.00	0.00
10	0.50	2.99	3.34	0.29
Total	**0.50**	**6.79**	**3.34**	**0.29**

STV: 3,200,560 FCFA	Pre-harvest basal area: 40 m^2/ha
Trees cut: 10.92 trees/ha	Post-harvest basal area: 28.06 m^2/ha
Volume cut: 110 m^3/ha	Number of trees after cut: 292.67 trees/ha
Commercial volume cut: 104.5 m^3/ha	Commercial harvest: 7.12 trees/ha

The *STV* based on h_{ij}, can now be calculated and the result of a run with these additional constraints gives the new cutting strategy and the *STV* associated with it. In section 6.4, the results of the forest inventory are presented, and for all species groups Γ_j = 6.7%. The model can be run for different values of τ_j. In this case τ_j is assigned two successive arbitrary values, 0% meaning that all the trees should be exempted from logging and 50% meaning that half of the NTFP trees can be harvested.

The decision to preserve all trees of NTFP species from timber harvesting and to maintain them for the sole production of NTFPs leads to a decrease in the STV from 3,360,390 FCFA in table 7.9 to 3,135,244 FCFA, which in relative terms represents a decline of 6.7%. On the other hand, a restriction to harvest only 50% of NTFP trees leads to a decrease in STV from 3,360,390 FCFA to 3,243,112 FCFA or 3.5% in relative terms. The associated steady state stand structures are given in tables 7.12 and 7.13.

Table 7.13: Steady state stand structure before harvest and harvest for a cutting cycle of 30 years (discount rate 5%, maximum permitted basal area reduction of 35%, corrected prices logging damage included and a harvesting limit of 50% on NTFP trees)

Diameter class	Species group 1	Species group 2	Species group 3	Species group 4
		Stand structure before cut (trees/ha)		
1	1.43	117.50	50.60	6.64
2	0.80	49.70	12.62	2.14
3	0.51	26.55	5.33	0.87
4	0.37	15.92	3.04	0.45
5	0.29	10.21	2.23	0.26
6	0.27	6.80	1.78	0.17
7	0.25	5.49	1.54	0.12
8	0.23	5.19	1.42	0.09
9	0.30	4.63	1.39	0.07
10	0.53	3.21	3.58	0.30
Total	**4.98**	**245.20**	**83.53**	**11.11**
		Damage (trees/ha)		
1	0.62	7.28	10.10	1.32
2	0.00	7.28	0.00	0.00
3	0.00	7.28	0.00	0.00
4	0.00	7.28	0.00	0.00
Total	**0.62**	**29.12**	**10.10**	**1.32**
		Cut (trees/ha)		
4	0.00	3.80	0.00	0.00
5-9	0.00	0.00	0.00	0.00
10	0.52	3.09	3.46	0.30
Total	**0.52**	**6.89**	**3.46**	**0.30**

STV: 3,313,760 FCFA	Pre-harvest basal area: 40 m^2/ha
Trees cut: 11.17 trees/ha	Post-harvest basal area: 27.75 m^2/ha
Volume cut: 113 m^3/ha	Number of trees after cut: 292.42 trees/ha
Commercial volume cut: 107.5 m^3/ha	Commercial harvest: 7.37 trees/ha

7.4 Conclusions on the steady state characteristics

One specific objective of this research is to assess the effects of different management options on the financial returns of the logging enterprise as well as the structure of the forest. This objective has been addressed in section 7.2 and 7.3 above. In this section, the intention is to put emphasis on the management options selected by TROPFOMS and to compare them with results obtained elsewhere. Further discussion of these results is done in chapter 9. In addition, this section addresses the relationships between alternative management objectives according to research objective 3.

7.4.1 Conclusions on the steady state characteristics with alternative management objectives

The outcomes presented in section 7.2 show that the cutting cycle to retain is 30 years if the objective of management is the maximization of financial returns from timber harvesting. The related steady state structure is the one of table 7.9. Although a further discussion of the results is done later in chapter 9 which is devoted to reflections, it can already be said that such a cutting cycle is within the wide range of those already proposed in many cases for tropical forests. In fact, a variety of cutting cycles has been used or suggested in the management of tropical forests ranging from 15 years to 80 years.
In Cameroon, suggestions have been done to adopt a minimum cutting cycle of 25 years (MINEF, 1997) or 30 years (ONADEF, 1998). The values already used in some management plans undergoing implementation include 20 years in the So'o Lala (Mbolo, 1996), 30 years in the South Bakundu and 40 years in the Lokoundje Nyong (Poulin Theriault Inc., 1998) production forests. In some cases, the cutting cycles were estimated by simulations of growth as the time needed to reconstitute the initial forests and to allow the harvest of a constant crop over the cycles.

Elsewhere in Africa, simulations have been made for cutting cycles of 40 and 80 years in Uganda (Neil, 1981). Ghana adopted a cutting cycle of 25 years during the 1950s and 1960s, in the 1970s it was reduced to 15 years and it is now up to 40 years (Neil, 1981; Nolan and Ghartey, 1992). The efforts did not include targeting a different and better structure for forest stands as is the case with TROPFOMS. In other cases the choices were more based on literature and expert judgment.

On other tropical continents, examples of adopted cutting cycles used for production forest are 35 years in Indonesia (Sist *et al.*, 1998), 40 years in Trinidad (Bell, 1972; Dawkins and Philip, 1998) and 25 years in Brazil (de Camino, 1998).

The cutting cycle alone does not say much about the sustainability of a management option. It should be combined with the level of harvest and harvest regulations to be able to take into account a more complete array of aspects. The target steady state stand structure proposed by TROPFOMS for this objective is the one of table 7.9. It involves a cut of 11.42 trees/ha once the forest will be fully regulated. However, not all trees of all species groups are commercialized (See section 6.1.1 for the description of species groups and their respective commercial status). The most commercialized species under current market conditions are those of group 1 and 4, of which the cut amounts to 0.83 trees /ha. Therefore, it can be anticipated that only part of the 11.42 trees will be cut through logging, the remaining should be eliminated by silviculture to make more space for growth.

The trees to be cut represent a volume of 117 m^3/ha or a mean annual increment of 3.9 m^3/ha and a reduction of a basal area of 12.54 m^2/ha which accounts both for tree removal and logging damage. These harvest statistics may seem high at first view as compared to some values observed in tropical forests. In fact, Bedel *et al.* (1998) have reported volume increments of 0.9 m^3/ha/year in control plots in the M'Baiki forest in the Central African Republic. These increments moved up to 2 m^3/ha/year after logging and 2.8 m^3/ha/year when both logging and thinning took place. Logging involved a harvest of 4 trees/ha and the combination of both logging and thinning removed 8.8 m^2/ha. Comparable increments have been observed in Côte d'Ivoire namely 2.9 m^3/ha/year in the Irobo Forest Reserve 12 years after thinning at the intensity of 6 m^2/ha (Durrieu de Madron *et al.*, 1998).

However, much depends on the number of species concerned. The studies of the Central African Republic and Côte d'Ivoire concentrated on the currently commercialized species only. Experiences gathered in other tropical countries show higher figures as a greater proportion of the species is harvested. For example in Brazil, it is estimated that a volume increment of 5.2 m^3/ha/year for commercial species will be reached once the forest will be fully regulated (de Camino, 1998). Such a forest may be reached after 75 to 100 years from now. In Nigeria, Lowe (1997) reported mean annual increments ranging from 5 to 6 m^3/ha in natural forests in which logging had occurred ten years ago but no silvicultural treatments were carried out. Trees of all species from five centimeters and up were taken into account in the study in Nigerian forests. De Graaf *et al.* (in press) have observed a periodic volume increment of 14 m^3/ha/year for all species five years after silvicultural treatments had been conducted in Suriname. During the next five years this increment decreased to 6 m^3/ha/year, leading to an average of about 10 m^3/ha/year for the period of 10 years after the treatments.
The value of 117 m^3/ha expected in the model outcomes of table 7.9 can be separated in two: the currently most commercialized species and those which are commercialized less regularly. Such a separation gives a volume of 13.41 m^3/ha for the most commercialized species groups (1 and 4) and 103.59 m^3/ha for the remaining species. Therefore the PAI (See section 4.2 for definition) is 0.45 m^3/ha/year for the most commercialized species and 3.45 for the others. All this shows that, although the growth data used by TROPFOMS had some imperfections, the outcomes of TROPFOMS fit with other observations throughout the tropical region. Harvests, in numbers of trees, have in some cases been more important as is the case in some regions of Indonesia where harvest amounts up to 17 trees/ha (Sist *et al.*, 1998), but it is not sure whether such a harvest leads towards sustainability especially if the forest is still in its conversion phase.

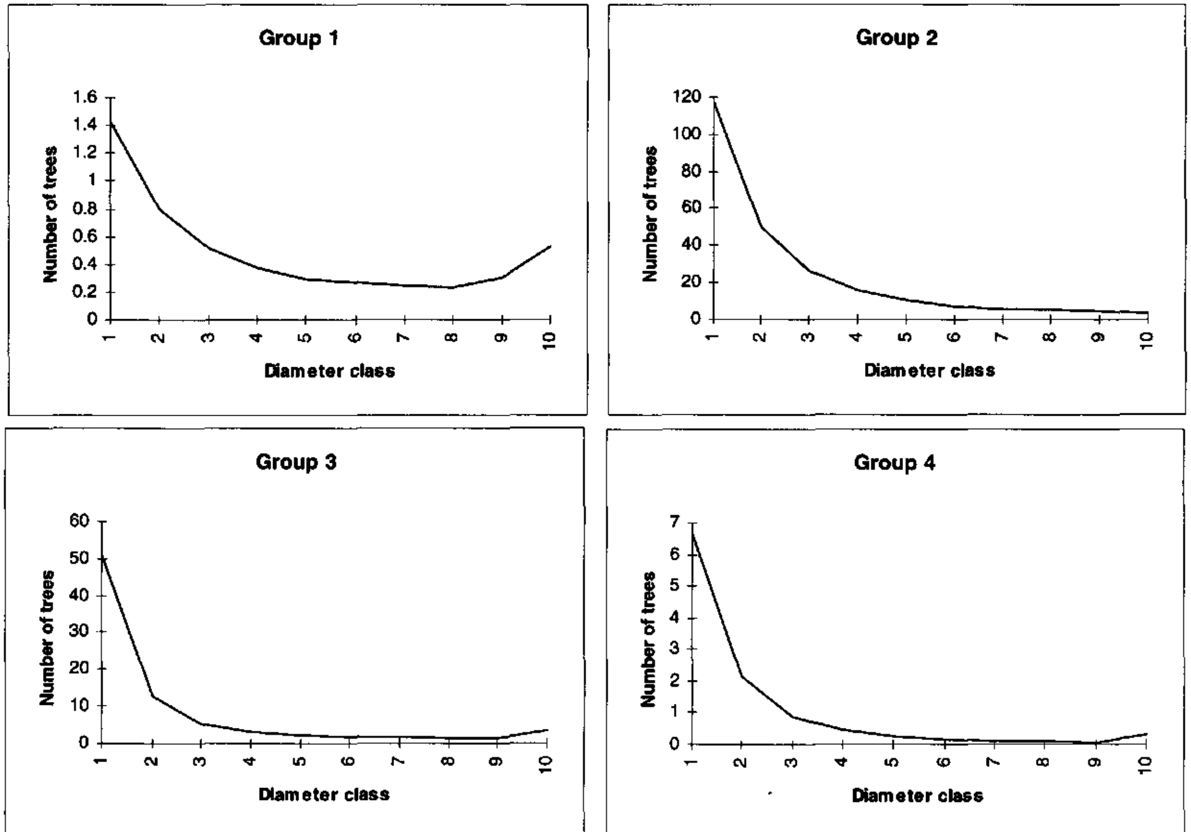

Figure 7.1: Steady state diameter class distribution for different species groups before harvest (discount rate 5%, corrected prices, logging damage included and maximum permitted basal area reduction of 35%)

As for the harvest regulations, the outcomes suggest that the harvest should concentrate on the big trees. The outcomes shown in table 7.9 restrict cut mostly to diameter class 10, except for species group 2 for which it is advised to harvest trees in a smaller diameter but only to allow space for growing as the trees removed there have no commercial value. This means that current diameter limits used in Cameroon should be raised for species groups 1, 3 and 4. Such a raise is rather conservative but may improve the value of the target structure to be reached. The structure of the steady state forest is shown in Figure 7.1. From this Figure it can be seen that the diameter class distribution of all species has in general a reverse J shape. Such a forest is often referred to as a well-balanced forests. The shape of the curves in Figure 7.1 contribute to the opinion that the outcome of TROPFOMS leads forest management towards sustainability. The curves tend to raise again towards the end because diameter class 10 is an open class. Similar shapes have been encountered in other cases of uneven-aged forest management (Buongiorno *et al.*, 1995).

The combination of the objectives nature conservation through species-size diversity up to the level of full representation of all diameter classes within 50 ha has not changed the cutting cycle, nor did the inclusion of a restriction with respect to harvesting of NTFPs.

7.4.2 Trade off between management objectives

An important objective of this research is to assess the trade off between timber production and other management objectives (specific research objective three mentioned in chapter 3) which in this case are mainly biological diversity and the production of NTFPs. Table 7.14

Table 7.14: Characteristics of steady state forest associated with alternative management options.

	Management objectives				
	SY	SY + C100	SY + C50	SY + NTFP50	SY + NTFP100
Cutting cycle (years)	30.00	30.00	30.00	30.00	30.00
Number of trees/ha after harvest	292.17	293.14	295.04	292.42	292.70
Cut (trees / ha)	11.42	11.39	11.31	11.17	10.92
N_{min} before harvest	0.07	0.07	0.07	0.07	0.07
N_{min} after harvest	0	0.01	0.05	0	0
STV (1000 FCFA)	3360.39	3335.97	3238.27	3243.11	3135.24

Note: SY = sustained yield (Table 7.9),
SY + C100 = sustained yield and a minimum of 0.01 trees left in each diameter class and for all species groups after cutting,
SY + C50 = sustained yield and a minimum of 0.05 trees left in each diameter class and for all species groups after cutting (Table 7.11)
SY + NTFP50 = sustained yield and logging ban on 50% of the NTFP trees (Table 7.13)
SY + NTFP100 = sustained yield and a logging ban on all NTFP trees (Table 7.12)
N_{min} = minimum number of trees in any species-size class

recapitulates steady state characteristics associated with different management options. In general, the objectives are more or less compatible for the analyzed levels. The deviations of the STV are less than 10%. The most important deviation comes from banning logging of all NTFP trees which reduces the STV by 6.7%. It should be observed that this proportion is equal to the proportion of NTFP trees inventoried in the forest. Therefore, one would expect that forests that are more rich in NTFP trees will have a higher reduction in logging benefits.

Chapter 8

The outcomes of TROPFOMS for the conversion of the Tropenbos Cameroon research site

In the preceding chapter, the effect of management options on the steady state characteristics of the forest were presented and the trade off between alternative forest management objectives were discussed in accordance with research objectives two and three. It should be emphasized that the characteristics of the forest stands mentioned in chapter 7 constitute a target which would be achieved once the forest is fully regulated. The harvest, the stand structure and the revenues shown there cannot be obtained now, but are possible in the future, provided that the forest undergoes conversion and its structure is progressively transformed.

This chapter addresses research objective 4 and studies the conversion of the forest at the Tropenbos Cameroon research site. It deals with the management options of the current forest which can lead to approaching the steady state as characterized in chapter 7. Insights into the conversion period are very important because the target steady state is an ideal situation which can hardly be reached, but this state gives direction to management practices during the conversion period, that is, the present and near future.

The questions of interest in this chapter are: what actions are needed to convert a stand, how long should the conversion period be and what financial returns can be expected from the forest during conversion? These questions have been addressed for the cutting cycle of 30 years with the steady state structure of table 7.9, which was found to be optimal for timber production. In general, the design of a conversion strategy requires a comparison between the current stand structure and the target steady state structure. If the current structure has more trees in any given species-size class, then the target structure can be achieved immediately by removing all trees in excess by harvest and/or silvicultural operations. Otherwise the conversion takes the time necessary to guide the forest towards the target structure by harvesting and/or silvicultural operations. It should be noted that no attempt was made to search for optimal characteristics of the conversion period. This was adopted to avoid problems related with the linearity assumption of LP as mentioned in section 2.3.3. The approach adopted consists of applying the new harvest rules defined with the desired steady state repeatedly over an indefinite time period and approaching the desired steady state gradually.

8.1 Management actions during the conversion period

Table 8.1 provides a comparison between characteristics of the current average stand, and characteristics of the steady state stand before and after harvest. The table shows that with a

Table 8.1: Comparison between current stand characteristics at the TCP research site and the steady state stand before harvest

Diameter class	Steady state stand structure before harvest (trees/ha)				Current average stand structure at the TCP research site (trees/ha)			
	Species group 1	Species group 2	Species group 3	Species group 4	Species group 1	Species group 2	Species group 3	Species group 4
1	1.43	117.50	50.60	6.64	3.1	171.1	107.8	6.7
2	0.80	49.70	12.62	2.14	1.2	51.4	36.6	1.4
3	0.51	26.55	5.33	0.87	0.3	24.4	13.0	0.3
4	0.37	15.92	3.04	0.45	0.1	9.6	7.2	0.2
5	0.29	10.21	2.23	0.26	0.2	4.2	5.6	0.3
6	0.27	6.80	1.78	0.17	0.1	2.9	3.7	0.2
7	0.25	5.49	1.54	0.12	0.1	2.4	2.0	0
8	0.23	5.19	1.42	0.09	0.1	0.8	1.1	0.1
9	0.30	4.63	1.39	0.07	0.0	0.6	1.1	0
10	0.53	3.21	3.58	0.30	0.0	2.6	4.4	0.1
Trees/ha	4.98	245.20	83.53	11.11	5.2	270	182.2	9.3
BA/ha (m^2)	1.44	27.01	10.54	1.02	0.34	16.65	16.44	0.57
Total number of trees: 344.82 trees/ha					Total number of trees: 466.7 trees/ha			
Total BA (basal area): 40 m^2/ha					Total BA (basal area): 33.98 m^2/ha			

Source: Bibani (1996)

basal area of 33.98 m^2/ha, the actual stand has not reached the maximum basal area before harvest (40 m^2 /ha). Instead, it is at an intermediary state between the level to be left after harvest at steady state (27.44 m^2 /ha) and the level before harvest. However, the number of trees in the current forest (466.70 trees/ha) is greater than the one desired at steady state before harvest (344.82 trees/ha), which means that on average trees are smaller in the current forest than they would be in the desired steady state stand.

A comparison of characteristics of different species groups also shows important differences. Concerning the basal area, the current values are inferior to those of the steady state before harvest except for group 3. However, things are considerably different for the number of trees: all groups in the current stand have more trees than in the target steady state structure except for group 4, the most valuable. It can also be remarked that groups 1 and 4 have particularly low numbers of trees in diameter class 10, perhaps due to past timber exploitation which focused especially on these two groups.

Figure 8.1 shows a comparison between the current stand structure and the structure targeted at steady state after harvest and logging damage. It should be noted that the steady state distribution shown in Figure 8.1 concerns the same stand as in Figure 7.1. However, the shape of the curves are modified by the inclusion of the effects of harvest and damage. Harvest, which is affecting the largest diameter class has given a downward trend to the curve at the right end, while damage has brought modifications mostly at the left end of the curve.

The general course of action to be taken in the current forest is to bring the stocking of the current stand down to the level of a steady state stand after harvest if possible. This means removing trees in diameter classes where the curve of the current stand is above the curve of the steady state. However, trees cannot be added in diameter classes for which the curve of the current stand is below the one of the steady state. This can only be done by regeneration and growth in the course of time. Using this approach it is apparent that for all species groups, there are trees in excess in diameter classes 1 and 2. This suggests that trees should be removed in smaller diameter classes for all species groups. However, species group 3 is the one which presents the most important excess in small trees. Table 8.2 gives a detailed numerical account of the numbers of trees to be removed in each diameter class at the beginning of the conversion period. It shows that if the rule is followed rigorously about 200 trees/ha should be removed at the beginning of the conversion period representing a basal area of 17 m^2/ha. However, only a maximum of 7.1 trees/ha in class 10 will be considered for logging. The remaining will be removed either by logging damage or by silvicultural operations. Moreover, if the commercial interest is mostly on species group 1 and 4 as it is currently, only 0.1 trees/ha may be removed by logging.

8.2 Simulations of the duration of the conversion period

The simulations done here aim at making projections of the evolution of the current forest stand in the future. This allows monitoring the successive changes in the structure of the

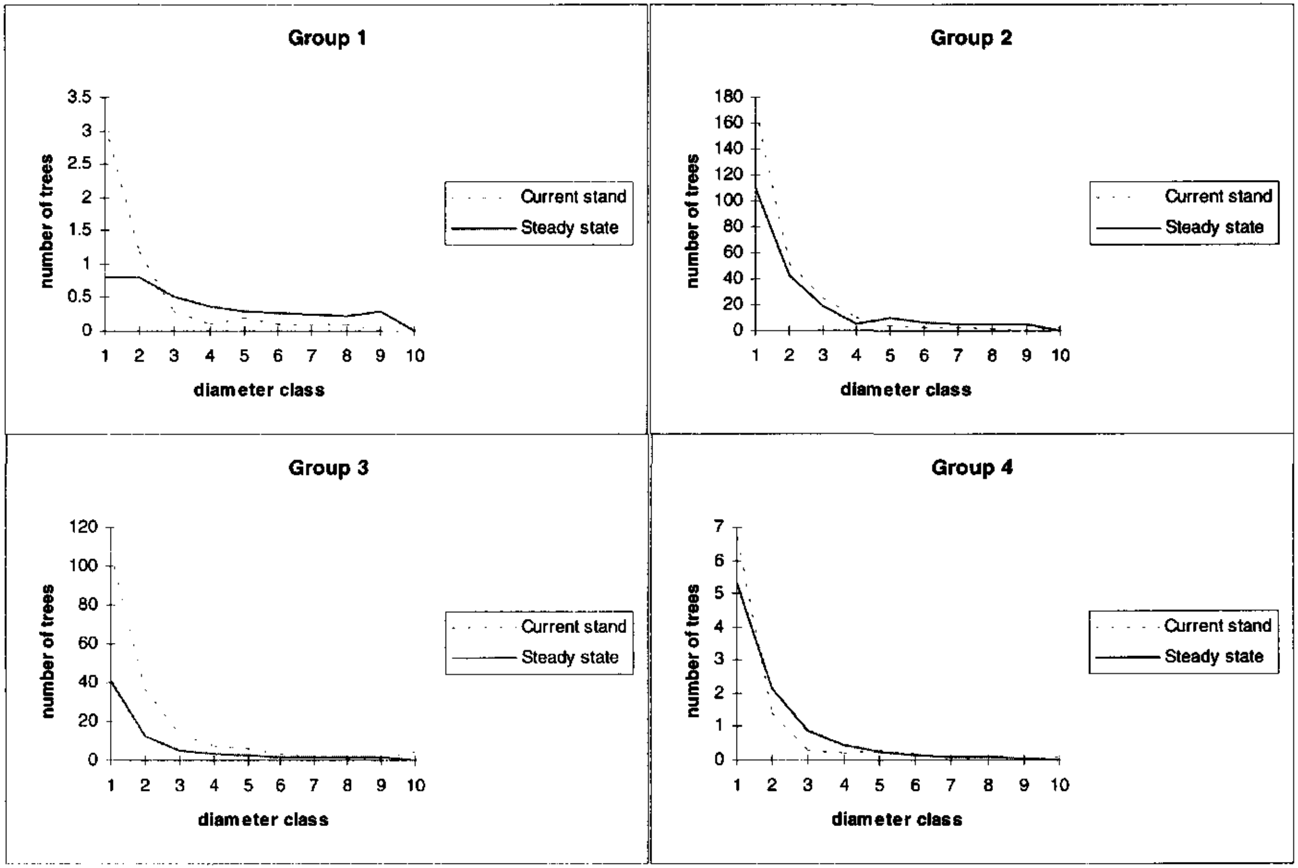

Figure 8.1: Comparison between diameter class distributions of the current and the steady state stands (after harvest) for different species groups

Table 8.2: Numbers of trees to be cut per species group and diameter class at the beginning of the conversion period

Diameter class	Species group 1	Species group 2	Species group 3	Species group 4
1	2.29	60.88	67.3	1.38
2	0.40	8.98	23.98	0.00
3	0.00	5.13	7.67	0.00
4	0.00	4.76	4.16	0.00
5	0.00	0.00	3.37	0.00
6	0.00	0.00	1.92	0.00
7	0.00	0.00	0.46	0.00
8	0.00	0.00	0.00	0.01
9	0.00	0.00	0.00	0.00
10	0.00	2.6	4.40	0.10
Total	2.69	82.35	113.26	1.49
Trees to be cut: 199.79 trees/ha		Basal area to be cut: 17 m^2/ha		

forest stand under management from one cutting cycle to the next one, until it is similar to the desired target structure. The general approach for the simulation of the conversion period explained in the introductory remarks of this chapter is followed. The structure of the forest 30 years later is found by computing equation 8.1

$$Y_{j,30} = G^6 Y_{j,0} + \sum_{k=0}^{5} G^k I_j \tag{8.1}$$

Where:

$Y_{j,30}$ = column vector of the number of trees of species group j expected 30 years from the beginning of the conversion period

$Y_{j,0}$ = a column vector of the number of trees left for species group j after harvest, damage and treatment at the beginning of the conversion period[6]

G = the growth matrix

I_j = the average ingrowth for species group j

Similarly, the structure of the stand can be projected for 60, 90, 120 years as shown in equation 8.2.

$$Y_{j,30q} = G^6 Y_{j,(30q-30)} + \sum_{k=0}^{5} G^k I_j \tag{8.2}$$

[6] The vector of stand structure at the beginning of the conversion period is estimated by subtracting from the current average stand at the TCP research site all trees in excess to the steady state stand structure. The steady state stand structure is the one shown in tables 7.9 and 8.1 in which cut and damage are subtracted.

Where: q = a positive integer designating the number of cutting cycles for which the projected stand structure is estimated.

Tables 8.3 to 8.7 show the evolution of simulated stand characteristics after 30, 60, 90, 120 and 150 years. The assumption is that trees are removed as indicated in table 8.2. Therefore, the stand had 266.91 trees/ha and about 17 m^2/ha after cutting trees at the beginning. Thirty years later, the stand has gained 12.22 m^2/ha of basal area and 64.42 trees/ha (Table 8.3). Given that harvest will be concentrated on diameter class 10 only, the maximum harvest of timber has decreased from 7.1 trees/ha at year 0 to 4.1 trees/ha. However, the harvest in most valuable species groups (1 and 4) has gone up from 0.1 trees at the beginning to 0.36 trees/ha at year 30. From year 30 to year 60, the basal area before harvest has again increased by 3.39 m^2/ha from 29.22 m^2/ha to 32.61 m^2/ha (Table 8.4). During the three cutting cycles from 60 years to 150 years the increase of the basal area before harvest changes positively by 2.49 m^2/ha, 1.03 m^2/ha and 0.30 m^2/ha respectively. These numbers and a closer look at changes in distribution of trees in the diameter classes reveal that the conversion to the steady state structure will take 120 years during which the changes will be made in the forest. The basal area will change from 17 m^2/ha in year 0 to 36.13 m^2/ha in year 120. After 120 years, species group 1, which is the fastest growing (See section 6.1.1), will have reached the steady state structure while the other groups will still be approaching that state. The cut will then be 6.12 trees/ha which is still far from 11.42 at steady state, however, the harvest of the most valuable species will already be 0.76 trees/ha which is closer to 0.83 trees/ha as expected at steady state for these species groups.

The preceding observations show that a complete conversion may take many more cutting cycles. However, the most important part of it is done during the first 120 years. After 120 years the structure of the stand converges gradually and almost asymptotically towards the steady state. The analysis of the conversion period done later will focus on these first 120 years.

8.3 Revenues expected during the conversion period

The calculations of the revenues during the conversion period will include the first 120 years and the estimation will be done using the Net Present Value (NPV). The difference between the STV used in the preceding chapter and the NPV is that, the STV estimates the value of a land devoted to a certain type of forest production indefinitely, while the NPV estimates the value of forest management for a finite time horizon. In the case of this study, the steady state supposes an equilibrium over an infinite number of cutting cycles while the conversion is supposed to take a certain number of cutting cycles. The formula of the NPV is shown in equation 8.3.

$$NPV = \sum \frac{PH_t}{(1+r)^t} - \sum \frac{C_t}{(1+r)^t} \tag{8.3}$$

Table 8.3: Simulated stand structure (trees/ha) before harvest after 30 years and cutting during the first cutting cycle

Diameter class	Species group1		Species group 2		Species group 3		Species group 4	
	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal
1	1.44	0.63	117.59	7.37	50.60	10.10	6.65	1.33
2	0.80	0.00	50.23	7.81	12.66	0.04	2.01	0.00
3	0.51	0.00	27.36	8.09	5.43	0.10	0.71	0.00
4	0.36	0.00	16.49	11.65	3.33	0.29	0.30	0.00
5	0.28	0.00	9.87	0.00	2.68	0.45	0.15	0.00
6	0.22	0.00	5.23	0.00	2.16	0.38	0.08	0.00
7	0.17	0.00	2.91	0.00	1.41	0.00	0.05	0.00
8	0.12	0.00	2.07	0.00	0.91	0.00	0.04	0.00
9	0.13	0.00	1.35	0.00	0.89	0.00	0.04	0.00
10	0.15	0.15	0.63	0.63	3.11	3.11	0.21	0.21
Total	4.18	0.78	233.73	35.55	83.18	18.43	10.24	1.55

Total number of trees before cut: 331.33 trees/ha — Basal area before cut: 29.22 m^2/ha

Total number of trees to be cut: 56.31 trees/ha — Basal area cut: 8.71 m^2/ha

Table 8.4: Simulated stand structure (trees/ha) before harvest after 60 years and cutting during the second cutting cycle

Diameter class	Species group 1		Species group 2		Species group 3		Species group 4	
	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal
1	1.44	0.63	117.59	7.37	50.60	10.10	6.66	1.34
2	0.80	0.00	50.23	7.81	12.66	0.04	2.14	0.00
3	0.51	0.00	27.36	8.09	5.43	0.10	0.86	0.00
4	0.36	0.00	16.49	11.65	3.33	0.29	0.42	0.00
5	0.29	0.00	10.03	0.00	2.68	0.45	0.23	0.00
6	0.26	0.00	5.93	0.00	2.16	0.38	0.13	0.00
7	0.25	0.00	4.36	0.00	1.41	0.00	0.07	0.00
8	0.23	0.00	3.65	0.00	0.91	0.00	0.04	0.00
9	0.25	0.00	2.45	0.00	0.88	0.00	0.03	0.00
10	0.32	0.32	1.25	1.25	2.84	2.84	0.14	0.143
Total	4.71	0.95	239.33	36.17	82.90	14.20	10.71	1.48

Total number of trees before cut: 337.65 trees/ha — Basal area before cut: 32.61 m^2/ha

Total number of trees to be cut: 52.8 trees/ha — Basal area cut: 9.27 m^2/ha

Table 8.5: Simulated stand structure (trees/ha) before harvest after 90 years and cutting during the third cutting cycle

Diameter class	Species group 1		Species group 2		Species group 3		Species group 4	
	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal
1	1.44	0.63	117.59	7.37	50.60	10.10	6.66	1.34
2	0.80	0.00	50.23	7.81	12.66	0.04	2.178	0.00
3	0.51	0.00	27.36	8.09	5.43	0.10	0.91	0.00
4	0.36	0.00	16.49	11.65	3.33	0.29	0.47	0.00
5	0.29	0.00	10.03	0.00	2.68	0.45	0.26	0.00
6	0.26	0.00	5.96	0.00	2.16	0.38	0.15	0.00
7	0.25	0.00	4.56	0.00	1.41	0.00	0.09	0.00
8	0.24	0.00	4.26	0.00	0.91	0.00	0.05	0.00
9	0.29	0.00	3.42	0.00	0.88	0.00	0.04	0.00
10	0.50	0.50	2.06	2.06	2.83	2.83	0.18	0.18
Total	4.94	1.13	241.97	36.98	82.90	14.19	11.00	1.52

Number of trees before cut: 340.81 trees/ha — Basal are before cut: 35.10 m^2/ha

Number of trees cut: 53.82 trees/ha — Basal area cut: 10.52 m^2/ha

Table 8.6: Simulated stand structure (trees/ha) before harvest after 120 years and cutting during the fourth cutting cycle

Diameter class	Species group 1		Species group 2		Species group 3		Species group 4	
	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal
1	1.44	0.63	117.59	7.37	50.60	10.10	6.66	1.34
2	0.80	0.00	50.23	7.81	12.66	0.04	2.19	0.00
3	0.51	0.00	27.36	8.09	5.43	0.10	0.93	0.00
4	0.36	0.00	16.49	11.65	3.33	0.29	0.48	0.00
5	0.29	0.00	10.03	0.00	2.68	0.45	0.28	0.00
6	0.26	0.00	5.97	0.00	2.16	0.38	0.16	0.00
7	0.25	0.00	4.58	0.00	1.41	0.00	0.09	0.00
8	0.24	0.00	4.37	0.00	0.91	0.00	0.05	0.00
9	0.30	0.00	3.80	0.00	0.88	0.00	0.04	0.00
10	0.53	0.53	2.53	2.53	2.83	2.83	0.23	0.228
Total	4.98	1.16	242.94	37.45	82.90	14.19	11.12	1.57

Trees before cut: 341.94 trees/ha — Basal area before cut: 36.13 m^2/ha

Trees cut: 54.37 trees/ha — Basal area cut: 9.62 m^2/ha

Table 8.7: Simulated stand structure (trees/ha) before harvest after 150 years and cutting during the fifth cutting cycle

Diameter class	Species group 1		Species group 2		Species group 3		Species group 4	
	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal	Before harvest	Removal
1	1.44	0.63	117.59	7.37	50.60	10.10	6.66	1.34
2	0.80	0.00	50.23	7.81	12.66	0.04	2.193	0.00
3	0.51	0.00	27.36	8.09	5.43	0.10	0.94	0.00
4	0.36	0.00	16.49	11.65	3.33	0.29	0.49	0.00
5	0.29	0.00	10.03	0.00	2.68	0.45	0.28	0.00
6	0.26	0.00	5.97	0.00	2.16	0.38	0.16	0.00
7	0.25	0.00	4.58	0.00	1.41	0.00	0.10	0.00
8	0.24	0.00	4.39	0.00	0.91	0.00	0.05	0.00
9	0.30	0.00	3.89	0.00	0.88	0.00	0.05	0.00
10	0.53	0.53	2.69	2.69	2.83	2.83	0.24	0.242
Total	4.98	1.16	243.21	37.61	82.90	14.19	11.17	1.59

Trees before cut: 342.26 trees/ha — Basal area before cut: 36.43 m^2/ha

Trees cut: 54.55 trees/ha — Basal area cut: 11.41 m^2/ha

Table 8.8: Expected cut (number of trees and volume per ha) and associated values (1000 FCFA) during the conversion period

Year	Species group 1	Species group 2	Species group 3	Species group 4	Total
			Trees cut per ha		
0	0.00	2.60	4.40	0.10	7.10
30	0.15	0.63	3.11	0.21	4.10
60	0.32	1.25	2.84	0.14	4.55
90	0.50	2.06	2.83	0.18	5.57
120	0.53	2.53	2.83	0.23	6.12
Total	**1.50**	**9.07**	**16.01**	**0.86**	**27.44**
			Volume cut (m^3/ha)		
0	0.00	38.27	62.35	1.59	102.21
30	2.45	9.27	44.07	3.33	59.13
60	5.23	18.40	40.24	2.22	66.09
90	8.17	30.32	40.10	2.86	81.45
120	8.65	37.24	40.10	3.65	89.65
Total	**24.50**	**133.51**	**226.86**	**13.65**	**398.56**
			Value of cut (1000 FCFA per ha)		
0	-3.69	75.84	997.65	213.65	1283.45
30	148.88	-195.19	915.10	449.07	1317.86
60	324.90	-128.31	832.58	299.82	1328.99
90	504.48	-41.74	831.26	378.99	1672.99
120	537.55	9.12	830.52	479.78	1856.97
Total	**1512.18**	**-280.28**	**4407.11**	**1821.31**	**7460.26**

The terms of the equations are the same as defined in section 4.4.2, however, H_t indicates the harvest expected at year t. Table 8.8 shows the expected harvests at different points in time. All the harvests are done in diameter class 10 for all species, while table 8.9 gives the maximum and minimum NPV. The minimum corresponds to the case where only the species groups 1 and 4 are commercialized and the maximum is when all the species groups are commercialized.

The costs of management planning are those introduced in section 7.2.1 e. During the conversion period, a total of 38.15 m^3/ha to 398.56 m^3/ha may be harvested depending on whether the interest is only on the current most valuable species or on all species. It is more likely to be between the two options. The volumes are estimated using the figures in Table 6.10 for individual trees. During that time, the expected total revenues will vary from 3,333,430 FCFA/ha to 7,460,270 FCFA/ha, and for a NPV between 395,650 FCFA/ha to 1,685,560 FCFA/ha.

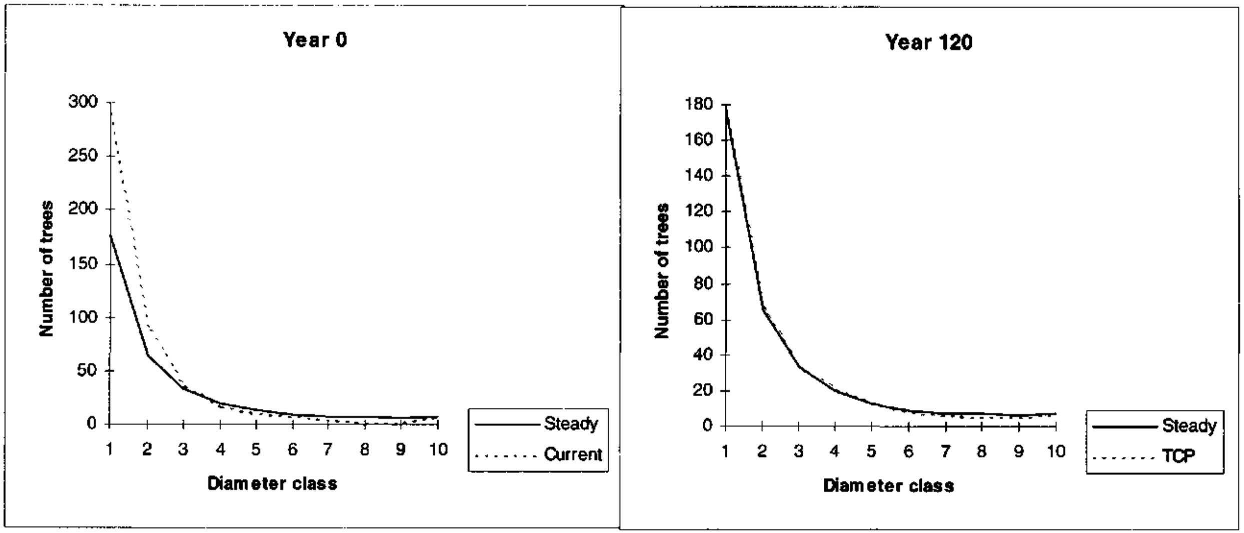

Figure 8.2: Comparison between steady state and projected TCP stand (all species combined) at years 0 and 120.

Table 8.9: Maximum and minimum NPV (1000 FCFA) for a discount rate of 5%.

Year	Minimum value of harvest	Maximum value of harvest	Costs of management Planning	Minimum NPV	Maximum NPV
0	209.96	1283.45	28.00	209.96	1283.45
30	597.95	1317.85	28.00	138.35	304.92
60	624.72	1328.99	28.00	33.44	71.15
90	883.47	1672.99	28.00	10.94	20.72
120	1017.33	1856.99	28.00	2.96	5.32
Total	**3333.43**	**7460.27**	**140.00**	**395.65**	**1685.56**

8.4 Conclusion on the conversion period

The simulations of the conversion period done in this chapter have been based on the outcomes presented in chapter 7 and particularly the ones in section 7.2 (Especially table 7.9). The main actions to be taken during the conversion consist of removing trees by timber harvesting and silvicultural operations whenever there are trees in excess as compared to the steady state structure in Table 7.9. Timber harvesting for commercial purposes concerns mainly trees of diameter class 10. However, logging damage is also accounted for in all calculations of the conversion period. Figure 8.2 provides an illustrated comparison between the steady state and the current forest stand and the projected stand structure 120 years later.

When these actions are undertaken at the beginning of every cutting cycle, the conversion period has shown to consist of two phases; one phase of 120 years during which there is important progress towards the steady state, and a second period not delimited here but during which the stand converges very slowly towards the steady state. At the end of the first phase, the stand has a basal area of about 36 m^2/ha.

Timber harvesting is done at 30 years intervals during the conversion period. However, in practice the amount harvested will depend on the market situation. It is possible to have a NPV of more than 396,000 FCFA/ha for the five cutting cycles considered.

It should be emphasized that this course of action is not the only possibility, it is a strict application of the outcomes in chapter 7. The forest manager can use the same methodology but decide to organize the conversion with a different removal scheme. For example, one may think that 50% of the removal at the beginning is high and he may remove less, and the same simulation can still be made.

Chapter 9

Reflections, conclusions and recommendations

The first four research objectives have been addressed in the preceding chapters. The current chapter addresses the last objective and reflects on the whole research.

This study is to help identifying the most important elements needed for the development of a tool to provide adequate technical and scientific support for decision-making in natural tropical forest management. These elements concern the data needs, the methods for analyzing the data, the equipment and the methodology for generating information about the consequences of alternative management options. In this chapter, key elements that decide on the quality of a system for supporting decision-making in tropical forest management are highlighted. A critical review of TROPFOMS is In addition made in order to identify its limitations.

9.1 The design of TROPFOMS and its mathematical programming approaches

9.1.1 Reflections on the design of TROPFOMS

The ambition of this research is to put together a methodological tool that can assist forest management decision-making within the complex ecological and socioeconomic environment in which tropical forests are managed. This tool has been designed using available scientific methods and techniques and information from many fields, and it is suggesting an approach to combine these elements and procedures to process the information in order to obtain the intended support. It uses quantitative information and provides quantitative guidance for forest management at the stand level.

The importance of the issues addressed by the output of TROPFOMS for forest management is self-evident. These issues relate to the key management parameters listed in section 2.3.3. However, there may be criticism about the level of analysis and the quantitative approach adopted.

In fact, many aspects of forest management are qualitative and this particularly applies to the case of tropical forests. For example, cultural values of forests and forest use by the local population are hard to quantify, and so are the political motivations of a government which designs forest policy. However, the attractiveness of a quantitative analysis is that it provides a common language for different stakeholders in forest management. Quantitative analytical methods also allow the analysts to be more neutral in their analyses. After all, the primary role of an analyst is to provide decision makers with a basis for their decisions, and it is the task of decision makers to combine quantitative and qualitative information while making decisions. Thus, the quantitative support provided by TROPFOMS can be combined with qualitative information to help in decision-making.

Similarly, concerning the level of analysis, stand level information does not constitute the only source of information needed for forest management at the Forest Management Unit (FMU) level. For example, more information on land utilization types, land suitability, land ownership and public forest policy is needed for land use planning and zoning at the forest level. However, stand level information should be incorporated in decision-making on a forest use at the FMU level. One of the interests of the design of TROPFOMS is that it puts together many aspects at the stand level. The intention of this research is not to assist in making the complete range of decisions required in tropical forest management, but to make a contribution to the information needed at stand level.

9.1.2 Reflections on the mathematical programming approaches of TROPFOMS

TROPFOMS includes Linear Programming (LP) as an optimization technique to obtain steady state stand characteristics. In addition, numerical simulations are used to make projections regarding the conversion period. LP is the most commonly used mathematical programming technique. It is an efficient and proven way to obtain optimal solutions for problems as defined in this study (Winston, 1987). The advantage of LP is that it can be used in a wide range of situations and its logic is simple to understand. However, the main problem of LP rests on meeting its underlying assumptions (See section 5.3).

In this case, the non-negativity assumption poses no problem. However, the linearity assumption makes it difficult to include the cutting cycle as a decision variable. To overcome such an obstacle, successive values of the cutting cycle were used in a step-wise simulation approach that can lead to a sub-optimal solution concerning the cutting cycle. However, the fact that the growth period (See section 4.4.1e) is five years long does not leave much choice, only cutting cycles that are multiples of five years could be examined meaningfully. Another point of concern is the available knowledge about the system to be modeled. The solutions provided by LP are as good as our knowledge of the system. Limitations in the knowledge of the system are further discussed in section 9.2. The information about the management environment certainly has shortcomings, but it was the best available. The positive side is that it makes clear what information is needed and determines which one is lacking (See section 9.2).

9.1.3 Conclusion on the reflections about the design and the mathematical programming approaches of TROPFOMS

The design of TROPFOMS uses information about the management environment expressed in quantitative terms and produces figures that can support forest management decision-making. The output of TROPFOMS has to be combined with other information at the forest level to provide a more complete basis for decision-making. The mathematical programming techniques used are well proven techniques, nevertheless, the usefulness of the outcomes depends on the input to the model.

To implement the methodology of TROPFOMS, good computing ability is needed, particularly a mathematical programming package such as AIMMS which was used in this study and a computer which has a sufficient capacity (24 to 32 megabytes (MB) of Random Access Memory (RAM)).

9.2 Reflection on the data needs and methods of analysis

The quality of the outcome of TROPFOMS depends much on the coefficients and parameters used. These coefficients and parameters concern characteristics of forest stands, market prices of timber products and the local use of forest products. The information that is necessary to implement and run TROPFOMS includes:

- A definition of species groups based on both the growth habits of different species and the market prices of timber products
- Transition probabilities which are estimated on the basis of diameter increments of trees of each species group. The diameter increments are obtained from periodic measurements of all trees in PSPs. In addition, an estimation of the ingrowth into the smallest diameter class is needed as well as an estimation of mortality.
- The stumpage prices expressed per tree for each species group and diameter class. The stumpage prices are derived on the basis of market prices of logs (or timber products), and information on logging waste and logging costs. All information on logging is expressed per species group and size class and preferably in relation to logging intensity.
- A discount rate.
- The maximum stocking achievable expressed as the maximum basal area per hectare that a stand can reach. This information may not be necessary if a significant relationship between stand growth and stand density can be established.
- Logging damage to the residual stand estimated as number of trees destroyed during logging operations for different species groups and diameter classes. The damage to the residual stand should be expressed in relation to logging intensity.
- The maximum proportion of the basal area which can be removed from a stand by logging and silviculture.
- The list and use of tree species by the local population with special emphasis on the ones which are also harvested by logging.
- The proportion of NTFP trees that management wishes to preserve.
- The minimum number of trees per species-size class that management wishes to preserve.

Among all this information, the definition of species groups, the transition probabilities and the stumpage prices are basic for any outcome. For that reason it appears to be important to pay special attention to them.

9.2.1 Methods of analysis and data needs for forest stands characterization

Species grouping. Natural tropical forest stands show a great deal of heterogeneity due to the high species diversity as well as their size diversity. This heterogeneity is an interesting feature for the multiplicity of uses that can be made of these forests, but it makes modeling difficult. It is generally agreed that species should be grouped according to some criteria and modeling and/or management would use species groups instead of individual tree species. Species grouping is done in almost every forest management organization throughout the tropical world. However, as inevitable as tree species grouping may be for forest management purposes, it appears worth noting that pooling tree species to groups, monitoring of species of special interest for conservation or other purposes is disadvantaged. Therefore, if there are tree species of special interest, forest management should record these during forest inventories and deal with their special issue when designing options.

Two approaches have in the past been used to aggregate tree species: an approach based on the commercial status of species, used mainly by forest management services and forest managers and a second approach based on diameter increment. Different techniques have been investigated by researchers (Meldthal *et al.*, 1985; Vanclay, 1991b; Atta-Boateng and Moser, 1998). The choice of using just one variable as the basis is inconvenient for projections needed in forest management planning. On one hand, the choice of using only the commercial status does not allow to make projections on future yields while on the other hand a grouping based on the diameter increment solely makes it difficult to make projections on values.

The approach used for grouping species within TROPFOMS bases species aggregation on both the commercial value and the diameter increment with a statistical method that is cluster analysis. This approach has interesting potentials provided that reliable data are available. However, a potential criticism against the species grouping made in this study is that the method assigned a commercial timber value to all species within a group, which may be different from market reality because all species are not currently commercialized at a regular basis, and thus the value projected may be inflated. But, it can also be argued that assigning commercial values to all species is positive because given the changes in the market, species not commercialized currently may have potentials to be better known in the future and commercialized more regularly. When industrial logging started in Cameroon earlier this century, the focus was only on Ebony (*Diospyros crassiflora*) and now more than 50 tree species are exported from the country.

Growth and yield module. The ability of making projections of future stand characteristics is essential in all approaches of forest management planning for timber production. In temperate forestry and especially for even-aged stands, models for predicting growth and yield exist already for a long time. However, uneven-aged stands are more complex and the modeling of their growth and yield has developed more slowly. Nevertheless, techniques now exist and recent developments have been substantial because of easy access to computers with a high level of performance. Among the methods used in growth and yield modeling of uneven-aged forests is the transition matrix method. Initially it has been criticized for the assumptions it includes, but it has gained more and more acceptance. The attractiveness of the transition matrix approach lies in its simplicity and it has been subject to many improvements, which, however, have decreased its simplicity as shown in chapter 2.

One of the most important difficulties encountered in using transition matrices relates to the lack of data for the estimation of transition probabilities. Working with data collected in temperate forests for decades, most authors, such as Michie and Buongiorno (1984), have preferred the use of simple proportions to estimate these probabilities. For the current research such data could not be obtained due to the lack of PSPs. In addition, simple proportions are not very suitable because some species groups may have no trees or only a few trees in some diameter classes, thus making proportions meaningless. It appears then desirable to develop some function that can use available data to estimate the probabilities needed. The logistic function was used for that purpose in this study and it has shown a quite interesting significance for some variables. But the analysis was not completely satisfactory due to the quality of data, which limited the sensibility of the model to stand conditions. Difficulties came particularly from the failure to obtain significant effects of the basal area on the ingrowth and the upgrowth probabilities. The basal area is considered an important variable and this research does not intend to contradict that, but the lack of significance encountered rather results from the quality of the available data. As mentioned in chapter 6, the range of variation was possibly too small to capture the importance of the basal area. Vanclay (1991b) alluded to such problems by regretting that: "Although experimental data are extensively used in developing plantation's growth models, it is more common to develop growth models for mixed forests solely from passive monitoring data." He later pointed out that there is a real danger that attempts to describe the behavior of the stand as a function of stand density may be confounded by other factors or fail. Another aspect of competition not incorporated in this study, as in most studies of growth and yield for tropical forests, is competition among different species groups. It is possible that different species groups compete with each other in special ways that need to be investigated.

Growth data. Modeling growth and yield requires a number of permanent sampling plots where all trees are measured periodically and records are kept, so that the evolution of individual trees may be traced over time. A major problem of this research was that there are no such plots in Cameroon. The data used were collected in another African tropical country (Liberia) and used in combination with information collected in Cameroon. This represents a serious limitation in the use of the model for practical applications, but hardly affects the theoretical analysis applied. It can be argued that, because the needed information on diameter increments is lacking in Cameroon, technical decisions are anyhow made at best on the basis of comparison with data from countries with similar forests. For example, Durrieu-de-Madron and Forni (1997) used a combination of data from Cameroon and the Central African Republic to propose a methodology for determining the cutting cycle for forests in East Cameroon. In the absence of information collected on the site, sound methodologies using imported data are still of interest.

The number of plots needed should be a function of the heterogeneity of the forest. In any case, it is advised to have more than 50 plots of one hectare per forest type (Synnott, 1979) measured periodically every two to five years. In the case of this study, the periodicity was right but only data from 20 plots where used and remeasured once with a five-year interval. The small number of plots and the fact that only two separate measures were taken made the data set skinny for some species groups and diameter classes, even after grouping.

9.2.2 Methods and data for the derivation of stumpage price

The residual approach which helped to derive the stumpage price for this research is a rather standard and widely used method for estimating such prices. The value of the raw material is obtained with this method after subtracting all availability costs from the sale price of related market products. The method is well accepted and does not present a source of problems in this study. However, a few problems may be mentioned in relation to the data. The application of the residual approach in this research can be criticized because the costs incorporated in the analysis include taxes that are paid to the government. The incorporation of taxes as costs means that the analysis is done from the standpoint of the forest manager and not the society as a whole. Such a criticism may appear pertinent, but the decisions supported by TROPFOMS usually confront the management at the concession level. Therefore, the primary users of the forests which are the local populations in and around the forest and the industrial logger are the first concerned. It should be noted that expenditures for the development of local infrastructure and fees due to local communities were not included. In Cameroon, it is required by law that an agreement be reached between the concessionaire and the local populations about the contribution of the logging company to the development of the local infrastructure within the first three years of concession holding. These three years are devoted to management planning. In addition, for sales of standing volumes, 1 000 FCFA/m^3 of timber harvested should be given directly to the local populations. Therefore, the analysis is not done only for the logging company but for both the local population and the logging company. In addition, logging taxes are low in Cameroon and are not expected to change a great deal of the solutions obtained.

The sale prices chosen are the FOB prices for logs as these are the best documented prices in Cameroon. The difficulty related with the data on prices is that they do not show variations with the size of the log as some market realities suggest. Instead, only average prices were obtained. To overcome this difficulty, theoretical assumptions were made in section 7.2.1b. Nevertheless, there is a need for a stronger basis to portray the relationships between the log size and price.

The most important limitation comes from the logging costs. To improve the quality of the outcomes, it is desirable to have information about the variation of logging costs with the diameter of the trees being logged and with logging intensity. There are at least two reasons why the stumpage value per unit volume is expected to be a function of the diameter. One reason is that, logging waste per cubic meter harvested tends to be higher for trees of smaller diameters than for trees of large diameters. Therefore, the commercialization coefficient which was defined in chapter 4 as the ratio of the marketable volume to the volume of stumpage estimated on standing trees during forest inventory before logging, will decrease as the diameter increases (CTFT, 1972; Fourier-Djimbi and Fouquet, 1998). The other reason stems from the fact that logging costs are higher for trees of smaller diameter than for the ones of bigger diameter when expressed per unit volume. This is because there are some fixed costs per tree harvested. Thus small trees with less volume have higher fixed costs per unit volume. Some of such costs are the costs of the times spent by a skidder or a felling crew to walk from one tree after felling to the next. Unfortunately, the available data did not allow differentiating between logging costs of trees of various size classes and different logging intensities.

Another shortcoming from the data on logging costs results from the transitional phase in which the logging industry in Cameroon was when the data was collected. The tax system was not stable. For example, with the former regulations, there was a fixed annual per hectare tax for holding a logging concession granted for five years. This tax was not due for logging companies that were granted one year "ventes de coupe". The new regulations made provisions for the same type of taxes but new concessions were not yet issued and only "vente de coupe" were granted to loggers with less taxes. For that reason, the logging costs in this research may have been underestimated compared to the reality faced by the logger when holding concessions, which are now granted for 15 years.

9.2.3 Conclusion on the data needs and methods of analysis for forest stand characterization

The data used are the best currently available and the methods for their analysis seem scientifically satisfactory. However, significant improvements of TROPFOMS outputs can be obtained if the information included in the system is more specific to south Cameroon and more precise. Specifically, there is a need to have growth data from PSPs established in south Cameroon which include enough variation in basal area in order to improve the sensitivity of the system to stand stocking level. The outcomes can further be improved if the stumpage prices are determined more specifically not only by species group, but also by diameter class and in relation to logging intensity. Such a determination of stumpage price will require more information about the relationships between logging waste and tree size on one hand, and logging costs and tree size on the other hand.

9.3 Reflections on the outcomes of TROPFOMS

The system designed uses matrix algebra, linear programming and numerical simulations. The outcomes relate both to the stand characteristics at steady state and during the conversion period.

9.3.1 The outcomes related to the steady state

The outcomes in chapter 7 suggest a steady state with a cutting cycle of 30 years for the sustainable production of timber and a cut as high as 117 m^3/ha or 11.42 trees/ha which corresponds to a PAI (See section 4.2 for definition) of 3.9 m^3/ha/year. Part of the discussion about these figures was done in section 7.4.1. Such a harvest may seem too high when compared to the current levels in Cameroon where 0.5 to 1 tree/ha are harvested with 6 to 10 m^3/ha (Eba'a, 1998b; van der Hout and van Leersum, 1998). However, two points are worth keeping in mind in the examination of these numbers.

The first one is that the harvest now is very selective and concerns species of group 1 and 4 almost exclusively. Thus, if the market remains the same as now only about one to two trees/ha would be harvested at steady state with a volume of 15 to 25 m^3/ha. However, because of the time span involved, the market is unlikely to stay the same. In fact, when observing the changes that have occurred in the history of logging in Cameroon (Eba'a, 1998b) and other African countries, there is a tendency towards diversification of species harvested. That tendency can be expected to continue either because of the exhaustion of the most valuable species and/or better knowledge of other timber species resulting from ongoing efforts for their promotion. The outcomes of the model are maximums because all species are included in the estimation of timber cuts.

The second point is that these values represent the expected harvest at steady state and not what can be obtained now from the current forest. To obtain such a forest structure many cutting cycles of conversion should first be completed.

Concerning the length of the cutting cycle, it falls within the range of values already suggested for the management of tropical forests. Nevertheless, it should be noted that the inclusion of ingrowth estimations and transition probabilities that are more sensitive to basal area may reduce this cutting cycle to a lower value. This is because there will be a tendency that the growth rate declines with the length of the cutting cycle. This makes it less beneficial to maintain the growing stock with a discount rate that will stay constant while the stand growth declines.

The suggested cutting cycle of 30 years or shorter goes in an opposite direction of the recent suggestions of cutting cycles for management of tropical forests in south Cameroon and elsewhere in Africa. Most of the existing estimations are based on professional judgment, but more and more estimations are based on scientific or technical arguments. Durrieu de Madron and Forni (1997) suggested a cutting cycle of 30 years for primary forests in east Cameroon and a longer harvesting periodicity for secondary forests. In the management plan of the Lokoundje Nyong permanent forest in south Cameroon, the cutting cycle has estimated to be 40 years (Poulin-Theriault Inc., 1998). In Ghana, the cutting cycle has shifted recently from 25 years to 40 years (Nolan and Garthey, 1992). In all these and in many other cases the basic reasoning is to estimate the time period that is necessary for the current forest to recover after logging. In other words, say a forest stand now has V m^3/ha of growing stock and a harvesting occurs that takes away h m^3/ha and leaves V_o m^3/ha. The question tackled in these cases is then: how many years of growth does it require to the reserve growing stock V_o to be increased by h and become equal to V again? Such an approach assumes that the stocking of the forest at the beginning is the best capable of meeting management objectives. Thus, knowledge of the current structure of the forest and the growth rhythm of different species groups that constitute the stand is enough to simulate the time needed to make up for the harvest damage and reach the initial stocking. Durrieu de Madron and Forni (1997) give a good illustration of such a line of thinking as they proposed the use of the *"pourcentage de réconstitution"* (percentage of reconstitution) to estimate timber harvesting periodicity (or cutting cycle). Their definition of the percentage of reconstitution is given by equation 9.1 as follows.

$$\% \mathrm{Re} = 100\frac{[N_0(1-\Delta)](1-\alpha)^T}{N_P} \tag{9.1}$$

Where:
$\%Re$ = percentage of reconstitution of the number of stems that were above the DME at year 0,
N_o = number of trees in the three or four diameter classes immediately below the DME,
Δ = rate of logging damage,
α = mortality rate,
T = time needed for a tree in a given diameter class to grow up to the next diameter class
N_P = number of mature (DBH $\geq$ DME) trees in the stand at year 0.

To calculate *Re* with this formula, only inventory data and growth characteristics are needed. For different values of multiples of *T*, it is possible to find out the time that is necessary to have *Re*=100, which means the stand will have recovered from timber exploitation entirely. However, based on a subjective professional judgment one can also desire to reconstitute a proportion of the harvest different from the initial one.

The basic concern of the above mentioned approach is to determine the cutting cycle and the harvesting rules in relation to some level of wood production. In fact, if data allow it would be better to determine the number of years after logging for which the highest PAI is obtained.

In contrast to the preceding line of thought, the reasoning in this research does not suppose that the structure of the initial forest is the one to maintain, but it looks for the stand structure that is best capable of meeting forest management objectives at any given cutting cycle. The production of timber in a sustainable way per se is not seen as an objective here, but income generation through sustainable timber production, nature conservation and improved living conditions for the local populations through production of NTFP are the actual objectives. Therefore, in addition to growth and inventory data, other aspects such as the characteristics of the timber product market or the plant species utilized by the local population are incorporated. This can result in a tendency to reduce the cutting cycle also because the opportunity costs of both land and capital are taken into account.

Another important point that may affect the outcomes for the steady state is the maximum basal area set at 40 m^2/ha. The constraint was included to limit the growth since the expected relationship between stand growth and stand density was not established with the available data. The value of 40 m^2/ha may appear too high, which means the resulting cutting cycles are probably longer. However, the observations of Bibani (1996) on the TCP research site show that, although the average stand has a basal area of about 34 m^2/ha, the actual basal area of individual plots varied from 30 to 40 m^2/ha. Therefore, since the interest was to set a maximum and not an average, it appeared reasonable to chose 40 m^2/ha. Nevertheless, it would be better to avoid setting such a maximum if better information on the relationship between stand density and stand growth exists.

9.3.2 Outcomes related to the conversion period

The outcomes for the conversion period have been obtained in the case of a strict application of the cutting rules for the target steady state in chapter 7. The basic actions to be conducted during the conversion period consist of removing trees not only by timber harvesting and related damage, but also by silvicultural operations to orient the forest towards the desired structure. This resulted in removing 50% of the basal area at the beginning of the conversion period. It is believed that such a strict application may be the fastest approach to move towards the steady state. However, such an approach may be questionable on ecological and social considerations especially because of the high level of removal.

In fact, because the conversion period did not undergo an optimization sequence but was rather simulated, some room is left for the manager to use professional judgment and adopt an intensity of actions to orient the stand towards the steady state. For example the manager may avoid removing trees of species groups 1 and 4 at the beginning and focus more on removing trees of the less valuable species. This may allow trees of the most valuable groups to be removed in later cycles when they will have reached commercial sizes. This may extent the conversion period but may prove more interesting on financial grounds.

In any case, it should be reminded that the steady state will probably never be achieved because of the time span involved. For a period as long as 120 years, it is almost certain that management objectives will change during that long period. Then the estimated steady state will no longer be suited to best meet the revised objectives. Similarly, the technological environment will progress and new techniques and parameters specifications will lead to new solutions. Nevertheless, the interest of these solutions is that they help orient the course of action today with the long-term future horizon in mind, and today's concern about the future is one central element of the notion of sustainability.

9.3.3 Conclusions on the outcomes

The numerical outcomes of this research presented many interesting points as mentioned in previous sections. These outcomes are obtained not in the interest of maximizing wood production, but with the idea of achieving better satisfaction of management objectives beyond wood production. Therefore, it is important to include in the analysis more information than only stand characteristics.

However, when examining these outcomes one should have in mind that: "the purpose of mathematical programming is insight, not numbers" (Dykstra, 1984). An important suggestion that can be retained from these outcomes is that it is possible to find a more valuable stand structure that can generate higher income levels through logging in the future, in coexistence with other objectives. Compared with the current logging intensity, it is possible to achieve a higher timber harvest in south Cameroon in the future and maintain it. However, silvicultural operations seem necessary in order to modify the structure of forest stands.

Cutting cycles of 30 years or a bit lower are viable options and possibly the most attractive for production forests where sustainable production of timber is foreseen. At each cutting cycle, it is better to harvest trees that have reached the maximum size. The conversion period should take a long time (more than 100 years), but while undergoing conversion, positive financial returns can be attained from forest management.

This study confirms the conclusions of van Dijk (in press) that generation of income through timber production and other forest productions for the benefit of the local populations do not have a high level of incompatibility. On one hand, a complete ban of timber harvesting of the critical tree species that are of interest for both the logging company and the local populations results in a decrease of less than 7% of the STV. On the other hand, it is expected that cutting trees of NTFP species which have 100 cm of diameter or more as suggested by the outcomes here, will not have an important impact on the supply of forest products to the local populations. This is because these trees with a DBH of 100 cm or more will have been producing products of interest to the local populations for some decades. Cutting these trees may help regeneration of NTFP species, and trees smaller than the ones eligible for harvesting are able to supply the local populations with needed forest products. However, management should check the current inventory of these trees and take special measures if there are irregularities in regeneration. One of the observations made by van Dijk and Wiersum (1999) is that "the most limiting factor to further development of NTFP extraction from the natural forest is the relative low density of NTFP species rather than damage caused by commercial logging", which goes in the same direction as the conclusion of this study.
Similarly, a strong incompatibility between timber production and species-size diversity has not been established with TROPFOMS. The outcomes of all runs of TROPFOMS under different assumptions suggest that all the species groups will be rather substantially represented in the steady state stand. In addition, it is possible to have at least one tree per size class and per species group within 50 hectares at steady state without important sacrifice in financial returns. The possibility of having a representation of all species-size classes within smaller areas seems to be more limited by the growth characteristics of different groups than by timber harvesting.

9.4 Final conclusions

The overall objective of this research was the development of a system which can support decision-making for the management of natural tropical forests. This overall objective was subdivided into five specific objectives as presented in section 3.2.2. The main points which can be retained in accordance with the specific objectives and related research questions are:

a) A methodological tool was developed and given the acronym TROPFOMS. It provides quantitative information at stand level to support decision-making for tropical forest management. The information obtained from TROPFOMS concerns the optimum cutting cycle and stand structure both for the steady state and the conversion period. To provide support for forest management the system combines information from forest stands, timber products markets, use of the forest by the local population and ecological limitations of the forests. In addition, characteristics of the logging techniques used and the statement of management objectives are needed.
b) The system developed is based on tree species groups. The basic coefficients included in the system relate to the growth characteristics of forest stands and market prices of timber products. The growth characteristics are incorporated in the form of transition probabilities, which permits to make growth and yield projections. The timber market information is included as stumpage prices and it permits to estimate the timber values of forest stands at different points in time. Tree species were grouped by cluster analysis based on both diameter increment and FOB prices of logs. Transitions probabilities were estimated by logistic regression analysis while stumpage prices are derived by residual approach.
c) The optimal cutting cycle obtained for sustainable timber production was estimated to be 30 years. The steady state harvest for species that are currently commercialized was estimated at 13.41 m^3/ha but can raise as high as 117 m^3/ha if all the species are harvested. The harvesting rule only allows cutting of trees of 100 cm of diameter or more. The structure of the stand before harvest is constituted by all species groups with a negative exponential distribution of trees among diameter classes. Such a distribution is characteristic for uneven-aged forest stands.
d) The average forest stand at the TCP research site shows important differences with the desired steady state structure. The total number of trees per hectare is currently higher. However, for the most commercialized species group, this number is smaller. It would require about 120 years to convert the current forest stand at the TCP research site to the desired steady state structure, but during the conversion timber harvest with positive financial returns is possible.
e) The objective of income generation can be achieved simultaneously with the use of the forest by the local population without important consequences to income due to this use. Similarly, it is possible to have at least one tree of every species group in every diameter class within an area of 50 ha without important reduction of financial returns from logging.

9.5 Recommendations

9.5.1 Recommendations for policy and management

- ***Increase of minimum diameters for felling (DMEs).*** One of the most important measures taken to promote sustainable management in Cameroon is the utilization of DME. From this study, it can be concluded that the use of DMEs is a legitimate tool for the sustainable management of tropical forests. The optimization has also proposed a harvesting policy for the commercial species, which consists of harvesting trees from a certain diameter class onwards. However, the difference is that all the harvest here occurs only at the highest diameter class, which disagrees with the current setting of DMEs (See section 6.1.1). The suggestion is that current DMEs are low, it is both economically and ecologically sound to raise the DME towards the maximum size of trees of each group. Raising the DMEs for all species to be around 100 cm (about the maximum size for every species group) will lead to a decrease of the harvest at the beginning of the conversion period with the current characteristics of timber products markets, but will increase the value of forest stands in the long run.

- ***Silvicultural operations***. Another important point to be considered by the management is the necessity of opening up the forest stand by removing trees to allow more growth. If trees of species groups 2 and 3 are not demanded in the market, it is recommended to remove trees of these groups to make room for more growth of higher valued species. Removing trees of these groups is not necessarily done by logging operations. Silvicultural techniques may be used with less damage than logging.
- ***Periodicity of timber harvesting***. The cutting cycle to be adopted should be around 30 years in production forests. However, slightly lower values may be acceptable because it is anticipated that if the model becomes sensitive to stand density, it will recommend a reduction of the cutting cycle (See also section 9.3.1). In general, the outcomes suggest having more frequent harvests than 40 years or more, but smaller harvests because the DME will be increased.
- ***Computations equipment and trained personnel***. The research as a whole has highlighted the complexity of the computations to be performed for adequate technical support to forest management decision-making. It is therefore important for the management to acquire the necessary logistic equipment for the needed computations. In general, a computer with adequate capacity (about 24 to 32 MB RAM) is sufficient. In addition, trained manpower capable of using the software adequately as well as planning and implementing silvicultural prescriptions should be present. It is presently not in the habits of logging companies to have such personnel among their staff.
- ***Information base and archives***. The quality of the information on which the analysis made with TROPFOMS is based, is of primary importance. Therefore, management should carefully archive all information related to all management activities to improve the quality of future analyses. All information about the quality and the quantities of forest products harvested as well as various costs and benefits should be well gathered and stored.
- ***Permanent Sample plots***. In order to improve forest management gradually, a good monitoring system of the forest is needed. It is necessary that for each forest type, a number of PSPs be maintained.

9.5.2 Recommendations for further research

In order to improve the outcomes of TROPFOMS and implement them more confidently, more research is needed in relation to the following items:

- ***Silviculture***. The importance of removing trees in order to achieve the expected harvest at steady state has been shown in chapter 7. Similarly, in chapter 8 the steady state is approached by tree removal during the conversion period. Not all trees removed are harvested for timber production because of market characteristics. Therefore silvicultural operations are necessary. In order to obtain the desired results, more knowledge is needed to assess the impact of silvicultural treatments on stand dynamics in general and on tree growth in particular. In addition, the costs of treatments should be studied in comparison with the gains in growth.
- ***Growth and yield***. The information on stand growth and yield is a key factor on which all outcomes depend. One weakness of this research is that it relies on growth information gathered outside Cameroon (See section 9.2.1). Therefore it is of primary importance that a network of PSPs be established and monitored properly in south Cameroon. Such a network should consist of at least 50 plots of one hectare per forest type, and all trees should be monitored irrespective of their current commercial status. These PSPs should provide a framework within which the effects of changes in stand density on growth and ingrowth will be investigated.
- ***Maturity of tree species***. One constraint incorporated in the analysis was to restrict harvesting to mature trees that have been in a reproductive stage for a number of years. This was necessary because the system relies on natural regeneration. It makes sense to leave to a tree an opportunity to reproduce before it can be harvested. Therefore, a more accurate knowledge of the relationship between tree size and reproductive maturity is needed. A study should be conducted to determine at which sizes different species groups start to produce enough viable seeds.
- ***Ecological information***. A few ecological constraints were introduced, such as the restriction on the proportion of basal area permitted to be removed. The values used came from common practice described in the literature. There is a need to improve the understanding of the sensitivity of ecological variables to logging.
- ***Logging efficiency, costs and damage***. In addition to growth and yield, the stumpage price is one of the main factors that determine the steady state as well as the conversion period. Therefore there is a need to obtain an accurate estimation of stumpage price. However, the stumpage price is affected by logging efficiency and costs. In this research a need has come up to characterize the relationship between the total volume harvested, the size of the trees and the logging costs expressed in FCFA/m^3. Similarly, it is important to know how logging waste varies with the size of the trees and how logging damage is distributed between different size classes. All these themes need to be studied to improve the needed insight obtained while modeling forest management with the methodological tool presented here.
- ***The utilization of forest by the local population***. The research presented here has used information about the utilization of forest by the local population. The information about forest use by the local population should be better developed to include not only NTFP

trees and other plants, but also non-plant products. In addition, it appears that not all the existing NTFP trees effectively supply the local populations with the needed products. The understanding of the way the local population chooses NTFP supplier trees should be developed in order to better conceive the type of restrictions to be imposed on timber harvesting to guarantee proper supply of the local populations with desired products. Similarly, it is important to improve the understanding of the effects of logging and silvicultural treatments on NTFP supplier trees.

- ***Royalties.*** Sensitivity of forest management to royalties should be investigated. Such an investigation will allow to obtain more insight into the way tropical forest management can better contribute to generating government revenues, and the way a forest revenue system can contribute to sustainable forest management.

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SUMMARY

Natural forests play an important role in the economy of Cameroon, at both the national and local levels. At the national level, logging, which takes place exclusively in natural forests, contributes by about 7% to the Gross Domestic Product and by 20% to the export of Cameroon. At the local level, the forests constitute a life support system for the populations who collect non-timber forest products in it. The Government of Cameroon has made a number of efforts in recent years to create adequate settings for the sustainable management of the Cameroon's forests. Despite those efforts, there is still a general sense that in Cameroon, like in most tropical countries, forests are not managed in a sustainable way. There are concerns about both the degradation of forests resources and the failure of the forestry sector to contribute as much as it potentially can to the improvement of the well being of Cameroon nationals.

The poor forest management practices which still prevail in Cameroon, result from both an inadequate institutional context and insufficient scientific and technical knowledge. To gradually decrease the problem of insufficient knowledge in tropical forestry many research projects have been undertaken. However, the research efforts concentrate on developing silvicultural systems and more and more on predicting growth and yield of forest stands. Research on supporting decision-making for forest management has been negligible in tropical forestry. This is true despite the fact that forest management planning, in which decision-making plays an important role, is recognized to be vital for the quest of sustainable forest management. Decisions related to management parameters of production forests, such as the cutting cycle, stocking level and structure, and the need to incorporate silvicultural treatments have by and large been based on subjective experience of decision-makers or at best, on fragmented scientific knowledge in different sub-disciplines of forestry.

The research presented here was initiated from the thought that forest management planning involves making decisions to affect the forest now and in the future. Therefore, it should use the best available methods, which combine knowledge collected in different scientific fields to support decision-making and generate practical management strategies for field implementation. From this line of thinking, a general objective of the research was conceived as: to design a system which can support decision-making for the management of natural tropical forests. This general objective was further differentiated in five specific objectives listed as:

1. To design a system for supporting decision-making with respect to the management of tropical forests.
2. To assess the effects of different management options on the economic returns of the logging enterprise as well as on the structure of the forest at steady state.
3. To provide insights into the trade off between income generation through sustainable timber harvesting and the use of the forest by the local population on the one hand, and

between income generation through sustainable timber production and nature conservation on the other hand.

4. To derive recommendations for conversion of the current forest at the Tropenbos Cameroon Programme (TCP) research site into a steady state forest.
5. To suggest and evaluate adaptations of existing strategies aimed at sustainable management of the tropical moist forest of south Cameroon

The conceptual framework of the research was based on two main assumptions, which are:

a) The goal of sustainability in forest management can be attained only if ecological, economic and sociological constraints are taken into account within any management strategy developed and implemented.
b) There are ways to reconcile forest conservation (maintenance of forest cover and a high biological diversity) with some levels of both industrial timber harvesting and forest utilization by the local population.

These assumptions mean that a tool to support decision-making for the management of natural tropical production forests should be able to incorporate different aspects related to the biological characteristics of forests stands, the market of timber products, the needs of the local populations and the needs for forest conservation.

To address the research problem effectively and meet the objectives the following research questions were formulated:

a) What methodological approaches can be used to design a system, which supports decision-making for the management of tropical forests of south Cameroon? What are the components of such a system and how can they be related?
b) What coefficients and parameters need to be included in a system which is designed to support decision-making in south Cameroon and how can these coefficients and parameters be estimated given the current availability of information?
c) What outcomes does the system designed provide concerning optimal steady state forest stand structure, harvest and financial returns of logging? How are these outcomes affected by changes in management parameters and objectives?
d) How do the outcomes of the system developed compare with the structure of the current forest in the Tropenbos Cameroon research site and which guidelines can be derived for the sustainable management of this forest?
e) What insights can be obtained from the outcomes of the system developed concerning the trade off between alternative management objectives?
f) What can be recommended for the improvement of forest management strategies in south Cameroon on the basis of the insights obtained from the system designed?

The efforts to answer these questions provided the direction and the layout for the research methods and results. Based on research questions, the following main points were considered with respect to research methods, results and conclusions:

A system to support tropical forest management decision-making. A methodological tool was developed to support decision-making with respect to tropical forest management. The system was given the acronym TROPFOMS which means TROPical FOrest Management support System. The management items to which TROPFOMS provides support for decision-making include:

1) The target steady state growing stock characteristics, mainly the structure in terms of number of trees per size class to be found both before and after harvest and the species composition of the stand,
2) The appropriate cutting cycle for timber harvest,
3) The amount of wood to be harvested at the end of each cutting cycle,
4) The expected length of the conversion period and the expected levels of harvest during that period,
5) The multiple use of the forest through an analysis of the trade off between alternative land use types and especially between timber production, nature conservation and forest utilization by the local population and,
6) Consequences in changes of management parameters.

The focus of TROPFOMS is on the level of the stand instead of on that of the Forest Management Unit.

TROPFOMS uses tree species groups instead of individual tree species and consists of four main components which are:

- A growth and yield module based on transition matrices
- An economic module consisting of stumpage prices derived from market prices of timber products and harvesting costs
- A constraint formulation module included into the model concerns diversity of species groups and tree sizes
- A mathematical programming module which uses linear programming techniques to search for optimal stand characteristics at steady state and performs simulations to achieve projections of forest stand characteristics during the conversion period.

Coefficients and parameters in TROPFOMS. The information needed by TROPFOMS in order to provide support for decision-making include:

- *A definition of tree species groups.* An important characteristic of tropical forests is its heterogeneity which results from the large number of tree species. The great number of species makes growth and yield modelling difficult. Thus, tree species should be aggregated in groups. In this research, tree species were aggregated in four groups by cluster analysis. The grouping was based on commercial value, diameter increment, minimum diameter for felling, and diameter at the beginning of the growth period. The data used to group species were collected in permanent sample plots in Liberia, as there is no such information from Cameroon. Remeasurement was done every five years (growth period).
- *Transition probabilities.* These are probabilities that a tree of a certain species group and in a given diameter class grows up one diameter class or stays in the initial diameter class after a certain time interval. The transition probabilities were estimated by logistic

regression analysis. However, mortality was estimated from results of prior studies. Ingrowth was included as average number of trees that entered the smallest diameter class after each growth period.

- *Stumpage prices.* They were expressed in CFA francs[7] (FCFA) per tree for each species group and each diameter class. The stumpage prices were estimated following a residual approach. The basis of the approach was the FOB price of logs from which the cost of availability were deducted also taking into account the efficiency of the logging process.
- *Discount rate.* A discount rate of 5% was chosen based on the literature. A sensitivity analysis was also conducted which showed that the effects of the discount rate was not very important for the studied forest management parameters up to 10%.
- *List of non-timber forest products (NTFP) tree species.* To be able to incorporating the use of the forest by the local population in the system, a list of trees species that are used by both the local population and the logging industry was needed. A study was conducted in south Cameroon to obtain such a list (van Dijk, in press).
- *Forest inventory results.* These results are necessary for the estimation of characteristics of the conversion period. The inventory results provided information about the current structure and stocking of the average forest stand in terms of number of trees per hectare per species group and per diameter class.
- *Technical information on logging.* The information needed concerns logging intensity, logging damage and logging costs, and the relationships among these items and with the structure of the forest stands.
- *Ecological limits in basal area removal.*
- *Definition of management objectives.* It is important to know which forest management objectives are of interest and which levels of satisfaction of these objectives can be accepted. This research examined the objective of income generation through sustained timber production in relationship with the objectives of nature conservation through species group diversity and tree size diversity and the objective of improved living conditions for the local population through continued supply of NTFPs.

The outcomes of TROPFOMS for the optimal steady state. The optimal cutting cycle obtained for sustainable timber production was estimated to be 30 years. The steady state harvest for species which are currently commercialized was estimated at 13.4 m^3/ha but can be as high as 117 m^3/ha if all the species are harvested. The harvesting rule only allows cutting of trees of 100 cm of diameter or more. The structure of the stand before harvest is constituted by all species groups with a negative exponential distribution of trees among diameter classes. Such a distribution is characteristic for uneven-aged forest stands. The outcomes have shown a great deal of sensitivity to assumptions on stumpage prices especially as related to logging costs and waste.

Conversion of the current forest to the steady state forest. The average forest stand at the TCP research site shows important differences with the desired steady state structure. The total number of trees per hectare is currently higher. However, for the most commercialized

[7] 1 Euro = 656 FCFA

species group, this number is smaller. It would require more than 120 years to convert the current forest stand at the TCP research site to the desired steady state structure, but during the conversion timber harvest with positive financial returns is possible.

Trade off between management objectives. The forest can be used by the local population without important consequences of this use for the income generation objective. Similarly, it is possible to have at least one tree of every species group in every diameter class within an area of 50 ha without important reduction of financial returns from logging.

Recommendations for forest policy and management and for further research. The research had limitations which in general relate to the quality of information available. The most important limitations came from the lack of data from Permanent Sample Plots (PSPs) in Cameroon which forced to used data from another African country for the growth and yield module. The other important limitations are related to logging costs which affect the stumpage prices. The available information on these costs did not allow to investigate thoroughly the different relationships between logging practices and optimal stand characteristics. Many other points deserve to be studied in order to improve the outcomes of TROPFOMS. The following recommendations were made for policy and management and for research.

Policy and management:

- *Increase minimum permitted diameters for felling to 100 cm*
- *Apply silvicultural operations.*
- *Adopt a cutting cycle of about 30 years.*
- *Acquire adequate computation equipment and trained human resources.* It is important for the management to acquire the necessary equipment for the needed computations by the model. In addition, trained manpower capable of using the software adequately as well as for planning and implementing silvicultural prescriptions should be present.
- *Create an information base.* Management should carefully archive all information related to management activities to improve the quality of future analyses. All information about the quality and the quantities of forest products harvested as well as various costs and benefits should be well gathered and stored.
- *Create a network of permanent sample plots.* In order to improve forest management gradually, a good monitoring system of the forest is needed. It is necessary that for each forest type a number of PSPs be maintained.

Further research:

- *Costs and returns of silvicultural operations.* More knowledge is needed to assess the impact of silvicultural treatments on stand dynamics in general and on tree growth in particular. In addition, the costs of treatments should be studied in comparison with the gains in growth.
- *Relationship between growth and yield and density of forest stands.*
- *Reproductive maturity of different tree species.* A study is needed to determine at which sizes different species groups start to produce enough viable seeds.

- *Logging efficiency, costs and damage.* There is a need to characterise relationships between logging costs on one hand and logging intensity and tree size on the other hand.
- *The utilization of the forest by local population.* The way the local population chooses NTFP supplier trees should be better understood in order to better conceive the type of restrictions to be imposed on timber harvesting and to guarantee proper supply of the local populations with desired products. Similarly, it is important to improve the understanding of the effects of logging and silvicultural treatments on NTFP supplier trees and other plant and animal products utilized by the local population.
- *Royalties.* Sensitivity of forest management to royalties should be investigated. Such an investigation will allow obtaining more insight into the way tropical forest management can better contribute to generating government revenues, and the way a forest revenue system can contribute to sustainable forest management.

SAMENVATTING

Titel: TROPFOMS, een model voor het ondersteunen van beslissingen aangaande duurzaam beheer van het regenbos in zuid Kameroen.

Natuurlijke bossen spelen een belangrijke rol in de economie van Kameroen, zowel op het nationale als het locale niveau. Op het nationale niveau draagt de houtkap, die alleen plaats vindt in natuurlijke bossen, ongeveer 7% bij aan het bruto binnenlands product en 20% aan de export. Op het locale niveau vormen de bossen een bron van bestaan voor de bevolking die er allerlei producten in verzameld. De regering van Kameroen heeft recent een aantal pogingen gedaan om een geschikte basis te creNren voor het duurzaam beheer van Kameroen's bossen. Ondanks deze inspanningen is de algemene indruk nog dat in Kameroen, zoals in de meeste tropische landen, bossen niet duurzaam worden beheerd. Er is bezorgdheid over zowel de degradatie van de bossen als het falen van de bosbouwsector om zoveel als mogelijk bij te dragen aan de verbetering van het welzijn van de bevolking van Kameroen.

De summiere beheerspraktijken die nog overheersen in Kameroen, zijn het resultaat van zowel de ongeschikte institutionele context als onvoldoende wetenschappelijke en technische kennis. Om het probleem van onvoldoende wetenschappelijke kennis geleidelijk te verminderen in de tropische bosbouw zijn veel onderzoeksprojecten uitgevoerd. De onderzoeksinspanningen concentreren zich op de ontwikkeling van teeltkundige systemen en wel steeds meer op de voorspelling van groei en opbrengst van bossen. Onderzoek op het gebied van ondersteuning van beslissingen in het tropisch bosbeheer ontbreekt vrijwel geheel. Dit, ondanks het feit dat bosbeheerplanning, waarin het nemen van beslissingen een belangrijke rol speelt, van vitaal belang is voor duurzaam bosbeheer. Beslissingen over parameters van productiebossen, zoals kapcyclus, houtvoorraad en bosstructuur, en de noodzaak teeltkundige maatregelen te nemen zijn grotendeels gebaseerd op de subjectieve ervaring van de beslissers. Op zijn hoogst wordt gebruik gemaakt van wetenschappelijke kennis die fragmentarisch aanwezig is bij de verschillende sub-disciplines van de bosbouw, waarbij met name de sociale(-economische) input ontbreekt.

Het onderzoek dat hier wordt gepresenteerd werd geçnitieerd vanuit de gedachte dat bosbeheerplanning beslissingen met zich meebrengt die het bos nu en in de toekomst beçnvloeden. Om beslissingen te ondersteunen dienen daarom de best beschikbare methoden te worden gebruikt die kennis combineren uit verschillende wetenschapsgebieden en die praktische beheersstrategiNen genereren die in het veld kunnen worden toegepast. Vanuit deze gedachtegang werd de volgende algemene doelstelling voor het onderzoek geformuleerd: het ontwerpen van een systeem dat beslissingen kan ondersteunen voor het beheer van natuurlijke tropische bossen. Deze algemene doelstelling werd verder gedifferentieerd in vijf meer specifieke doelstellingen:

1 Het ontwerpen van een systeem voor beslissingsondersteuning met betrekking tot het beheer van tropische bossen.
2 Het bepalen van de effecten van verschillende beheersopties op zowel de financiNle opbrengsten voor de houtkapmaatschappij als de structuur van het bos in de *steady state* (situatie van evenwicht tussen oogst en bijgroei van de gewenste producten).

3 Inzicht geven in de *trade off* tussen het inkomen gegenereerd door duurzame houtkap en het gebruik van bos door de locale bevolking aan de ene kant en tussen het genereren van inkomen door duurzame houtkap en natuurbescherming aan de andere kant.
4 Het afleiden van aanbevelingen voor de omvorming van het huidige bos op de onderzoekslocatie van het Tropenbos Cameroon Programma (TCP) in een *steady state* bos.
5 Het vaststellen en evalueren van aanpassingen van huidige strategiën die duurzaam beheer van het tropische regenbos in zuid Kameroen beogen.

Het conceptuele kader van dit onderzoek was gebaseerd op de volgende twee hoofdveronderstellingen:
a) Het doel van duurzaam bosbeheer kan slechts dan worden bereikt als ecologische, economische en sociale beperkingen in acht worden genomen binnen iedere beheerstrategie die wordt ontwikkeld en uitgevoerd.
b) Er zijn manieren om conservering van bos (handhaven bosbedekking en een hoge biologische diversiteit) in overeenstemming te brengen met één of ander niveau van industriële houtkap en bosgebruik van de locale bevolking.

Deze vooronderstellingen betekenen dat een hulpmiddel voor ondersteuning van beslissingen voor het beheer van natuurlijke tropische productiebos in staat moet zijn de verschillende aspecten die zijn gerelateerd aan de biologische kenmerken van bos, de houtmarkt en de behoeften van de locale bevolking en de eisen gesteld aan conservering van bos, te incorporeren. Om het onderzoeksprobleem effectief te kunnen aanpakken en de doelstellingen te kunnen realiseren werden de volgende onderzoeksvragen geformuleerd:
a) Welke methodologische benaderingen kunnen worden gebruikt om een systeem te ontwerpen dat beslissingen ondersteunt in het beheer van tropische bossen in zuid Kameroen? Wat zijn de onderdelen van zo'n systeem en hoe kunnen deze worden gekoppeld?
b) Welke coëfficiënten en parameters dienen opgenomen te worden in een systeem dat is ontworpen om deze beslissingen in zuid Kameroen te ondersteunen en hoe kunnen deze coëfficiënten en parameters worden geschat gegeven de informatie die thans beschikbaar is?
c) Welke resultaten geeft het ontworpen systeem betreffende de optimale *steady state* betreffende bosstructuur, oogst en financiële resultaten van de houtoogst? Hoe worden deze resultaten beïnvloed door veranderingen in parameters en doelstellingen van het beheer?
d) Hoe verhouden deze resultaten zich vergeleken met de structuur van het huidige bos op de TCP onderzoekslocatie en welke richtlijnen kunnen er uit worden afgeleid voor het duurzaam beheer van het bos?
e) Welke inzichten kunnen worden verkregen uit de resultaten van het systeem betreffende de *trade off* tussen de verschillende beheersdoelen?
f) Welke aanbevelingen kunnen worden gedaan ten behoeve van het verbeteren van de beheersstrategiën in zuid Kameroen op basis van de inzichten die zijn verkregen met het ontworpen systeem?

De pogingen om deze vragen te beantwoorden geven de richting en de wijze van opzet van onderzoek en bepalen de te verkrijgen resultaten. De volgende hoofdpunten, gebaseerd op de onderzoeksvragen, kregen aandacht in de onderzoeksmethoden, resultaten en conclusies:

Een beslissingen ondersteunend systeem voor het beheer van tropisch bos. Een methodologisch hulpmiddel werd ontwikkeld om het tropisch bosbeheer te ondersteunen. Het systeem kreeg de acroniem TROPFOMS, hetgeen is afgeleid van TROPical FOrest Management support System. De aspecten van het beheer waarvan de beslissingen worden ondersteund door TROPFOMS zijn onder meer:

1) De kenmerken van de houtvoorraad in de *steady state*, hoofdzakelijk tot uitdrukking komend in de structuur van het bos in termen van het aantal bomen per diameterklasse voor en na de oogst en de soortensamenstelling,
2) De geschikte dunningcyclus,
3) De hoeveelheid hout die wordt geoogst op het eind van elke dunningcyclus,
4) De verwachte lengte van de omvormingsperiode en de verwachte houtoogst gedurende die periode,
5) Het meervoudig gebruik van het bos door een analyse van de *trade off* tussen de alternatieve grondgebruiktypes en in het bijzonder tussen houtproductie, natuurbescherming en gebruik door de locale bevolking, en
6) Gevolgen van veranderingen van de parameters van het beheer.

De focus van TROPFOMS is op het niveau van de opstand in plaats van op dat van het bos / concessie.

TROPFOMS gebruikt boomsoortengroepen in plaats van individuele boomsoorten en bestaat uit een viertal hoofdcomponenten:

- Een groei- en opbrengstenmodule gebaseerd op *transition matrices*,
- een economische module die bestaat uit prijzen op stam die afgeleid worden van de marktprijzen van houtproducten en de oogstkosten,
- een module waarin de beperkingen zijn geformuleerd onder andere ten aanzien van diversiteit van soortengroepen en diameterklassen,
- een wiskundige programmeringmodule die Lineaire Programmeringtechnieken gebruikt om de optimale kenmerken van het bos in de *steady state* op te zoeken en die simulatie uitvoert om projecties van de bosopstand gedurende de omvormingsperiode te bepalen.

Coëfficiënten en parameters in TROPFOMS. De informatie die nodig is om TROPFOMS te laten functioneren omvat:

- *Een definitie van boomsoortengroepen.* Een belangrijk kenmerk van tropische bossen is hun heterogeniteit die het resultaat is van het groot aantal boomsoorten. Het groot aantal boomsoorten bemoeilijkt het modelleren van groei en opbrengst. Daarom dienen boomsoorten te worden geaggregeerd. In dit onderzoek werden boomsoorten door middel van clusteranalyse geaggregeerd in vier groepen. De vorming van groepen werd gebaseerd op commerciële waarde, diametergroei, minimum diameter bij velling en diameter bij het begin van de groeiperiode. De data die werden gebruikt om soorten te groeperen werden verzameld in permanente steekproefplots (PSPs) in Liberia omdat dergelijke informatie in Kameroen ontbreekt. Hermeting van deze plots vond om de vijf jaar (de groeiperiode) plaats.
- *Overgangswaarschijnlijkheid.* Dit is de kans dat een boom van een bepaalde soortengroep en in een bepaalde diameterklasse in een zeker tijdsinterval naar de volgende diameterklasse groeit of in de initiële diameterklasse blijft. De overgangswaarschijnlijkheden werden geschat door middel van logistische regressie-analyse. Mortaliteit werd echter geraamd op basis van eerdere studies elders. De ingroei (in de laagste diameterklasse) werd opgenomen als het gemiddelde aantal bomen die gedurende een groeiperiode ingroeit.

- *Prijzen op stam.* Deze werden uitgedrukt in CFA francs[8] (FCFA) per boom voor elke soortengroep en elke diameterklasse. De prijzen op stam werden bepaald volgens de restwaarde methode. De basis van de methode waren de FOB-prijzen van stammen die vervolgens zijn verminderd met oogst- en transportkosten en waarbij de efficiëntie van het houtoogstproces werd meegenomen.
- *Disconteringsvoet.* Op basis van de literatuur werd een disconteringsvoet van 5% gekozen. Een gevoeligheidsanalyse werd echter uitgevoerd die aantoonde dat tot 10% de effecten van de disconteringsvoet niet erg belangrijk waren voor de parameters van het bosbeheer.
- *Lijst met boomsoorten die niet-houtige producten (NTFPs) produceren.* Om het gebruik van het bos door de locale bevolking te kunnen opnemen in het systeem, was een lijst nodig met deze soorten voor gebruik door zowel de locale bevolking als door de houtkapbedrijven. Een studie werd uitgevoerd om een dergelijke lijst te krijgen (van Dijk, in press).
- *Resultaten bosinventarisatie.* Deze resultaten zijn nodig voor de bepaling van de omvormingsperiode. De resultaten van de inventarisatie gaf inzicht in de huidige structuur en voorraad van de gemiddelde bosopstand in termen van het aantal bomen per hectare per soortengroep en diameterklasse.
- *Technische informatie over de houtkap.* De benodigde informatie betreft intensiteit van de houtkap, vellingschade en oogstkosten, alsmede de relatie tussen deze aspecten en de structuur van de opstanden.
- *Ecologische beperkingen van vermindering van het grondvlak.*
- *Definitie van de beheersdoelstellingen.* Het is belangrijk te weten welke beheersdoelstellingen van belang zijn en welk niveau van satisfactie van deze doelstellingen wordt geaccepteerd. In dit onderzoek werd de doelstelling van inkomensgeneratie door middel van duurzame houtproductie in relatie met de doelstelling van conservering door diversiteit van soortengroepen en diameterklasse en de doelstelling van verbetering van de leefomstandigheden voor de locale bevolking door duurzaam aanbod van NTFPs bestudeerd.

De resultaten van TROPFOMS voor de optimale *steady state*. De optimale dunningscyclus voor duurzame houtproductie werd geraamd op 30 jaar. De oogst in de *steady state* voor de huidige commerciële soorten werd geraamd op 13,4 m^3/ha, maar bedraagt 117 m^3/ha als alle soorten worden geoogst. De regel die voor de oogst geldt, is dat alleen bomen met een diameter van 100 cm of meer mogen worden gekapt. De structuur van de opstand vóór de oogst is zodanig dat alle boomsoortengroepen aanwezig zijn met een negatief exponentiële verdeling van de bomen over de diameterklasse. Een dergelijke verdeling is karakteristiek voor ongelijkjarige bosopstanden. De resultaten laten een sterke gevoeligheid zien voor veronderstellingen ten aanzien van prijzen op stam zoals die gerelateerd zijn aan oogstkosten en uitval.

Omvorming van het huidige bos naar het steady state bos. De gemiddelde bosopstand op de TCP onderzoekslocatie geeft belangrijke verschillen te zien met de gewenste *steady state* structuur. Het totaal aantal bomen per hectare is thans hoger. Voor de meest commerciële soortengroepen is dit aantal bomen echter kleiner. Meer dan 120 jaar is nodig om de huidige opstanden op de TCP onderzoekslocatie om te vormen tot de gewenste *steady state* structuur, maar gedurende de omvorming is houtoogst met financiële resultaten mogelijk.

[8] 1 Euro = 656 FCFA

***Trade off* tussen beheersdoelen.** Gebruik van het bos door de locale bevolking kan worden bereikt zonder belangrijke consequenties voor de financiële doelstelling door middel van houtproductie. Het is eveneens mogelijk om op zijn minst één boom van iedere boomsoortengroep in iedere diameterklasse te aanwezig te doen zijn binnen een gebied van 50 ha zonder dat dit een belangrijke reductie met zich meebrengt in financiële resultaten uit de houtoogst.

Aanbevelingen voor bosbeleid en -beheer en voor verder onderzoek. De beperkingen van het onderzoek zijn in het algemeen gerelateerd aan de beschikbare informatie. De meest belangrijke beperking is die betreffende het ontbreken van PSP data in Kameroen die het gebruik van gegevens voor de groei- en opbrengstmodule van een ander Afrikaans land noodzakelijk maakte. Andere belangrijke beperkingen hebben te maken met informatie over oogstkosten. De beschikbare informatie over deze kosten stonden het niet toe om de verschillende relaties te bestuderen tussen gebruiken bij de houtoogst en kenmerken van de optimale *steady state*. Verschillende andere punten verdienen verdere studie om de resultaten van TROPFOMS te verbeteren. De volgende aanbevelingen werden gedaan voor beleid en beheer en voor onderzoek.

Bosbeleid en –beheer:

- *Verhoog toegestane minimum diameter voor kap tot 100cm.*
- *Pas bosteeltkundige ingrepen toe.*
- *Houdt een dunningscyclus van ongeveer 30 jaar aan.*
- *Schaf geschikte hulpmiddelen aan en voorzie in getraind personeel.* Het is belangrijk voor het beheer de hulpmiddelen aan te schaffen om de noodzakelijke berekeningen met het model te kunnen uitvoeren. Bovendien dient personeel beschikbaar te zijn die de software op juiste wijze kan gebruiken alsmede personeel voor planning en teeltkundige maatregelen.
- *Creëer een informatie bank.* Het beheer moet zorgvuldig alle informatie archiveren om de kwaliteit van toekomstige analyses te verbeteren. Alle informatie over de kwaliteit en kwantiteit van geoogste bosproducten en over kosten en opbrengsten dienen op de juiste manier te worden verzameld en opgeslagen.
- *Creëer een netwerk van permanente steekproefplekken.* Om het bosbeheer geleidelijk te verbeteren is een goede monteringsysteem nodig. Het is noodzakelijk dat voor elk bostype een aantal PSPs wordt in stand gehouden.

Verder onderzoek:

- *Kosten opbrengsten van teeltkundige ingrepen.* Meer kennis is nodig om de invloed te bepalen van teeltkundige ingrepen op de ontwikkeling van de opstand, in het bijzonder op de groei van bomen. Bovendien dienen de kosten van deze ingrepen te worden bestudeerd in vergelijking tot de winst in groei.
- *Relatie tussen groei en opbrengst en dichtheid van verschillende boomsoorten.*
- *Reproductieve rijpheid van verschillende boomsoorten.* Onderzoek is nodig naar de afmeting waarop de verschillende boomsoorten(groepen) voldoende levensvatbare zaden beginnen te produceren.
- *Efficiency, kosten en schade bij de houtkap.* Het is nodig de verschillende relaties te bestuderen tussen oogstkosten enerzijds en intensiteit van de houtkap en de boomgrootte anderzijds.

- *Het gebruik van het bos door de locale bevolking.* De wijze waarop de locale bevolking bomen kiest die NTFPs geven, dient beter te worden begrepen ten einde het type van restricties op de houtkap beter te kunnen formuleren en om de juiste aanbod voor de locale bevolking met gewenste producten te kunnen garanderen. Eveneens is het belangrijk het inzicht te verbeteren in de effecten van houtkap en teeltkundige ingrepen op bomen en andere planten die NTFPs geven en op dierlijke producten die worden gebruikt door de locale bevolking.
- *Royalties.* Gevoeligheid van het bosbeheer voor royalties dient te worden onderzocht. Een dergelijk onderzoek kan bijdragen aan meer inzicht in de manier waarop bosbeheer kan bijdragen aan het genereren van opbrengsten voor de overheid en de manier waarop een royaltysysteem duurzaam bosbeheer kan bevorderen.

RESUME

Titre: TROPFOMS, un modèle d'aide à la prise de décisions pour l'aménagement durable des forêts sempervirentes du sud Cameroun

Les forêts naturelles jouent un rôle important dans l'économie camerounaise tant au niveau national qu'au niveau local. Au niveau national, l'exploitation forestière industrielle, qui a lieu exclusivement dans les forêts naturelles, contribue à environ 7% au Produit Interieur Brut et à 20% aux recettes des exportations du Cameroun. Au niveau local, les forêts constituent un support de vie pour les populations qui y récoltent des produits forestiers non ligneux (PNFL). Le gouvernement du Cameroun a entrepris un certain nombre d'efforts ces dernières années pour créer un cadre adéquat à la gestion durable des forêts Camerounaises. Malgré ces efforts, il y a toujours un sentiment général qu'au Cameroun comme dans la plupart des pays tropicaux, les forêts ne sont pas gérées de manière durable. Il y a des inquiétudes concernant à la fois la dégradation des ressources forestières, et l'incapacité du secteur forestier à contribuer autant que les potentialités le permettent, à l'amélioration des conditions de vie des Camerounais.

Les mauvaises pratiques de gestion forestière qui dominent encore au Cameroun résultent à la fois d'un contexte institutionnel inadéquat, et des connaissances scientifiques et techniques insuffisantes. Afin d'atténuer progressivement les problèmes liés à l'insuffisance des connaissances, plusieurs projets de recherches ont été entrepris. Cependant, les efforts de recherche sont concentrés sur le développement des systèmes de sylviculture et de plus en plus sur la prévision de la croissance et de la production des peuplements forestiers. Les recherches concernant l'appui à la prise de décisions sont restées négligeables en foresterie tropicale. Ceci reste vrai nonobstant le fait que la planification de la gestion forestière, dans laquelle la prise décision jouent un rôle important, est reconnue comme vitale dans la poursuite de l'idéal d'aménagement forestier durable. Les décisions relatives aux paramètres d'aménagement des forêts de production tels que: la rotation des coupes, la densité et la structure des peuplements et la nécessité des traitements sylvicoles; ont souvent été prises sur la base de l'expérience subjective des décideurs ou au mieux, sur la base de connaissances scientifiques fragmentaires rassemblées dans différentes sous disciplines de la foresterie.

La recherche présentée ici a été initiée de l'idée que la planification de la gestion forestière implique la prise de décisions qui auront des effets sur la forêt maintenant et dans l'avenir. Par conséquent, la planification forestière doit utiliser les meilleures méthodes disponibles qui permettent de combiner des connaissances collectées dans différentes disciplines scientifiques, pour générer des stratégies de gestion forestière pratiques à mettre en œuvre sur le terrain. D'une telle pensée, l'objectif général de la recherche a été défini comme: mettre au point un système qui aide à la prise de décisions pour l'aménagement des forêts tropicales. Cet objectif général a été plus tard subdivisé en cinq objectifs spécifiques à savoir:

1. Mettre au point un système qui aide à la prise de décisions concernant l'aménagement des forêts de production.
2. Evaluer les effets de différentes options d'aménagement sur les revenus économiques de l'entreprise d'exploitation forestière ainsi que sur la structure de la forêt équilibrée.

3. Améliorer les connaissances les échanges de gains entre la génération des revenus à travers la production durable de grumes et l'utilisation de la forêt par les populations locales d'une part, et d'autre part entre la production durable de grumes et la conservation de la nature.
4. Faire des recommandations pour la conversion de la forêt actuelle au site du Programme Tropenbos Cameroon en une forêt équilibrée
5. Faire des suggestions et évaluer les adaptations des stratégies existantes ayant pour but l'aménagement durable des forêts de production du sud Cameroun.

Le cadre conceptuel de l'étude était basé sur deux hypothèses qui sont:

a) L'objectif de durabilité en aménagement forestier peut être atteint seulement si des contraintes écologiques, économiques et sociologiques sont prises en compte dans toute stratégie de gestion mise au point et appliquée sur le terrain.
b) Il existe des moyens de concilier la conservation des forêts (maintenance du couvert forestier et une diversité biologique élevée) avec certains niveaux d'exploitation forestière industrielle et d'utilisation de la forêt par les populations locales.

Afin de faire face à la problématique de recherche et atteindre les objectifs définis de manière effective, les questions de recherches suivantes ont été formulées:

a) Quelles approches méthodologiques peuvent être utilisées pour mettre au point un système qui aide la prise de décision pour l'aménagement des forêts tropicales du Sud Cameroun? Quelles sont les composantes d'un tel systèmes et comment peuvent-elles être liées?
b) Quels coefficients et paramètres doivent être inclus dans un système qui est conçu pour aider à la prise de décisions d'aménagement forestier au sud Cameroun et comment ces coefficients et paramètres peuvent-ils être estimés en tenant compte des données actuellement disponibles?
c) Quels résultats le système ainsi mis au point donnent-ils concernant la structure optimale, la possibilité et les revenus financiers de l'exploitation des grumes dans une forêt en équilibre? Comment ces résultats varient-ils avec les changements dans les paramètres et les objectifs d'aménagement?
d) Comment les résultats obtenus avec le système mis au point se comparent-ils avec la structure actuelle de la forêt sur le site de recherche du PTC et quelles règles peuvent être déduites pour l'aménagement durable de cette forêt?
e) Quelles améliorations de la connaissance peut on obtenir des résultats du système mis au point concernant les échanges de gains entre objectifs alternatifs d'aménagement?
f) Que peut-on recommander pour l'amélioration des stratégies d'aménagement des forêts au sud Cameroun sur la base des nouvelles connaissances obtenues du système mis au point?

Les efforts pour répondre à ces questions ont donné la direction et le cadre pour les méthodes et résultats de recherche. Sur la base des questions de recherche, les points suivants ont élaborés concernant les méthodes, les résultats et les conclusions de la recherche:

Un système d'aide à la prise de décision en aménagement des forêts de production. Un outil méthodologique d'aide à la prise de décision en aménagement des forêts tropicales a été mis au point. Le système a reçu l'acronyme de TROPFOMS de l'anglais «TROPical FOrest

Management support System» (Système d'Aide à l'Aménagement des Forêts Tropicales). Les paramètres d'aménagement sur lesquels TROPFOMS aide à la prise de décisions sont:

1. Les caractéristiques des peuplements en équilibre dont principalement la structure en terme de nombre de tiges par classe de grosseur avant et après chaque récolte et la composition du peuplement,
2. La rotation des coupes appropriée,
3. La possibilité des coupes,
4. La longueur de la période de conversion et les prélèvements attendus pendant cette période,
5. L'utilisation multiple de la forêt à travers une analyse des échanges de gains entre des utilisation alternatives du terroir forestier et particulièrement entre la production de grumes, la conservation de la nature et l'utilisation des ressources forestières par les populations et,
6. Les conséquences des changements dans les paramètres d'aménagement.

Le point focal de TROPFOMS est le peuplement forestier plutôt que l'unité forestière d'aménagement.

TROPFOMS utilise des groupes d'essences forestières au lieu des essences prises individuellement. Le système est constitué de quatre principales composantes qui sont:

- Un module de prévision de la croissance et de la production basé sur les matrices de transition
- Un module économique constitué des prix des bois sur pieds dérivés des prix des grumes sur le marché et des coûts de l'exploitation forestière
- Un module de formulation des contraintes prenant en compte la diversité des groupes d'espèces et des tailles

Un module de programmation mathématique utilisant des techniques de programmation linéaire pour rechercher les caractéristiques optimales des peuplements en équilibre et effectuant des simulations pour obtenir des prévisions des caractéristiques des peuplements forestiers pendant la transition.

Coefficients et paramètres dans TROPFOMS. Les informations dont TROPFOMS a besoin pour donner de l'aide à la prise de décisions comprennent:

- *Une définition des groupes d'essences.* Une caractéristique importante de la forêt tropicale est son hétérogénéité qui résulte de l'existence d'un grand nombre d'essences forestières. Le grand nombre d'essences forestières rend la modélisation de la croissance et de la production difficile. Ainsi, les essences doivent souvent être regroupées. Dans cette recherche, les essences forestières ont été regroupées en quatre à l'aide de l'analyse des agrégats. Le regroupement a été basé sur la valeur commerciale, l'accroissement en diamètre, le diamètre minimum d'exploitabilité et le diamètre au début de la période de croissance. Les données utilisées pour le regroupement des essences ont été récoltées dans des parcelles échantillons permanentes au Liberia étant donné l'absence de telles données au Cameroun. Les arbres de ces parcelles étaient mesurés tous les cinq ans.
- *Les probabilités de transition.* Ce sont des probabilités qu'un arbre, d'une essence donnée et appartenant à une classe de diamètre donnée, passe à la classe de diamètre supérieure ou demeure dans la classe de diamètre initiale après un certain laps de temps. Les probabilités de transition ont été estimées à l'aide de l'analyse de régression logistique. Cependant, la mortalité a été estimée à partir des résultats des études antérieures. Le passage à la futaie a été introduit comme le nombre moyen de tiges par espèces qui accèdent à la plus petite classe de grosseur au bout d'une période de croissance.

- *Les prix des arbres sur pieds.* Ils ont été exprimés en francs CFA[9] (FCFA) par arbre pour chaque groupe d'essences et chaque classe de diamètre. Les prix des arbres sur pieds ont été estimés suivant une approche résiduelle. La base de cette approche était le prix FOB des grumes desquels les coûts de disponibilité ont étaient déduits prenant en compte le rendement de l'exploitation forestière.
- *Le taux d'actualisation.* Un taux d'actualisation de 5% a été choisi basé sur la littérature. Une analyse de sensibilité a été conduite et a montré que l'impact du taux d'actualisation n'était pas très important jusqu'à 10%.
- *La liste des essences donnant des produits forestiers non ligneux.* Afin d'être capable d'incorporer l'utilisation de la forêt par les populations locales dans le système, une liste d'essences utilisées à la fois par les populations locales et l'exploitant forestier industriel était nécessaire. Une étude a été conduite au sud Cameroun pour obtenir une telle liste (van Dijk, in press).
- *Les résultats de l'inventaire forestier.* Ces résultats sont nécessaires pour l'estimation des caractéristiques de la période de conversion. Les résultats de l'inventaire ont donné des informations sur la structure actuelle et la densité d'un peuplement moyen exprimée comme nombre de tiges par hectare, par groupe d'espèces et par classe de diamètre.
- *Des informations techniques sur l'exploitation forestière.* Les informations nécessaires concernaient l'intensité de l'exploitation, les dégâts et les coûts d'exploitation, et les relations entre ces éléments ainsi qu'avec la structure des peuplements forestiers.
- *Les limites écologiques de la réduction de la surface terrière.*
- *La définition des objectif d'aménagement.* Il est important de savoir quels objectifs d'aménagement forestier sont à considérer et quels niveaux de satisfaction de ces objectifs sont acceptables. La présente recherche a examiné l'objectif de génération des revenus à travers une production durable de grumes, en relation avec les objectifs de conservation de la nature à travers une diversité des espèces et des classes de diamètres, et l'amélioration des conditions de vie des populations locales à travers l'approvisionnement continu en PFNL.

Les résultats de TROPFOMS pour une forêt en équilibre. La rotation des coupes optimale pour une production de grumes durable a été estimée à 30 ans. Le prélèvement à l'équilibre pour les essences qui sont actuellement commercialisées a été estimé à 13.4 m^3/ha mais peut devenir aussi élevé que 117 m^3/ha si toutes les essences sont commercialisées. La règles des prélèvement est de récolter les arbres de 100 cm de diamètre ou plus. La structure des peuplements avant exploitation consiste pour tous les groupes d'essences en des courbes exponentielles négatives. Une telle distribution est caractéristique des forêts à peuplements innéquiennes. Les résultats ont montré une grande sensibilité aux hypothèses sur les prix des bois sur pied, spécialement en relation avec les coûts et dégâts d'exploitation.

La conversion de la forêt actuelle en forêt équilibrée. Le peuplement forestier moyen du site du Programme Tropenbos Cameroun présente des différences importantes avec la forêt équilibrée désirée. Le nombre actuel d'arbres par hectare est actuellement plus élevé. Cependant, pour les groupes d'essences les plus commercialisées, ce nombre est plus petit. Il demanderait 120 ans pour convertir la forêt actuelle du site de recherche du PTC en forêt équilibrée, toutefois, pendant la conversion, il est possible de conduire une exploitation forestière financièrement rentable.

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[9] 1 Euro = 656 FCFA

Echanges de gains entre objectifs de gestion. La forêt peut être utilisée par les populations locales sans grand danger pour l'objectif de génération des revenus à travers l'exploitation industrielle de la forêt. De même, il est possible d'avoir au moins un arbre par groupe d'essence et par classe de diamètre sur une superficie de référence de 50 ha sans réduction importante des revenus de l'exploitation industrielle de la forêt.

Recommandations pour la politique et la gestion forestière et pour des recherches futures. La recherche a été limitée par la qualité des informations disponibles. La plus importante limite est venue du manque de données sur les parcelles échantillons permanentes au Cameroun, ceci a obligé d'utiliser des données d'autres pays africains pour le module de prévision de la croissance et de la production. Les autres limites importantes sont liées aux coûts de l'exploitation qui influencent les prix des bois sur pieds. Les informations disponibles sur ces coûts n'ont pas permis de faire des investigations poussées sur les relations entre les techniques d'exploitation et les caractéristiques optimales des peuplements forestiers. Beaucoup d'autres aspects méritent d'être étudiés pour améliorer les résultats de TROPFOMS. Les recommandations suivantes ont été faites pour la politique et la gestion ainsi que pour la recherche:

Politique et gestion forestière:

- *Monter les diamètres minimums d'exploitabilité à 100 cm*
- *Mener des opérations sylvicoles*
- *Adopter une rotation de 30 ans*
- *Acquérir des équipements de calcul appropriés et un personnel formé.* Il est important pour les gestionnaires d'acquérir des équipements capable d'effectuer tous les calculs exigés par le model. En plus, un personnel formé capable d'utiliser correctement des logiciels et mener des opérations sylvicoles est nécessaire.
- *Créer une base de données.* Les gestionnaire des forêts doivent archiver toutes les informations relatives à l'aménagement forestier, ceci permettra d'améliorer les analyses dans l'avenir. Toutes les informations concernant tant les quantités et qualités des produits forestiers récoltés que les coûts et bénéfices doivent être collectées et conservées dans de bonnes conditions.
- *Créer un réseau de parcelles échantillons permanentes.* Afin d'améliorer progressivement la gestion forestière, on a besoin d'un bon système de suivi de la forêt. Il est nécessaire d'avoir un certain nombre de parcelles échantillons pour chaque type de forêt.

Recherches nécessaires:

- *Coûts et bénéfices des opérations sylvicoles.* On a besoin de plus de connaissances pour évaluer l'impact des traitements sylvicoles sur la dynamique de la forêt de façon générale, et en particulier sur la croissance des arbres. En plus, les coûts des traitements sylvicoles doivent être étudiés en relation avec les gains en croissance.
- Les relations entre la croissance et la production, et la densité des peuplements forestiers.
- *La maturité sexuelle des différentes essences forestières.* Il est nécessaire de mener une étude visant à déterminer les grosseurs auxquelles les différents groupes d'espèces commencent à donner des graines viables en quantité suffisante.
- *Le rendement, le coût et les dégâts de l'exploitation forestière.* Il existe un besoin de caractériser des relations entre les coûts de l'exploitation forestière d'une part, et l'intensité de l'exploitation et la grosseur des arbres d'autre part.

- *L'utilisation de la forêt par les populations locales.* La manière avec laquelle les populations locales choisissent les arbres sur lesquels elles récoltent les PFNL doit être mieux comprise afin de mieux concevoir les types de restrictions à imposer à l'exploitation des grumes et garantir un bon approvisionnement des populations locales en produits désirés. De la même façon, il est important de mieux comprendre les effets de l'exploitation forestière et des traitements sylvicoles sur les arbres fournisseurs de PFNL, ainsi que sur les autres végétaux et animaux utilisés par les populations locales.
- *Les royalties.* La sensibilité de l'aménagement forestier aux royalties doit faire l'objet d'investigations. De telles investigations peuvent permettre de mieux comprendre la manière avec laquelle la gestion des forêts tropicales peut mieux contribuer aux revenus publics, et de quelles manières les système de revenues forestiers peuvent contribuer à l'aménagement durable des forêts.

Annex 1: List of species analyzed for grouping

Species[10]	Number of trees	Average diameter (cm)	Average diameter increment (cm)	Commercial status[11]	DME[12] (cm)
Allanblackia floribunda	9	12.53	0.25	2	50
Alstonia boonei	8	117.00	5.38	2	60
Anthonota fragrans	184	40.04	2.83	2	50
Canarium schweinfurthii	14	61.28	2.38	1	60
Ceiba pentandra	82	36.81	3.83	2	60
Dacryodes klaineana	455	29.62	1.04	2	50
Daniella oblonga	14	28.82	3.19	2	60
Diospyros crassiflora	247	13.19	0.71	1	50
Diospyros sanza-minika	947	21.17	0.75	2	50
Entandrophragma angolense	15	60.33	4.04	1	80
Entandrophragma candollei	9	18.17	1.16	1	80
Entandrophragma cylindricum	31	13.73	0.75	1	100
Entandrophragma utile	48	35.48	1.54	1	80
Erythrophleum ivorense	25	60.39	3.43	1	60
Erythroxylum mannii	36	34.35	4.39	2	60
Fagara heitzii	10	32.13	4.1	2	60
Fagara macrophylla	6	62.30	0	2	60
Funtumia elastica	12	57.26	1.73	2	50
Garcinia cola	40	14.31	0.88	2	50
Irvingia gabonensis	17	18.60	1.14	2	50
Khaya ivorensis	19	56.10	6.72	1	80
Lannea welwitschii	7	18.40	1.45	2	50
Lophira alata	8	67.23	1.25	1	60
Lovoa trichilioides	68	33.76	2.85	1	80
Mammea africana	22	55.4	1.11	2	60
Nauclea diderrichii	16	48.39	1.25	1	60
Nesogordonia papaverifera	130	49.86	3.08	1	50
Newtonia griffoniana	26	13.82	2.06	2	50
Panda oleosa	159	28.88	1.6	2	50
Parinari excelsa	67	57.88	2.40	2	50
Parkia bicolor	108	75.61	0.78	2	50

[10] See annex 2 for pilot names
[11] 1=currently commercial, 2=potentialy commercial
[12] Minimum Diameter Exploitable

Pentaclethra macrophylla	17	65.02	2.2	2	50
Pentadesma grandifolia	19	37.23	1.1	2	50
Pericopsis elata	37	25.02	0.53	1	100
Petersianthus macrocarpus	40	12.91	0.65	2	50
Piptadeniastrum africanum	37	41.6	0.7	2	60
Pterocarpus soyauxii	7	11.24	1.00	1	60
Pterygota macrocarpa	134	51.19	5.25	1	60
Pycnanthus angolensis	122	67.88	2.09	1	60
Ricinodendron heudelotii	13	87.42	1.55	2	50
Scottelia coriacea	231	23.01	0.86	2	50
Terminalia superba	36	55.81	3.05	1	60
Triplochiton scleroxylon	16	74.88	1.61	1	80
Uapaca guineensis	168	76.57	2.27	2	50
Xylopia staudtii	19	14.11	6.56	2	50
Total	**3735**				

Annex 2: Correspondence between pilot and scientific names for tree species[13] inventoried at the TCP research site

Pilot names	***Scientific names***
Abale	*Petersianthus macrocarpus*
Abam a poil rouge	*Gambeya beguei*
Abam fruts jaune	*Gambeya gigantea*
Abam littoral	*Berlinia craibiana*
Abam vrai	*Gambeya lacourtiana*
Abura	*Mitragyna stipulosa*
Acajou à grandes folioles	*Khaya grandifoliola*
Acajou blanc	*Khaya anthotheca*
Acajou de bassam	*Khaya ivorensis*
Aiélé	*Canarium schweinfurthii*
Ako A	*Antiaris africana*
Ako W	*Antiaris welwitschii*
Akodiakede	*Pterygota bequaertii*
Alep	*Desbordesia glaucescens*
Alumbi	*Julbernardia seretii*
Amvout	*Tricoscypha acuminata*
Amvout a poils	*Tricoscypha abut*
Andok	*Irvingia gabonensis*
Andok Ngoe	*Irvingia grandifolia*
Andok osoe	*Irvingia excelsa*
Andoung rose	*Monopetalanthus letestui*
Angelin	*Andira inermis*
Angueuk	*Ongokea gore*
Aningré A	*Aningeria altissima*
Aningré R	*Aningeria robusta*
Anzem	*Copefera religiosa*
Asila koufani	*Maranthes chrysophylla*
Assamela	*Pericopsis elata*
Atom	*Dacryodes macrophylla*
Avodiré	*Turraeanthus africanus*
Awoura	*Paraberlinia bifoliolata*
Ayous	*Triplochiton scleroxylon*
Azobé	*Lophira alata*
Bahia	*Mitragyna ciliata*
Bete	*Mansonia altissima*
Bilinga	*Nauclea diderrichii*
Bodia	*Anopyxis klaineana*

[13] Most of these species are also met in west Africa

Bongo H	*Faraga heitzii*
Bossé clair	*Guarea cedrata*
Bossé Foncé	*Guarea thompsonii*
Bubinga E	*Guibourtia ehie*
Bubinga Rouge	*Guibourtia demeusei*
Bubinga Rose	*Guibourtia tessmannii*
Crabwood d'Afrique	*Carapa procera*
Crabwood de montagne	*Carapa grandiflora*
Dabéma	*Piptadeniastrum africanum*
Dambala	*Discoglypremna caloneura*
Diana	*Celtis tessmannii*
Diana parallele	*Celtis adolfi-friderici*
Diana Z	*Celtis zenkeri*
Dibetou / Bibolo	*Lovoa trichilioides*
Difou	*Morus mesozygia*
Divida	*Scorodophleus zenkeri*
Doussié blanc	*Afzelia pachyloba*
Doussié rouge	*Afzelia bipindensis*
Doussié sanaga	*Afzelia africana*
Ebène	*Diospyros crassiflora*
Ebiara edea	*Berlinia bracteosa*
Ebiara Yaounde	*Berlinia grandiflora*
Ekaba	*Tetraberlinia bifoliolata*
Ekop leke	*Brachystegia zenkeri*
Ekop naga akolodo	*Brachystegia eurycoma*
Ekop naga nord-ouest	*Brachystegia kennedyi*
Ekop ngombe mamelle	*Didelotia unifoliolata*
Ekouné	*Coelocaryon preussii*
Emien	*Alstonia boonei*
Esabem	*Berlinia confusa*
Eseng grandes feuilles	*Parkia filicoidea*
Essak	*Albizia glaberrima*
Essesang	*Ricinodendron heudelotii*
Esson	*Stemonocoleus micranthus*
Etimoé	*Copaïfera mildbraedii*
Eveuss	*Klainedoxa gabonensis*
Evoula	*Vitex grandifolia*
Eyek	*Pachyelasma tessmannii*
Eyong	*Eribroma oblongum*
Eyoum	*Dialium pachyphyllum*
Eyoum petites feuilles	*Dialium dinklagei*
Eyoum rouge	*Dialium bipindense*
Faro	*Daniellia ogea*
Faro mezilli	*Daniellia klainei*
Fraké	*Terminalia superba*

Framiré	*Terminalia ivorensis*
Fromager	*Ceiba pentandra*
Gombe	*Didelotia letouzeyi*
Gombe zing	*Toubaouate brevipaniculata*
Ilomba	*Pycnanthus angolensis*
Johimbe	*Pausinystalia johimbe*
Kanda	*Beilschmiedia obscura*
Kanda grandes feullies	*Beilschmiedia anacardioides*
Kapokier	*Bombax buonopozense*
Kekele	*Holoptelea grandis*
Kibakoko feuilles argentees	*Anthonotha fragrans*
Kondroti	*Rhodognaphalon brevicuspe*
Kossipo	*Entandrophragma candollei*
Kotibé	*Nesogordonia papaverifera*
Koto	*Pterygota macrocarpa*
Kumbi	*Lannea welwitschii*
Landa	*Erythroxylum mannii*
Lantandza	*Albizia ferruginea*
Lati	*Amphimas ferrugineus*
Limbali	*Gilbertiodendron dewevrei*
Lo	*Parkia bicolor*
Longhi	*Guambea africana*
Lotofa	*Sterculia rhinopetala*
Makoré	*Tieghemella africana*
Mambode	*Detarium macrocarpum*
Miama	*Calpocalyx heitzii*
Miove	*Staudtia kamerunensis*
Moabi	*Baillonella toxisperma*
Moambe jaune	*Enantia chlorantha*
Movingui	*Distemonanthus benthamianus*
Mubala	*Pentaclethra macrophylla*
Mukulungu	*Autranella congolensis*
Mukumari	*Cordia platythyrsa*
Mutondo	*Funtumia elastica*
Naga	*Brachystegia cynometriodes*
Naga parrallele	*Brachystegia mildbraedii*
Nganga	*Cynometra hankei*
Nom abam	*Gambeya boukokoensis*
Nom andok	*Irvingia robur*
Nom kanda	*Beilschmiedia sp.*
Oboto	*Mammea africana*
Odouma	*Gossweilerodendron joveri*
Ohia	*Celtis mildbraedii*
Okan	*Cylicodiscus gabunensis*
Okoumé	*Aucoumea klaineana*

Omang bikodok	*Maranthes gabunensis*
Onzambili K	*Antrocaryon klaineanum*
Onzambili M	*Antrocaryon micraster*
Osanga	*Pteleopsis hylodendron*
Ouochi	*Albizia zygia*
Ovoga	*Poga oleosa*
Ozigo	*Dacryodes buettneri*
Ozouga	*Sacoglottis gabonensis*
Padouk blanc	*Pterocarpus mildbraedii*
Padouk rouge	*Pterocarpus soyauxii*
Pao rosa	*Swartzia fistuloides*
Podo	*Podocarpus milanjianus*
Rikio	*Uapaca guineensis*
Saliyemo	*Albizia adianthifolia*
Sapelli	*Entandrophragma cylindricum*
Sipo	*Entandrophragma utile*
Tali	*Erythrophleum ivorense*
Tali Yaounde	*Erythrophleum suaveolens*
Tchitola	*Oxystigma oxyphyllum*
Tiama	*Entandrophragma angolense*
Tiama congo	*Entandrophragma congoense*
Tola	*Gossweilerodendron balsamiferum*
Tsanya-akela	*Pausinystalia macroceras*
Wamba	*Tessmannia anomala*
Wamba grande feuilles	*Tessmannia africana*
Wengé	*Milletia laurentii*
Yungu	*Drypetes gossweileri*
Zingana	*Microberlinia bisulcata*
Zoa ele	*Monopetalanthus hedinii*

Annex 3: SPSS Cluster analysis output for species aggregation

Data written to the working file:
6 variables and 43 cases written.

Variable: SPP	Type: String	Format: A12
Variable: NTREES	Type: Number	Format: F12.2
Variable: DIA	Type: Number	Format: F10.2
Variable: DINC	Type: Number	Format: F10.2
Variable: DME	Type: Number	Format: F10.2
Variable: FOB	Type: Number	Format: F10.2

Variable codes:

SPP	= Species
DIA	= Diameter at first mensuration
DINC	= Diameter increment
DME	= Minimum diameter exploitable
FOB	= Free on board price
NTREES	= Number of trees

Case Processing Summary:

Cases					
Valid		Missing		Total	
N	Percent	N	Percent	N	Percent
43	100.0%	0	0%	43	100.0%

A Squared Euclidean Distance used

Cluster Membership:

Case	4 Clusters
1:Acajou	1
2:Ayous	1
3:Bibolo	1
4:Tiama	1
5:Adjouaba	2
6:Afane	2
7:Andock	2
8:Babang	2
9:Essia	2
10:Kiasose	2
11:Kumbi	2
12:Natui	2
13:Ngobisolbo	2
14:Nsangomo	2
15:Odjobi	2
16:Tola	2

17:Aiele	3
18:Azobe	3
19:Bilinga	3
20:Bongo	3
21:BongoH	3
22:Dabema	3
23:Ezang	3
24:Faro	3
25:Frake	3
26:Fromager	3
27:Ilomba	3
28:Kibekoko	3
29:Kotibe	3
30:Koto	3
31:Landa	3
32:Mubala	3
33:Mutondo	3
34:Oboto	3
35:Parkia	3
36:Rikio	3
37:Sougue	3
38:Tali	3
39:Assamela	4
40:Ebene	4
41:Kossipo	4
42:Sapelli	4
43:Sipo	4

HIERARCHICAL CLUSTER ANALYSIS

Dendrogram using Centroid Method

Rescaled Distance Cluster Combine

```
    C A S E .....0..................5.................10 .............15 ......... 20........... 25

Label       Num +----------------+--------------+-------------+----------+-----------+
Babag       8   -+
Ngobisolbo  13  -+
Andock      7   -+
Kumbi       11  -+
Odjobi      15  -+-----+
Tola        16  -+     I
Essia       9   -+     I
Nsangomo    14  -+     I
Adjouaba    5   -+     +---------------------+
Kiasose     10  -+-----+                     I
Afane       6   -+     I                     I
Natui       12  -------+                     I
Frake       25  -+                           I
Tali        38  -+-------+                   I
Aiele       17  -+       +-----+             I
Kotibe      29  ---------+     I             I
Bongo       20  -+---+         I             +--------------------------+
Oboto       34  -+   I         +-------+     I                          I
Bilinga     19  ---+-----+     I       I     I                          I
Dabema      22  ---+     I     I       I     I                          I
Azobe       18  ---+     I     I       I     I                          I
Mutondo     33  -+---+   +-----+       I     I                          I
Sougue      37  -+   +---+             I     I                          I
Mubala      32  -+---+   I             I     I                          I
Rikio       36  -+   I   I             +-----+                          I
Ilomba      27  -----+   I                   I                          I
Ezang       23  ---+-----+                   I                          +----------------------------------------------+
Parkia      35  ---+                         I                          I                                              I
BongoH      21  -+                           I                          I                                              I
Landa       31  -+                           I                          I                                              I
Fromager    26  -+-----+                     I                          I                                              I
Faro        24  -+     +-------+             I                          I                                              I
Kibekoko    28  -------+       +-------------+                          I                                              I
Koto        30  ---------------+                                        I                                              I
Acajou      1   -+-----------------+                                    I                                              I
Tiama       4   -+                 +---------+                          I                                              I
Bibolo      3   -------------------+         +--------------------------+                                              I
Ayous       2   -----------------------------+                                                                         I
Assamela    39  ---+-------------+                                                                                     I
Sapelli     42  ---+             +-------------------------------------------------------------------------------------+
Kossipo     41  -----+-----+     I
Sipo        43  -----+     +-----+
Ebene       40  -----------+
```

Annex 4: Summary of data used for the development of bole volume equations

Species	Felled trees	Standing trees	Total
		number of trees	
Aiele	0	12	12
Amouk	0	3	3
Azobe	34	39	73
Bibolo	5	10	15
Bilinga	0	6	6
Bongo	0	6	6
Bosse	3	0	3
Dabema	0	10	10
Diana	0	4	4
Doussie	4	9	13
Ebiara	0	5	5
Ekoune	0	8	8
Emien	0	9	9
Eyong	0	10	10
Frake	2	55	57
Fromager	0	5	5
Illomba	0	5	5
Iroko	0	11	11
Kossipo	1	1	2
Kumbi	0	2	2
Moabi	2	13	15
Movingui	8	58	66
Mutondo	0	4	4
Ngollon	7	0	7
Niove	1	7	8
Okang	0	6	6
Ozambili	0	8	8
Padouk	16	52	68
Sipo	1	3	4
Tali	17	34	51
Tiama	2	1	3
Tola	0	1	1
Total	**103**	**397**	**500**

Annex 5: Statistics of the estimation of bole volume equations for different species groups

A.5.1: Statistics for curve estimation models for species group 1

Method	R^2	Standard Error	b_0	b_1	b_2	curve model
Linear	0.896	1.442	-4.887	14.914		$V=b_0+b_1(DBH)$
Logarithmic	0.811	1.948	9.614	9.174		$V=b_0+b_1\ln(DBH)$
Quadratic	0.915	1.320	-1.020	2.451	8.510	$V=b_0+b_1(DBH)+b_2(DBH)^2$
Power	0.932	0.267	9.891	2.247		$V=b_0(DBH)^{b1}$

A.5.2: Statistics for curve estimation models for species group 2

Method	R^2	Standard Error	b_0	b_1	b_2	curve model
Linear	0.864	0.936	-3.610	11.610		$V=b_0+b_1(DBH)$
Logarithmic	0.744	1.283	6.818	6.104		$V=b_0+b_1 ln(DBH)$
Quadratic	0.898	0.813	-0.713	1.513	7.808	$V=b_0+b_1(DBH)+b_2(DBH)^2$
Power	0.910	0.255	8.872	2.270		$V=b_0(DBH)^{b1}$

A.5.3: Statistics for curve estimation models for species group 3

Method	R^2	Standard Error	b_0	b_1	b_2	curve model
Linear	0.816	2.768	-5.507	15.723		$V=b_0+b_1(DBH)$
Logarithmic	0.680	3.653	10.546	10.143		$V=b_0+b_1 ln(DBH)$
Quadratic	0.842	2.572	-1.519	4.376	6.526	$V=b_0+b_1(DBH)+b_2(DBH)^2$
Power	0.886	0.413	8.683	2.196		$V=b_0(DBH)^{b1}$

A.5.4: Statistics for curve estimation models for species group 4

Method	R^2	Standard Error	b_0	b_1	b_2	curve model
Linear	0.911	3.338	-8.524	21.622		$V=b_0+b_1(DBH)$
Logarithmic	0.708	6.067	15.009	15.618		$V=b_0+b_1 ln(DBH)$
Quadratic	0.944	2.671	-2.579	6.598	6.876	$V=b_0+b_1(DBH)+b_2(DBH)^2$
Power	0.946	0.326	9.576	2.264		$V=b_0(DBH)^{b1}$

In the four preceding tables the terms are defined as:
V= average tree volume for a given diameter in m^3
b_o = a constant
b_n = regression coefficient
DBH = tree diameter at breast height in m
ln = the natural log base
R^2= the coefficient of determination

Annex 6: Summary of permanent sample plots data

Plot	Ing1	Ing2	Ing3	Ing4	Basal area (m2)	nt1	nt2	nt3	nt4	Ntot
1	0	10	18	0	25.27	60	114	65	59	298
2	1	10	19	0	22.8	64	145	70	63	342
3	0	55	1	0	25.06	89	136	98	96	419
4	0	28	2	0	25.86	55	152	59	55	321
5	0	71	1	1	23.71	71	86	82	87	326
6	0	45	16	0	20.10	69	95	79	91	334
7	0	30	13	2	21.24	85	147	89	108	429
8	1	60	30	7	25.02	59	72	64	100	295
9	0	11	0	1	22.40	72	87	101	117	377
10	0	43	5	4	23.69	59	103	65	68	295
11	0	22	5	2	25.70	57	209	67	57	390
12	0	11	4	1	19.95	71	188	76	71	406
13	0	12	1	0	19.95	57	70	71	55	253
14	1	19	10	3	24.46	73	97	113	103	386
15	3	22	6	0	20.46	73	136	75	79	363
16	3	30	4	0	28.64	86	178	92	90	446
17	0	18	21	1	21.51	63	100	70	61	294
18	0	33	7	3	20.65	76	105	71	69	321
19	0	12	20	0	21.60	73	128	81	70	352
20	2	30	15	1	21.75	81	199	84	82	446
Total	11	572	198	26	459.82	1393	2547	1572	1581	7093
Average	0.6	28.6	9.9	1.3	22.991	69.7	127.35	78.6	79.05	354.65

Notes: Ing1, Ing2, Ing3 and Ing4 represent the number of ingrowth trees for respective species group in each plot. Similarly, nt1, nt2, nt3 and nt4 represent number of trees per plot and respective species groups, while Ntot represents the total number of trees per plot.

Annex 7: Statistics on variable selection for the estimation of transitions probabilities by logistic regression analysis[14]

A.7.1: Species group 1 (59 cases)

Variable	B	S.E.	Wald	Sig
BA	-0.1088	0.0878	1.5348	0.2154
D^2	-6.8518	3.5569	3.7107	0.0541
D	8.1934	4.1212	3.9527	0.0468
N	-0.0032	0.0053	0.3489	0.5548
Constant	1.6013	3.1365	0.2606	0.6097

A.7.2: Species group 2 (1220 cases)

Variable	B	S.E.	Wald	Sig.
BA	-0.2907	0.2290	0.8487	0.1720
D^2	-12.4234	2.3987	26.8254	0.0000
D	13.3004	2.1492	38.2965	0.0000
N	-0.0010	0.0019	0.2709	0.6027
Constant	2.7677	1.0684	6.7100	0.0096

A.7.3: Species group 3 (200 cases)

Variable	B	S.E.	Wald	Sig.
BA	-0.1180	0.0829	2.0263	0.1546
D^2	-10.4284	1.8956	30.2651	0.0000
D	15.1394	2.6275	33.2004	0.0000
N	0.0046	0.0037	1.5354	0.2153
Constant	-3.5668	1.8879	3.5694	0.0589

A.7.4: Species group 4 (256 cases)

Variable	B	S.E	Wald	Sig.
BA	-0.92135	0.5468	1.7352	0.2635
D^2	-7.1892	6.8265	1.1091	0.2923
D	11.1278	5.5820	3.9741	0.0462
N	1.0027	0.7592	0.6235	0.1985
Constant	-3.9901	0.8209	23.6273	0.0000

BA = basal area
D^2 = diameter squared
D = diameter
N = number of trees in the stand
B = regression coefficient
S.E = standard Error
Sig. = level of significance

[14]These statistics were considered only for variable selection. Once the significant variables were known, new coefficients were estimated based only on the significant variables.

Annex 8: Data for testing the homogeneity of measurements

Tree number	Standing volume (m^3)	Felled volume (m^3)	Difference
1	14.53	14.58	-0.05
2	10.27	10.01	0.26
3	12.94	12.60	0.34
4	11.84	12.04	-0.20
5	33.13	33.44	-0.31
6	14.08	13.49	0.59
7	17.64	17.50	0.14
8	9.96	10.01	-0.05
9	8.86	9.96	-1.10
10	15.55	14.64	0.91
11	16.07	15.28	0.79
12	8.61	8.62	-0.01
13	36.10	37.17	-1.07
14	11.63	11.24	0.39
15	7.93	8.09	-0.16
16	12.81	13.33	-0.52
17	8.57	8.93	-0.35
18	11.44	13.33	-1.88
19	9.39	8.50	0.89
20	14.03	13.55	0.48
21	14.10	14.64	-0.55
22	14.66	13.96	0.70
23	13.71	14.24	-0.53
24	8.13	7.05	1.09
25	18.49	18.27	0.22
26	20.99	19.77	1.23
27	14.63	14.25	0.38

Annex 9: Estimated growth matrices per species group

A.9.1: Growth matrix for species group 1

0.59	0	0	0	0	0	0	0	0	0
0.31	0.47	0	0	0	0	0	0	0	0
0	0.43	0.37	0	0	0	0	0	0	0
0	0	0.53	0.31	0	0	0	0	0	0
0	0	0	0.59	0.28	0	0	0	0	0
0	0	0	0	0.62	0.29	0	0	0	0
0	0	0	0	0	0.61	0.33	0	0	0
0	0	0	0	0	0	0.57	0.41	0	0
0	0	0	0	0	0	0	0.49	0.62	0
0	0	0	0	0	0	0	0	0.38	0.9

A.9.2: Growth matrix for species group 2

0.76	0	0	0	0	0	0	0	0	0
0.14	0.68	0	0	0	0	0	0	0	0
0	0.22	0.61	0	0	0	0	0	0	0
0	0	0.29	0.56	0	0	0	0	0	0
0	0	0	0.34	0.55	0	0	0	0	0
0	0	0	0	0.35	0.56	0	0	0	0
0	0	0	0	0	0.34	0.61	0	0	0
0	0	0	0	0	0	0.29	0.68	0	0
0	0	0	0	0	0	0	0.22	0.75	0
0	0	0	0	0	0	0	0	0.15	0.9

A.9.3: Growth matrix for species group 3

0.82	0	0	0	0	0	0	0	0	0
0.08	0.7	0	0	0	0	0	0	0	0
0	0.2	0.54	0	0	0	0	0	0	0
0	0	0.36	0.38	0	0	0	0	0	0
0	0	0	0.52	0.28	0	0	0	0	0
0	0	0	0	0.62	0.23	0	0	0	0
0	0	0	0	0	0.67	0.22	0	0	0
0	0	0	0	0	0	0.68	0.26	0	0
0	0	0	0	0	0	0	0.64	0.35	0
0	0	0	0	0	0	0	0	0.55	0.9

A.9.4: Growth matrix for species group 4

0.82	0	0	0	0	0	0	0	0	0
0.08	0.77	0	0	0	0	0	0	0	0
0	0.13	0.69	0	0	0	0	0	0	0
0	0	0.21	0.59	0	0	0	0	0	0
0	0	0	0.31	0.47	0	0	0	0	0
0	0	0	0	0.43	0.33	0	0	0	0
0	0	0	0	0	0.57	0.21	0	0	0
0	0	0	0	0	0	0.69	0.11	0	0
0	0	0	0	0	0	0	0.79	0.03	0
0	0	0	0	0	0	0	0	0.87	0.9

Annex 10: Sample list file of AIMMS for the determination of steady state characteristics for the 30-year cutting cycle

!Extended formulation CC=30

Variables:
y11->[0,inf),
y12->[0,inf),
Y13->[0,inf),
y14->[0,inf),
y15->[0,inf),
y16->[0,inf),
y17->[0,inf),
y18->[0,inf),
y19->[0,inf),
y10->[0,inf),
h11->[0,inf),
h12->[0,inf),
h13->[0,inf),
h14->[0,inf),
h15->[0,inf),
h16->[0,inf),
h17->[0,inf),
h18->[0,inf),
h19->[0,inf),
h10->[0,inf),
y21->[0,inf),
y22->[0,inf),
Y23->[0,inf),
y24->[0,inf),
y25->[0,inf),
y26->[0,inf),
y27->[0,inf),
y28->[0,inf),
y29->[0,inf),
y20->[0,inf),
h21->[0,inf),
h22->[0,inf),
h23->[0,inf),
h24->[0,inf),
h25->[0,inf),
h26->[0,inf),
h27->[0,inf),
h28->[0,inf),
h29->[0,inf),
h20->[0,inf),
y31->[0,inf),
y32->[0,inf),

```
Y33->[0,inf),
y34->[0,inf),
y35->[0,inf),
y36->[0,inf),
y37->[0,inf),
y38->[0,inf),
y39->[0,inf),
y30->[0,inf),
h31->[0,inf),
h32->[0,inf),
h33->[0,inf),
h34->[0,inf),
h35->[0,inf),
h36->[0,inf),
h37->[0,inf),
h38->[0,inf),
h39->[0,inf),
h30->[0,inf),
y41->[0,inf),
y42->[0,inf),
Y43->[0,inf),
y44->[0,inf),
y45->[0,inf),
y46->[0,inf),
y47->[0,inf),
y48->[0,inf),
y49->[0,inf),
y40->[0,inf),
h41->[0,inf),
h42->[0,inf),
h43->[0,inf),
h44->[0,inf),
h45->[0,inf),
h46->[0,inf),
h47->[0,inf),
h48->[0,inf),
h49->[0,inf),
h40->[0,inf),

d1->[0,inf),
d2->[0,inf),
d3->[0,inf),
d4->[0,inf),
DTOT->[0,inf),
d11->[0,inf),
d12->[0,inf),
d13->[0,inf),
d14->[0,inf),
d15->[0,inf),
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d16->[0,inf),
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d18->[0,inf),
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d26->[0,inf),
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d45->[0,inf),
d46->[0,inf),
d47->[0,inf),
d48->[0,inf),
d49->[0,inf),
d40->[0,inf),

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l25->[0,inf),
l26->[0,inf),
l27->[0,inf),
l28->[0,inf),
l29->[0,inf),
l20->[0,inf),
l30->[0,inf),
l40->[0,inf),

NY1->[0,inf),
NY2->[0,inf),

```
NY3->[0,inf),
NY4->[0,inf),
NH1->[0,inf),
NH2->[0,inf),
NH3->[0,inf),
NH4->[0,inf),
NY->[0,inf),
NH->[0,inf),
NTOT->[0,inf),
BAH1->[0,inf),
BAH2->[0,inf),
BAH3->[0,inf),
BAH4->[0,inf),
BAH->[0,inf),
BAY->[0,inf),
BAY1->[0,inf),
BAY2->[0,inf),
BAY3->[0,inf),
BAY4->[0,inf),
VH1->[0,inf),
VH2->[0,inf),
VH3->[0,inf),
VH4->[0,inf),
VH->[0,inf),
BATOT->[0,inf);

Constraints:

!sustained yield constraints
S1..0.04*(y11-d11)=y11-1.40,
S2..0.08*(y11-d11)+0.01*(y12-d12)=y12-0.73,
S3..0.11*(y11-d11)+0.04*(y12-d12)+0.00*(y13-d13)=y13-0.39,
S4..0.12*(y11-d11)+0.08*(y12-d12)+0.01*(y13-d13)+0.00*(y14-h14-d14)=y14-0.20,
S5..0.10*(y11-d11)+0.13*(y12-d12)+0.05*(y13-d13)+0.01*(y14-h14-d14)+0.00*(y15-h15-
d15)=y15-0.08,
s6..0.06*(y11-d11)+0.15*(y12-d12)+0.12*(y13-d13)+0.04*(y14-h14-d14)+0.01*(y15-h15-
d15)+0.00*(y16-h16-d16)=y16-0.02,
s7..0.02*(y11-d11)+0.10*(y12-d12)+0.18*(y13-d13)+0.12*(y14-h14)+0.05*(y15-h15-
d15)+0.01*(y16-h16-d16)+0.00*(y17-h17-d17)=y17,
s8..0.03*(y12-d12)+0.13*(y13-d13)+0.20*(y14-h14-d14)+0.15*(y15-h15-d15)+0.07*(y16-
h16-d16)+0.02*(y17-h17-d17)+0.00*(y18-h18-d18)=y18,
s9..0.03*(y13)+0.14*(y14-h14-d14)+0.24*(y15-h15-d15)+0.25*(y16-h16-d16)+0.20*(y17-
h17-d17)+0.12*(y18-h18-d18)+0.06*(y19-h19-d19)=y19,
s10..0.02*(y14-h14-d14)+0.11*(y15-h15-d15)+0.26*(y16-h16-d16)+0.42*(y17-h17-
d17)+0.55*(y18-h18-d18)+0.64*(y19-h19-d19)+0.50*(y10-h10-d10)=y10,


s11..0.193*(y21-d21)=y21-96.20,
s12..0.164*(y21-d21)+0.099*(y22-d22)=y22-27.41,
```

s13..0.102*(y21-d21)+0.149*(y22-d22)+0.052*(y23-d23)=y23-7.99,
s14..0.050*(y21-d21)+0.140*(y22-d22)+0.120*(y23-d23)+0.031*(y24-h24-d24)=y24-2.01,
s15..0.018*(y21-d21)+0.094*(y22-d22)+0.160*(y23-d23)+0.107*(y24-h24-d24)+0.028*(y25-h25-d25)=y25-0.36,
s16..0.004*(y21-d21)+0.040*(y22-d22)+0.128*(y23-d23)+0.171*(y24-h24-d24)+0.111*(y25-h25-d25)+0.031*(y26-h26)=y26-.03,
s17..0.0004*(y21-d21)+0.009*(y22-d22)+0.059*(y23-d23)+0.150*(y24-h24-d24)+0.193*(y25-h25)+0.141*(y26-h26-d26)+0.050*(y27-h27-d27)=y27,
s18..0.001*(y22-d22)+0.012*(y23-d23)+0.062*(y24-h24-d24)+0.150*(y25-h25-d25)+0.216*(y26-h26-d26)+0.200*(y27-h27-d27)+0.100*(y28-h28-d28)=y28,
s19..0.001*(y23-d23)+0.010*(y24-h24-d24)+0.045*(y25-h25-d25)+0.120*(y26-h26-d26)+0.210*(y27-h27-d27)+0.250*(y28-h28-d28)+0.180*(y29-h29-d29)=y29,
s20..0.000*(y24-h24-d24)+0.005*(y25-h25-d25)+0.024*(y26-h26-d26)+0.080*(y27-h27-d27)+0.180*(y28-h28-d28)+0.350*(y29-h29-d29)+0.500*(y20-h20-d20)=y20,

s21..0.304*(y31-d31)=y31-38.28,
s22..0.124*(y31-d31)+0.118*(y32-d32)=y32-6.11,
s23..0.056*(y31-d31)+0.116*(y32-d32)+0.025*(y33-d33)=y33-1.46,
s24..0.027*(y31-d31)+0.100*(y32-d32)+0.049*(y33-d33)+0.003*(y34-h34-d34)=y34-0.41,
s25..0.014*(y31-d31)+0.086*(y32-d32)+0.080*(y33-d33)+0.013*(y34-h34-d34)+0.000*(y35-h35-d35)=y35-0.11,
s26..0.005*(y31-d31)+0.065*(y32-d32)+0.113*(y33-d33)+0.040*(y34-h34-d34)+0.004*(y35-h35-d35)+0.000*(y36-h36-d36)=y36-0.02,
s27..0.001*(y31-d31)+0.037*(y32-d32)+0.130*(y33-d33)+0.095*(y34-h34-d34)+0.022*(y35-h35-d35)+0.002*(y36-h36-d36)+0.000*(y37-h37-d37)=y37,
s28..0.011*(y32-d32)+0.101*(y33-d33)+0.167*(y34-h34-d34)+0.086*(y35-h35-d35)+0.022*(y36-h36-d36)+0.003*(y37-h37-d37)+0.000*(y38-h38-d38)=y38,
s29..0.034*(y33-d33)+0.162*(y34-h34-d34)+0.196*(y35-h35-d35)+0.111*(y36-h36-d36)+0.041*(y37-h37-d37)+0.011*(y38-h38-d38)+0.002*(y39-h39-d39)=y39,
s30..0.052*(y34-h34-d34)+0.223*(y35-h35-d35)+0.396*(y36-h36-d36)+0.487*(y37-h37-d37)+0.520*(y38-h38-d38)+0.530*(y39-h39-d39)+0.531*(y30-h30-d30)=y30,

s31..0.304*(y41-d41)=y41-5.02,
s32..0.153*(y41-d41)+0.210*(y42-d42)=y42-0.88,
s33..0.052*(y41-d41)+0.160*(y42-d42)+0.110*(y43-d43)=y43-0.15,
s34..0.016*(y41-d41)+0.090*(y42-d42)+0.140*(y43-d43)+0.040*(y44-h44-d44)=y44-0.03,
s35..0.005*(y41-d41)+0.040*(y42-d42)+0.120*(y43-d43)+0.080*(y44-h44-d44)+0.010*(y45-h45-d45)=y45-0.004,
s36..0.001*(y41-d41)+0.020*(y42-d42)+0.080*(y43-d43)+0.100*(y44-h44-d44)+0.030*(y45-h45-d45)+0.001*(y46-h46-d46)=y46,
s37..0.0002*(y41-d41)+0.010*(y42-d42)+0.050*(y43-d43)+0.100*(y44-h44-d44)+0.050*(y45-h45-d45)+0.006*(y46-h46)+0.000*(y47-h47-d47)=y47,
s38..0.00*(y42-d42)+0.030*(y43-d43)+0.100*(y44-h44-d44)+0.080*(y45-h45-d45)+0.016*(y46-h46-d46)+0.001*(y47-h47-d47)+0.000*(y48-y48-d48)=y48,
s39..0.010*(y43-d43)+0.07*(y44-h44-d44)+0.110*(y45-h45-d45)+0.039*(y46-h46-d46)+0.002*(y47-h47-d47)+0.000*(y48-h48-d48)+0.000*(y49-h49-d49)=y49,

```
s40..0.04*(y44-h44-d44)+0.240*(y45-h45-d45)+0.469*(y46-h46-d46)+0.528*(y47-h47-
d47)+0.531*(y48-h48-d48)+0.531*(y49-h49-d49)+0.500*(y40-h40-d40)=y40,

!Total values for the stand

!Basal area
s41..BAH1=0.018*h11+0.05*h12+0.097*h13+0.16*h14+0.238*h15
     +0.332*h16+0.442*h17+0.568*h18+0.709*h19+1.228*l10,
s42..BAH2=0.018*h21+0.05*h22+0.097*h23+0.16*h24+0.238*h25
     +0.332*h26+0.442*h27+0.568*h28+0.709*h29+1.228*l20,
s43..BAH3=0.018*h31+0.05*h32+0.097*h33+0.16*h34+0.238*h35
     +0.332*h36+0.442*h37+0.568*h38+0.709*h39+1.228*l30,
s44..BAH4=0.018*h41+0.05*h42+0.097*h43+0.16*h44+0.238*h45
     +0.332*h46+0.442*h47+0.568*h48+0.709*h49+1.228*l40,

s45..BAY1=0.018*y11+0.05*y12+0.097*y13+0.16*y14+0.238*y15
     +0.332*y16+0.442*y17+0.568*y18+0.709*y19+1.228*y10,
s46..BAY2=0.018*y21+0.05*y22+0.097*y23+0.16*y24+0.238*y25
     +0.332*y26+0.442*y27+0.568*y28+0.709*y29+1.228*y20,
s47..BAY3=0.018*y31+0.05*y32+0.097*y33+0.16*y34+0.238*y35
     +0.332*y36+0.442*y37+0.568*y38+0.709*y39+1.228*y30,
s48..BAY4=0.018*y41+0.05*
y42+0.097*y43+0.16*y44+0.238*y45
     +0.332*y46+0.442*y47+0.568*y48+0.709*y49+1.228*y40,

s49..BAH=BAH1+BAH2+BAH3+BAH4,
s50..BAY=BAY1+BAY2+BAY3+BAY4,
s51..BATOT=BAY,

!Numbers of trees
s52..NY1=y11+y12+y13+y14+y15+y16+y17+y18+y19+y10,
s53..NY2=y21+y22+y23+y24+y25+y26+y27+y28+y29+y20,
s54..NY3=y31+y32+y33+y34+y35+y36+y37+y38+y39+y30,
s55..NY4=y41+y42+y43+y44+y45+y46+y47+y48+y49+y40,

s56..NH1=h11+h12+h13+h14+h15+h16+h17+h18+h19+h10,
s57..NH2=h21+h22+h23+h24+h25+h26+h27+h28+h29+h20,
s58..NH3=h31+h32+h33+h34+h35+h36+h37+h38+h39+h30,
s59..NH4=h41+h42+h43+h44+h45+h46+h47+h48+h49+h40,

s60..NY=NY1+NY2+NY3+NY4,
s61..NH=NH1+NH2+NH3+NH4,

s62..NTOT=NY,

!resources limitation
s63..BATOT<=40,

!Basal Area removal
```

```
s64..BAH<=0.35*BATOT,

!Volume
s65..VH1=0.139*h11+0.439*h12+0.935*h13+1.64*h14+2.58*h15
     +3.76*h16+5.18*h17+6.87*h18+8.81*h19+16.33*h10,
s66..VH2=0.12*h21+0.38*h22+0.82*h23+1.448*h24+2.284*h25
     +3.337*h26+4.618*h27+6.135*h28+7.897*h29+14.723*h20,
s67..VH3=0.135*h31+0.414*h32+0.866*h33+1.504*h34+2.336*h35
     +3.372*h36+4.616*h37+6.077*h38+7.758*h39+14.174*h30,
s68..VH4=0.131*h41+0.415*h42+0.889*h43+1.571*h44+2.474*h45
     +3.611*h46+4.99*h47+6.628*h48+8.526*h49+15.87*h40,

s69..VH=VH1+VH2+VH3+VH4,


!Bon sens
s70..h14<=y14,
s71..h15<=y15,
s72..h16<=y16,
s73..h17<=y17,
s74..h18<=y18,
s75..h19<=y19,
s76..h10<=y10,
s77..h24<=y24,
s78..h25<=y25,
s79..h26<=y26,
s80..h27<=y27,
s81..h28<=y28,
s82..h29<=y29,
s83..h20<=y20,
s84..h34<=y34,
s85..h35<=y35,
S86..h36<=y36,
s87..h37<=y37,
s88..h38<=y38,
s89..h39<=y39,
s90..h30<=y30,
s91..h44<=y44,
s92..h45<=y45,
s93..h46<=y46,
s94..h47<=y47,
s95..h48<=y48,
s96..h49<=y49,
s97..h40<=y40,


!Damage

s98..DTOT>=3.6*NH,
```

```
s99..d1=d11+d12+d13+d14+d15+d16+d17+d18+d19+d10,
s100..d2=d21+d22+d23+d24+d25+d26+d27+d28+d29+d20,
s101..d3=d31+d32+d33+d34+d35+d36+d37+d38+d39+d30,
s102..d4=d41+d42+d43+d44+d45+d46+d47+d48+d49+d40,

s103..DTOT=d1+d2+d3+d4,
s104..d1>=0.015*DTOT,
s105..d2>=0.708*DTOT,
s106..d3>=0.245*DTOT,
s107..d4>=0.032*DTOT,

s108..d11>=d12,
s109..d12>=d13,
s110..d13>=d14,
s111..d14>=d15,
s112..d15>=d16,
s113..d16>=d17,
s114..d17>=d18,
s115..d18>=d19,
s142..d19>=d10,
s116..d21>=d22,
s117..d22>=d23,
s118..d23>=d24,
s119..d24>=d25,
s120..d25>=d26,
s121..d26>=d27,
s122..d27>=d28,
s123..d28>=d29,
s124..d29>=d20,
s125..d31>=d32,
s126..d32>=d33,
s127..d33>=d34,
s128..d34>=d35,
s129..d35>=d36,
s130..d36>=d37,
s131..d37>=d38,
s132..d38>=d39,
s133..d39>=d30,
s134..d41>=d42,
s135..d42>=d43,
s136..d43>=d44,
s137..d44>=d45,
s138..d45>=d46,
s139..d46>=d47,
s140..d47>=d48,
s141..d48>=d49,
s143..d49>=d40,
```

```
!Nature conservation: 100 ha

s150..y14-h14>=0.01,
s151..y15-h14>=0.01,
s152..y16-h16>=0.01,
s153..y17-h17>=0.01,
s154..y18-h18>=0.01,
s155..y19-h19>=0.01,
s156..Y10-h10>=0.01,

s157..Y24-h24>=0.01,
s158..Y25-h24>=0.01,
s159..Y26-h26>=0.01,
s160..Y27-h27>=0.01,
s161..Y28-h28>=0.01,
s162..Y29-h29>=0.01,
s163..Y20-h20>=0.01,

s164..Y34-h34>=0.01,
s165..Y35-h34>=0.01,
s166..Y36-h36>=0.01,
s167..Y37-h37>=0.01,
s168..Y38-h38>=0.01,
s169..Y39-h39>=0.01,
s170..Y30-h30>=0.01,

s171..Y44-h44>=0.01,
s172..Y45-h44>=0.01,
s173..Y46-h46>=0.01,
s174..Y47-h47>=0.01,
s175..Y48-h48>=0.01,
s176..Y49-h49>=0.01,
s177..Y40-h40>=0.01;


/*!Nature conservation: 50 ha

s150..y14-h14>=0.05,
s151..y15-h14>=0.05,
s152..y16-h16>=0.05,
s153..y17-h17>=0.05,
s154..y18-h18>=0.05,
s155..y19-h19>=0.05,
s156..Y10-h10>=0.05,

s157..Y24-h24>=0.05,
s158..Y25-h24>=0.05,
s159..Y26-h26>=0.05,
```

```
s160..Y27-h27>=0.05,
s161..Y28-h28>=0.05,
s162..Y29-h29>=0.05,
s163..Y20-h20>=0.05,

s164..Y34-h34>=0.05,
s165..Y35-h34>=0.05,
s166..Y36-h36>=0.05,
s167..Y37-h37>=0.05,
s168..Y38-h38>=0.05,
s169..Y39-h39>=0.05,
s170..Y30-h30>=0.05,

s171..Y44-h44>=0.05,
s172..Y45-h44>=0.05,
s173..Y46-h46>=0.05,
s174..Y47-h47>=0.05,
s175..Y48-h48>=0.05,
s176..Y49-h49>=0.05,
s177..Y40-h40>=0.05;*/

!Nature conservation: 10 ha

/*s150..y14-h14>=0.1,
s151..y15-h14>=0.1,
s152..y16-h16>=0.1,
s153..y17-h17>=0.1,
s154..y18-h18>=0.1,
s155..y19-h19>=0.1,
s156..Y10-h10>=0.1,

s157..Y24-h24>=0.1,
s158..Y25-h24>=0.1,
s159..Y26-h26>=0.1,
s160..Y27-h27>=0.1,
s161..Y28-h28>=0.1,
s162..Y29-h29>=0.1,
s163..Y20-h20>=0.1,

s163b..Y34-h34>=0.1,
s164..Y35-h34>=0.1,
s165..Y36-h36>=0.1,
s166..Y37-h37>=0.1,
s167..Y38-h38>=0.1,
s168..Y39-h39>=0.1,
s169..Y30-h30>=0.1,

s170..Y44-h44>=0.1,
s171..Y45-h44>=0.1,
```

```
s172..Y46-h46>=0.1,
s173..Y47-h47>=0.1,
s174..Y48-h48>=0.1,
s175..Y49-h49>=0.1,
s176..Y40-h40>=0.1;*/


/*!Local populations

!100%
s177..L10<=0.966*h10,
s178..L24<=0.966*h24,
s179..L25<=0.966*h25,
s180..L26<=0.966*h26,
s181..L27<=0.966*h27,
s182..L28<=0.966*h28,
s183..L29<=0.966*h29,
s184..L20<=0.966*h20,
s185..L30<=0.966*h30,
s186..L40<=0.966*h40;*/

! Maximization of STV
Model:
 STV
 maximize:

!Corrected prices

!Corrected 10%

!0.301*(0*h11+2.35*h12+11.75*h13+34.28*h14+77.56*h15+150.4*h16+262.65*h17+425.03*h18+604.79*h19+1410.66*h10
!+0*h21+0*h22+0*h23+0*h24+0*h25+6.62*h26+22.87*h27+52.03*h28+100.83*h29+258.34*h20
!+0*h31+0*h32+1.14*h33+5.35*h34+16.09*h35+37.26*h36+73.50*h37+130.09*h38+214.5*h39+487.8*h30
!+0.15*h41+6.1*h42+26.24*h43+71.27*h44+153.7*h45+287.64*h46+488.59*h47+772.93*h48+1160.7*h49+2478.12*h40)

!+(0*h11+2.35*h12+11.75*h13+34.28*h14+77.56*h15+150.4*h16+262.65*h17+425.03*h18+604.79*h19+1410.66*h10
!+0*h21+0*h22+0*h23+0*h24+0*h25+6.62*h26+22.87*h27+52.03*h28+100.83*h29+258.34*h20
!+0*h31+0*h32+1.14*h33+5.35*h34+16.09*h35+37.26*h36+73.50*h37+130.09*h38+214.5*h39+487.8*h30
!+0.15*h41+6.1*h42+26.24*h43+71.27*h44+153.7*h45+287.64*h46+488.59*h47+772.93*h48+1160.7*h49+2478.12*h40)
```

```
!-
(0*y11+2.35*y12+11.75*y13+34.28*y14+77.56*y15+150.4*y16+262.65*y17+425.03*y18+
604.79*y19+1410.66*y10
!+0*y21+0*y22+0*y23+0*y24+0*y25+6.62*y26+22.87*y27+52.03*y28+100.83*y29+258.3
4*y20
!+0*y31+0*y32+1.14*y33+5.35*y34+16.09*y35+37.26*y36+73.50*y37+130.09*y38+214.5
*y39+487.8*y30
!+0.15*y41+6.1*y42+26.24*y43+71.27*y44+153.7*y45+287.64*y46+488.59*y47+772.93*y
48+1160.7*y49+2478.12*y40)


!Correction 25%

!0.301*(5.158*h15+28.911*h16+80.975*h17+182.325*h18+365.929*h19+1010.306*h10
!+8.445*h29+107.544*h20
!+0.145*h37+30.140*h38+92.00*h39+h30
!+2.089*h43+13.092*h44+41.215*h45+101.577*h46+218.786*h47+431.864*h48+801.945*
h49+2111.846*h40)

!+(5.158*h15+28.911*h16+80.975*h17+182.325*h18+365.929*h19+1010.306*h10
!+8.445*h29+107.544*h20
!+0.145*h37+30.140*h38+92.00*h39+h30
!+2.089*h43+13.092*h44+41.215*h45+101.577*h46+218.786*h47+431.864*h48+801.945*
h49+2111.846*h40)

!-(5.158*y15+28.911*y16+80.975*y17+182.325*y18+365.929*y19+1010.306*y10
!+8.445*y29+107.544*y20
!+0.145*y37+30.140*y38+92.00*y39+h30
!+2.089*y43+13.092*h44+41.215*y45+101.577*y46+218.786*y47+431.864*y48+801.945*
y49+2111.846*y40)


!Correction 30%

0.301*(-1.06*h11-3.15*h12-5.82*h13-7.31*h14-
3.82*h15+12.194*h16+54.544*h17+147.653*h18+333.498*h19+1010.306*h10
-1.06*h21-3.54*h22-7.87*h23-14.09*h24-21.68*h25-29.12*h26-33.01*h27-
26.82*h28+1.383*h29+107.544*h20
-1.05*h31-3.31*h32-6.89*h33-11.37*h34-15.43*h35-16.30*h36-
8.52*h37+17.758*h38+79.789*h39+303.422*h30
-0.85*h41-2.06*h42-
2.09*h43+2.922*h44+20.767*h45+66.063*h46+165.083*h47+363.514*h48+739.335*h49+
2111.846*h40)

+(-1.06*h11-3.15*h12-5.82*h13-7.31*h14-
3.82*h15+12.194*h16+54.544*h17+147.653*h18+333.498*h19+1010.306*h10
-1.06*h21-3.54*h22-7.87*h23-14.09*h24-21.68*h25-29.12*h26-33.01*h27-
26.82*h28+1.383*h29+107.544*h20
```

-1.05*h31-3.31*h32-6.89*h33-11.37*h34-15.43*h35-16.30*h36-
8.52*h37+17.758*h38+79.789*h39+303.422*h30
-0.85*h41-2.06*h42-
2.09*h43+2.922*h44+20.767*h45+66.063*h46+165.083*h47+363.514*h48+739.335*h49+
2111.846*h40)

!-(-1.06*y11-3.15*y12-5.82*y13-7.31*y14-
3.82*y15+12.194*y16+54.544*y17+147.653*y18+333.498*y19+1010.306*y10
!-1.06*y21-3.54*y22-7.87*y23-14.09*y24-21.68*y25-29.12*y26-33.01*y27-
26.82*y28+1.383*y29+107.544*y20
!-1.05*y31-3.31*y32-6.89*y33-11.37*y34-15.43*y35-16.30*y36-
8.52*y37+17.758*y38+79.789*y39+303.422*y30
!-0.85*y41-2.06*y42-
2.09*y43+2.922*y44+20.767*y45+66.063*y46+165.083*y47+363.514*y48+739.335*y49+2
111.846*y40)

!Uncorrected prices

!0.061*(8.60*h11+27.160*h12+57.847*h13+101.711*h14+159.681*h15+232.438*h16+320.
60*h17+424.724*h18+545.305*h19+1010.304*h10
!+0.876*h21+2.783*h22+5.982*h23+10.576*h24+16.682*h25+24.373*h26+33.73*h27+44.
81*h28+57.680*h29+107.537*h20
!+2.890*h31+8.862*h32+18.538*h33+32.196*h34+50.01*h35+72.184*h36+98.815*h37+13
0.09*h38+166.76*h39+303.423*h30
!+17.432*h41+55.225*h42+118.301*h43+209.056*h44+329.220*h45+480.532*h46+664.42
8*h47+882.001*h48+1134.572*h49+2111.853*h40)

!+8.60*h11+27.160*h12+57.847*h13+101.711*h14+159.681*h15+232.438*h16+320.60*h1
7+424.724*h18+545.305*h19+1010.304*h10
!+0.876*h21+2.783*h22+5.982*h23+10.576*h24+16.682*h25+24.373*h26+33.73*h27+44.
81*h28+57.680*h29+107.537*h20
!+2.890*h31+8.862*h32+18.538*h33+32.196*h34+50.01*h35+72.184*h36+98.815*h37+13
0.09*h38+166.76*h39+303.423*h30
!+17.432*h41+55.225*h42+118.301*h43+209.056*h44+329.220*h45+480.532*h46+664.42
8*h47+882.001*h48+1134.572*h49+2111.853*h40

!-
(8.60*y11+27.160*y12+57.847*y13+101.711*y14+159.681*y15+232.438*y16+320.60*y17
+424.724*y18+545.305*y19+1010.304*y10
!+0.876*y21+2.783*y22+5.982*y23+10.576*y24+16.682*y25+24.373*y26+33.73*y27+44.8
1*y28+57.680*y29+107.537*y20
!+2.890*y31+8.862*y32+18.538*y33+32.196*y34+50.01*y35+72.184*y36+98.815*y37+13
0.09*y38+166.76*y39+303.423*y30
!+17.432*y41+55.225*y42+118.301*y43+209.056*y44+329.220*y45+480.532*y46+664.42
8*y47+882.001*y48+1134.572*y49+2111.853*y40)

Subject to:all
method:lp;
Solve STV;

Curriculum vitae

Richard Eba'a Atyi was born on 15 May 1959 in Sangmelima, Cameroon. He received his primary education in his home village, Nko. In 1971, he started his secondary education in Sangmelima. He obtained his "Baccalauréat" in June 1979 and was admitted to the National Advanced School of Agriculture of the University Center of Dschang (now the University of Dschang (UDS)). Five years later (1984), he graduated from the University Center of Dschang as "Ingénieur des Eaux, Forêts et Chasses".

From July 1984 to October 1985, he worked at the National Center for Forestry Development (now dissolved) and contributed to the national inventory of the forest resources of Cameroon. He then changed to become a teaching assistant at the Department of Forestry of the UDS. From January 1987 to January 1989, he completed an MSc-program at Oregon State University (Department of Forest Resources Management) in Corvallis, USA. In February 1989, he became lecturer of Forest Management at the UDS and in July of that year he was appointed Head of the Belabo Antenna of the UDS.

From July 1991 to February 1992, he was part of a team of researchers to design a multidisciplinary research program for The Tropenbos Foundation in Cameroon. It was during that occasion that the topic of the research which is reported in this document was identified. From July 1994 to June 1999 he worked as a researcher within the Tropenbos Cameroon Programme and then conducted the research which resulted in this thesis.

From 1996 to 1998 he also conducted a study on "Cameroon's Logging Industry: Structure, Economic Importance and Effects of Devaluation" under the sponsorship of CIFOR. Similarly, he contributed to the Test of Criteria and Indicators for Sustainable Forest Management in Cameroon initiated by CIFOR (final report published in 1998). He is a member of the National Working Group on Forest Certification in Cameroon.

Richard Eba'a Atyi is married and father of three sons.