Radar for rain forest

A monitoring system for land cover change in the Colombian Amazon

Wietske Bijker

ITC
PUBLICATION
NUMBER 53

Promotoren:	Dr. ir. R.A. Feddes Hoogleraar bodemnatuurkunde, agrohydrologie en grondwaterbeheer
	Dr. ir. W. van Wijngaarden Gasthoogleraar ruimtelijke analyse Universidad de los Andes, Bogotá, Colombia Voormalig hoogleraar kartering van vegetatie en agrarisch landgebruik International Institute for Aerospace Survey and Earth Sciences - ITC
Co-promotor:	Dr. ir. D.H. Hoekman Universitair hoofddocent remote sensing

NN08201, 2314

Wietske Bijker

Radar for rain forest

A monitoring system for land cover change in the Colombian Amazon

Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van de Landbouwuniversiteit te Wageningen,
Dr. C.M. Karssen,
in het openbaar te verdedigen
op woensdag 17 september 1997,
des namiddags te 13.30 uur in de Aula

isn 944266

ISBN 90 6164 139X

ISBN 905485-740-4

© 1997 Wietske Bijker
All rights reserved. No part of this publication, apart from bibliographic data, brief quotations in critical reviews, may be reproduced, re-recorded or published in any form including print, photocopy, microfilm, electronic or electromagnetic record, without written permission.

Distribution by International Institute for Aerospace Survey and Earth Sciences ITC,
P.O. Box 6, 7500 AA Enschede, The Netherlands
ITC publication number 53

This research was funded by theTropenbos Foundation, the Netherlands Remote Sensing Board (BCRS) and the International Institute for Aerospace Survey and Earth Sciences (ITC).

Cover: Wietske Bijker, H.K. Scharrenborg, R. Boertje, R.H. Teekamp and F.B. Scholten

NN08201, 2314

STELLINGEN

1. Problemen in het landgebruik buiten het tropisch regenwoud zijn belangrijke drijvende krachten achter ontbossing en bosdegradatie. Wanneer daar geen oplossing voor gevonden wordt, zal door de toenemende druk duurzaam gebruik van het resterende bos steeds moeilijker te realiseren zijn.
   Dit proefschrift

2. Een monitoring systeem, gebaseerd op radar remote sensing, levert een belangrijke bijdrage aan de ruimtelijke informatie over zowel het tropisch regenwoud als de aangrenzende landbedekking.
   Dit proefschrift

3. Voor een goede interpretatie van landbedekking op radarbeelden is het nodig om de zeer uiteenlopende strukturen van vegetatie volgens eenzelfde methode te beschrijven. De meest gangbare methoden in de vegetatiekunde zijn hiervoor ongeschikt.
   Dit proefschrift

4. De nauwkeurigheid van de klassifikatie van landbedekking en het detecteren van veranderingen daarin, kan worden verbeterd met een model van de mogelijke veranderingen in die landbedekking.
   Dit proefschrift

5. Microgolven zijn geschikt voor méér dan koken alleen.

6. Ter beperking van het warmteverlies tijdens het spreken is de frequentie van klinkers in talen uit het noorden van Europa lager dan in talen uit het zuiden.

7. De rug van het kaft is het meest bekeken onderdeel van een proefschrift.

8. Een werkkamer is een ruimte waar het werk zich opstapelt.
   Ronald Boertje

9. Moeilijkheden zijn beter te verdragen als ze een goed verhaal opleveren.

10. Humor is overwinning.

Stellingen behorende bij het proefschrift:
Wietske Bijker: "Radar for rain forest - A monitoring system for land cover change in the Colombian Amazon", Wageningen, 17 September 1997.

Aan mijn ouders

ABSTRACT

Bijker, W., 1997. *Radar for rain forest: A monitoring system for land cover change in the Colombian Amazon.* Doctoral thesis. ITC, Enschede, the Netherlands, 189 p.

The uncontrolled conversion of forest into other land cover types is an internationally recognized problem. Most attention is focussed on the rapid disappearance of tropical rain forests, although deforestation is also a problem at higher latitudes. With an increasing demand for the wise and sustainable management of these forests, there is a growing need for up-to-date information on the location and extent of the forests and the surrounding land cover and the changes occurring. This information is needed for planning as well as for controlling the implementation of laws and regulations.

Extensive field data collection is often not feasible in forested areas because of poor accessibility. Remote sensing, especially radar, can provide a viable solution for mapping and monitoring such areas. This thesis presents a system for land cover monitoring in tropical rain forest areas, based on ERS-1 SAR images. Because of its generic structure, the system can be applied to a variety of areas.

The system was developed in the pilot site of San José del Guaviare, in the Amazon rain forest of Colombia. People from other parts of the country have migrated to this area in search of land and livelihood, clearing parts of the forest, cultivating crops and ultimately planting pastures for cattle breeding. Field data were collected between 1990 and 1994 in the pilot area. There were nine ERS-1 images available in the period 1992—1994.

Prior to classification, the images were divided into segments with the RCSEG segmentation algorithm, based on edge detection and segment growing. Each segmented image was classified by the subsequent application of two sets of rules and also taking into account the classification result of the previous image. The first set of rules is based on the relation between land cover structure class and backscatter level, as well as the maximum change in backscatter level over three subsequent images. Simulation of the level and variation of backscatter of different land cover structure classes with the theoretical model UTACAN confirmed the experimental findings. The second set of rules describes the possible changes in land cover between two moments in time as calculated by the BOSTOS model. Using this second set of rules enables unlikely changes to be excluded and the monitoring result becomes more accurate.

The study shows that it is possible to monitor land cover in a tropical rain forest area with ERS-1 images. Forests could be distinguished from other land cover types and changes in land cover could be detected. Classification accuracies, when classifying time series with both sets of formal rules, were more than 60% for forests, approximately 40% for secondary vegetation and 80--90% for pastures and natural grasslands, which were better than using a Maximum Likelihood classifier.

The accuracy of the system can be further improved by initialization with an accurate land cover map and by further development of the models underlying the sets of rules, including validation of the assumptions and parameters. If probabilities are used in the classification, instead of most probable choices as used in this research, the system can acquire self-learning capabilities.

The system can be expanded to include other types of sensors making it possible to monitor all or parts of the area with a different temporal, spatial and radiometric resolution, according to the user's needs with respect to how detailed the spatial, temporal and thematic information needs to be, the desired accuracy and the expected changes. The availability of new radar sensors on satellite platforms, planned for the beginning of the next century, will greatly improve the level of detail with which land cover can be monitored using satellite remote sensing. This has already been demonstrated by the development of advanced airborne SAR systems and the SIR-C mission.

Keywords: rain forest, monitoring, land cover change modelling, synthetic aperture radar, ERS-1, Amazon, Colombia

ACKNOWLEDGEMENTS

The research presented in this thesis was carried out at the International Institute for Aerospace Surveys and Earth Sciences (ITC), in cooperation with the Department of Water Resources, Wageningen Agricultural University (WAU), Tropenbos Colombia (Fundación Bosque Tropical), Corporación Colombiana para la Amazonia-Araracuara (COA) and the Instituto Geográfico Agustin Codazzi (IGAC). The research was started in 1990 as part of the Tropenbos Colombia project: *Development of geographical information systems for land use planning and management in a tropical rain forest environment* (*Project 18* or *el Proyecto SIG*). In later years, the research was part of the projects: *Monitoring system Colombia,* phases 1 and 2, and: *Remote sensing of tropical rain forests* financed by the Netherlands Remote Sensing Board (BCRS) and with logistical support from Tropenbos. The European Space Agency provided ERS-1 data as part of the SAREX-92 campaign in the framework of its Earth Observation Preparatory Program (EOPP). I sincerely thank all the above institutions for their support and collaboration, which made this research possible, and my employer, ITC, for giving me the opportunity to do this research.

Ideas do not come out of the blue, nor do they germinate from hard work alone. This thesis could not have been written without the research carried out by others, both in the past and present, nor without the fruitful and inspiring discussions with supervisors and colleagues, nor without the care and support received from friends and family. I am truly grateful for all these contributions. I wish to thank my promotor, Prof. R.A. Feddes, and co-promotors, Prof. W. van Wijngaarden and Dr. D.H. Hoekman, for their inspiration, encouragement, patience and valuable comments, and for giving me this opportunity.

I also wish to thank present and former ITC colleagues, especially Gerard Sicco Smit, Carlos Valenzuela and Jan de Vos tot Nederveen Cappel, who, together with Willem van Wijngaarden, initiated the Tropenbos project. Gerard Sicco Smit also introduced me to the wonders of the rain forest and to Colombian culture. My thanks go to Bart Krol, with whom I shared so many *Project 18* and *VAS* ups-and-downs, and to Pita Verweij and Jan de Leeuw for their help with the analysis of the vegetation. My thanks also to colleagues from the Image Processing Laboratory in ITC for their help at various stages of the research. I am grateful to Benno Masselink and Job Duim for drawing the figures, to Koert Sijmons for the lay-out of the maps, to Freek Scholten for printing the photographs, and to Henk Scharrenborg and Rob Teekamp for realizing the cover design.

Thanks, too, to Martin Vissers, for his work on image processing at WAU, to Jackie Senior for editing my "Dunglish" into English, to Karin Zomer for editing the Dutch summary and to Maria Bastides for translating the summary into Spanish. A sincere "gracias" to Marcela Quiñones, for her research on the AIRSAR data of Guaviare, for allowing me to use some of her data and for being a good friend. Thanks to Joost van der Sanden, colleague from WAU in several of the projects. I would also like to thank my Colombian colleagues in the Tropenbos project: Deyanira Vanegas, Carlos Alvarado, Joel Martínez, Christina Torres, Luciano Cardenas, Pedro Rubio and Rafael Molina for their work. Thanks also to Dr. Juan Saldarriaga, director of Tropenbos Colombia and to Gloria and Martha, for their support.

I owe much to the people of the COA in San José. They supplied not only transport, office space and housing, but they also explained much about the land use and land cover in the area to me, they always had good questions ready and proved to be excellent and patient teachers of Spanish and salsa. I wish to thank the director of the COA in Bogotá, Dr. Dario Fajardo and the subdirectors in San José, Dr. Julio Roberto del Cairo, Dr. Marco Aurelio Herrera, Dr. Hernando Valdés Carrillo, and Dr. Maria Claudia Walker, for their efforts in making this research possible. Alvaro, Armando, Bernardo, Carlos Hernando, Eimer, Gilberto, Hector, Hector Fabio, James, Jorge, Leonel, Marco Aurelio, Silvio Antonio: many thanks for the days in the field. As a tribute to them and all the others at the COA who collaborated on this thesis in one way or another, I have included a photo taken in 1991. I am truly grateful to the people of Guaviare, for sharing their knowledge and for their hospitality, the many 'preparadas', 'chichas', 'guarapos' and all those other things that made me feel welcome. I admire them for their pioneering spirit, never giving up, no matter how difficult the circumstances.

To my dear friends in Colombia, Myriam Martínez, Claudia Fonseca, Marco Antonio Durango, Henry Torres, Carlos García and John Sarmiento: thanks for all the joy and care. And thanks also to my friends in the Netherlands, Hykina Booij and James Grit, Ellen-Wien and Denie Augustijn, who never got tired of asking me about my thesis, and to Marga Bakker for always being there when I needed her.

Without Ronald Boertje, my husband, I would never have started nor finished this thesis. He convinced me I should start this work, gave me continuous love and support during the whole process, and gladly supplied a photo of his face for the cover of the book.

Finally, I wish to thank my parents, Jan-Arie Bijker and Sietsche Bijker-de Boer. They have always stimulated me to ask questions and to learn. Each time I went into another school class, my Dad always said "*Nu wordt het pas leuk!*" (*Now it's going to be fun!*). Frankly, I didn't always agree with him, but in the end he was right.

Figure 0.1: Most of the staff of the Corporación Colombiana para la Amazonia - Araracuara (COA) in San José del Guaviare, 30 October 1991.

CONTENTS

ABSTRACT *7*

ACKNOWLEDGEMENTS *9*

CONTENTS *11*

SYMBOLS *13*

ABBREVIATIONS AND ACRONYMS *15*

1. INTRODUCTION *17*
    1.1. Description of problem *17*
    1.2. Objectives *20*
    1.3. New aspects of this research *20*
    1.4. Contents of the thesis *22*
    1.5. Institutional framework of the research *23*

2. DESCRIPTION OF AREA *25*
    2.1. Location *25*
    2.2. Climate *25*
    2.3. Geology and geomorphology *27*
    2.4. Soils *30*
    2.5. Vegetation *30*
    2.6. History of the settlement in Guaviare *39*
    2.7. Actual land use *44*

3. OUTLINE OF A MONITORING SYSTEM *47*
    3.1. Introduction *47*
    3.2. Basic system architecture *48*
    3.3. Processing module *50*
    3.4. Temporal models of land cover change *53*
    3.5. System characteristics *55*
    3.6. Development strategy *56*
    3.7. Conclusions *56*

4. GENERAL APPROACH TO THE DEVELOPMENT OF DECISION RULES *57*
    4.1. Introduction *57*
    4.2. Field surveys *59*
    4.3. Spatial variability of the land cover data *65*
    4.4. Temporal variation in land cover data *69*
    4.5. Remote sensing data source *70*
    4.6. Analysis of image characteristics *71*
    4.7. Relation between land cover and image characteristics *71*

4.8. Image segmentation *73*
4.9. Role of the analysis in the operational monitoring system *75*
4.10. Conclusions *75*

5. ANALYSIS OF THE GUAVIARE DATA SET *77*
5.1. Field survey and land cover data *77*
5.2. Spatial variability of land cover data *79*
5.3. Remote sensing data *87*
5.4. Analysis of image characteristics *88*
5.5. Relation between land cover structure and image characteristics *90*
5.6. Image segmentation *99*
5.7. Land cover classification for change modelling *100*
5.8. Conclusions *103*

6. CHANGE MODELS *105*
6.1. Introduction *105*
6.2. Modelling *105*
6.3. Simulation *109*
6.4. Conclusions *114*

7. CLASSIFICATION, VALIDATION AND CHANGE DETECTION *117*
7.1. Image classification with decision rules *117*
7.2. Decision rules based on image characteristics *117*
7.3. Application of decision rules based on image characteristics *121*
7.4. Decision rules based on the possibility of land cover changes *130*
7.5. Application of decision rules based on the possibility of land cover change *132*
7.6. Maximum likelihood classification *138*
7.7. Application of the decision rules to the images *140*
7.8. Discussion and conclusions *155*

8. CONCLUSIONS AND OUTLOOK *159*

SUMMARY *167*

SAMENVATTING *173*

RESUMEN *179*

REFERENCES *185*

BIOGRAPHY *191*

SYMBOLS

c_i	Land cover class i
P	Probability
$P(c_i/t_n)$	Probability that the object belongs to land cover class i at time n
r_o	Remote sensing observable
r_s	Simulated image characteristic
t	Time
t_0	Time at start of the count
$t_i..t_j$	Time span between t_i and t_j
σ^0, Sigma-0	Normalized radar cross section per unit illuminated surface (backscatter), measured in dB (decibels)

ABBREVIATIONS AND ACRONYMS

AIRSAR	*AIRborne Synthetic Aperture Radar (from JPL)*
AVHRR	Advanced Very High Resolution Radiometer (instrument of NOAA satellites)
BOSTOS	BOSque-pasTOS (model of land cover change)
COA	Corporación Colombiana para la Amazonia - Araracuara
dbh	Diameter (of trees) at Breast Height (1.30 m high)
EC	European Community
ERS-1, -2	European Remote Sensing Satellite, first and second
ESA	European Space Agency
FRA	Forest Resources Assessment of FAO
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographical Information System
GPS	Global Positioning System
HH	Horizontal-Horizontal like polarization
HRV	High Resolution Visible (instrument of the SPOT satellite)
IGAC	Instituto Geográfico Agustín Codazzi (Colombian Geographic Institute)
INCORA	INstituto COlombiano de la Reforma Agraria (Colombian Institute of Agrarian Reform)
IDEMA	Instituto DE Mercadeo Agrícola (Colombian Institute for the Marketing of Agricultural Products)
INDERENA	INstituto de DEsarrollo de los REcursos Naturales Renovables y del Medio Ambiente (Institute for the Development of Renewable Natural Resources and Environment in Colombia)
ITC	International Institute for Aerospace Survey and Earth Sciences, the Netherlands
JERS-1	Japanese Earth Resources Satellite, first
JPL	Jet Propulsion Laboratory, California
JRC	Joint Research Centre of the European Community in Ispra, Italy
Landsat	U.S. A. remote sensing satellite
LUCC	ITC system of rural Land Use and land Cover Classification
MSS	MultiSpectral Scanner (instrument of the Landsat satellites)
NASA	National Aeronautics and Space Administration
NIR	Near InfraRed
NOAA	National Oceanic and Atmospheric Administration (satellite)
PRORADAM	PROyecto RADargrametrico del AMazonas, Colombia
RADAR	RAdio Detection And Ranging
RCSEG	Segmentation algorithm based on multi-scale edge detection and segment growing (Caves and Quegan, 1995)
RESPAS	REmote Sensing Processing and Archiving System
SAR	Synthetic Aperture Radar
SAREX	South American Radar EXperiment
SIR-C	Shuttle Imaging Radar -C
SLAR	Side Looking Airborne Radar

SPOT	Satellite Pour l'Observation de la Terre (French remote sensing satellites)
TFAP	Tropical Forestry Action Plan of FAO
TFIS	Tropical Forest Information System
TM	Thematic Mapper (instrument of the Landsat satellites)
TWINSPAN	Two Way Indicator Species ANalysis
TREES	TRopical Ecosystem Environment observations by Satellite project of EC
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTACAN	University of Texas at Arlington CANopy scattering model (Microwave scattering model for layered vegetation (Karam et al., 1992))
VV	Vertical-Vertical like polarization
VH	Vertical-Horizontal cross polarization
WAU	Wageningen Agricultural University, the Netherlands
XS (SPOT-XS)	Multispectral mode of SPOT

1. INTRODUCTION

1.1. Description of problem

Worldwide, tropical forests are under increasing pressure. People without land see the forest as still unoccupied land, new arrivals perceive their conversion of forest into farmland as land improvement and taming the wilderness, while timber companies see the forest as a stock of cubic metres of valuable woods. The forest provides a day-to-day livelihood for the people who live in it and from it, as well as a shelter and hiding place for refugees and illegal activities. Governments see the forest as a still unexploited economic resource, scientists as a biological and genetic resource, and environmentalists as one of the most diverse and important ecosystems. Climatologists stress the importance of large forested areas for the worldwide regulation of the climate. The tropical forest has many functions, on both a regional and a global scale, and the world community is worried about its rapid disappearance.

Worldwide, several initiatives have been taken to monitor (tropical) forests. Well-known initiatives are TREES (EC) and TFAP and FRA (FAO). Following the recommendations of the World Forest Watch Conference of Sao José dos Campos (May 1992) a Tropical Forest Information System (TFIS) was set up, based on satellite information. Within TFIS, the TRopical Ecosystem Environment observations by Satellite project (TREES) has been designed to demonstrate the feasibility of applying space observation techniques towards better monitoring of tropical forest areas. TREES is characterized by the fact that it addresses the deforestation issues on a global scale and it focuses on the use of data from a range of space sensors (AVHRR from NOAA satellites, Landsat, SPOT and ERS-1), (Malingreau and Dacunha, 1992). TREES uses low resolution data from NOAA-AVHRR for global coverage and high resolution data for validation. TREES is funded by the European Community and carried out by the Joint Research Centre (JRC) in Ispra, Italy.

FAO coordinates the Tropical Forestry Action Plan (TFAP), launched in 1985 as "an international effort to reduce tropical deforestation" (*Anonymus*, 1988). According to FAO (1990), "... the TFAP provides a framework for each tropical country to set up a consistent national action plan under which domestic and international efforts, including financial and technical assistance, can be pooled to save the forests ...". The Forest Resources Assessment (FRA) programme assesses the extent and state of the forest cover of the world. To support both TFAP and FRA, FAO has shown interest in the development of a monitoring system based on remote sensing. To meet the requirements of TFAP and FRA, the development of a Forest Assessment and Monitoring Environment (FAME) was proposed (Van der Burg et al., 1992), starting with a Remote Sensing Processing and Archiving System (RESPAS) as a first phase. These proposals are still under evaluation.

As in other parts of the world, the tropical rain forest of the Amazon part of Colombia is being exposed to growing pressure from different sides. According to the El Tiempo newspaper (El Tiempo, 10 June 1996), of the approximately 114 million hectares of the total territory of the country, 54 million are still covered with forest. During the last three decades, 40 million hectares have been deforested and, if the current trend continues, in the coming five years

150,000 hectares will be needed to satisfy the demand for wood. As only 44,010 hectares have been reforested for commercial purposes, the deforestation of natural forests will continue apace.

However, the demand for wood is not the only reason for deforestation. Many, often conflicting, claims are laid on the forest, thus increasing the necessity for good management. The Colombian Amazon region is a vast area, and difficult to access. Detailed data about the different landscapes in this region and the ongoing processes are still scarce (PRORADAM, 1979; Andrade and Etter, 1987; Andrade et al., 1992) and, if present, the data are not always available in a format the decision makers can use.

Pressure from settlers looking for land is increasing, as is the political awareness of the rights of indigenous people and of environmental issues. Good management of space and natural resources is required and the lack of information is an increasing problem, hampering wise management decisions. In many cases, none of the parties involved in land use conflicts can support their views with sufficient data on the different types of land cover, the processes or the rates and scales of change. This research is an effort to supply data to support management decisions (land use planning, resource management) for a pilot area in the Colombian Amazon forest: San José del Guaviare (see Figure 1.1).

Collecting data in an area like the Amazon region is difficult. For the pilot area, data on land cover have been collected by PRORADAM (1979) and Andrade and Etter (1987). In this research, additional spatial data on land cover were mainly collected using remote sensing techniques. For surveys in areas like this, remote sensing provides a faster and relatively inexpensive tool to survey and monitor the land cover and the ongoing processes.

The area of San José del Guaviare comprises two main landscapes: the undulating upland or *tierra firme*, and the flood plains or *vega* of the Guaviare, Guayabero and Ariari rivers. The flood plain, including river terraces, is heterogeneous in its soils and hydrology as well as its land use. Agricultural plots are usually small and often used for mixed cropping. There are two sowing periods and a number of crops, like cotton and cacao, are restricted to this landscape.

A small part of the upland consists of Paleozoic sandstone rocks of the Araracuara formation, covered with savannahs and natural shrubland. From an agricultural point of view, the savannahs are not very interesting; they are only used for extensive grazing. Changes are mainly cyclical, due to burning and regeneration. In the southwest of the study area, a few isolated hills of igneous rock breakthrough the Tertiary sediments covering the rest of the area. These are mainly covered with forest.

The larger part of the upland is an undulating Tertiary denudation surface with old, clayey soils. The area was covered with forest that has been disappearing rapidly over the last few decades. Fields are larger than on the river terraces and mixed cropping is far less common. There is only one sowing period for annual crops. Most farmers in this area regard annual crops as a transition phase to pastures for livestock. The monitoring work concentrated on this area, as this is where most forest is disappearing.

Figure 1.1: Location of the study area San José del Guaviare

1.2. Objectives

The objective of the research described in this thesis is to develop a method for monitoring that provides timely information on land cover to organizations involved in the management of the area. This method should interpret and integrate remote sensing data (multi-sensor, multi-temporal, multi-spectral) and other existing or new data on land cover and land use, spatial as well as non-spatial. The method should deliver timely spatial information on land cover, especially tropical rain forest, as well as on changes in land cover. This information is incorporated in a Geographic Information System (GIS). The method is developed for the pilot around area San José del Guaviare. After development, it can be used in other areas with small adjustments.

The direct users of this method are planning agencies at regional and local levels. Monitoring data on the Amazon are provided through these users to the national level. Users are interested in the type, location and extent of the forests and agricultural areas and in the area, location and quality of pastures. As pasture degradation is a serious problem in this area, users are interested in knowing the total amount of pasture and the amount of degraded pasture, and in monitoring its degradation.

At a later stage, the monitoring system can also be applied to other areas. Because of its generic structure, only a certain number of parameters will have to be adjusted and some of the models replaced by other area- and application-specific ones. Application of the system to a larger area requires more powerful hardware to store and manipulate the data if the same scale is to be maintained. The scale can be reduced if the information does not need to be at the same level of detail.

1.3. New aspects of this research

Data

The first radar satellite, ERS-1, was launched in 1992, so that any application of data collected by this satellite is relatively new. It is a *unique data set* because of the ample ground truth data collected at several points in time during the execution of the project, the data available from previous land cover and land use studies in the area and the optical data and high resolution radar data from the SAREX-92 and the AIRSAR-93 campaigns. This thesis is limited to the use of ERS-1 data and the airborne radar data is used only for illustration or reference purposes. The research on the airborne radar data has been reported in Hoekman et al., (1994b; 1996).

Field of application

As far as the author knows, *there was no monitoring system for tropical rain forest on a sub-regional scale, based on remote sensing.* Only production forests in the more temperate regions have been subjected to detailed monitoring and so far rain forests have only been monitored at a very general level. The *use of remote sensing in combination with GIS in providing information on land cover, and especially tropical rain forest, to planners rather than researchers* is also new. TREES as well as FRA have a global coverage and low resolution.

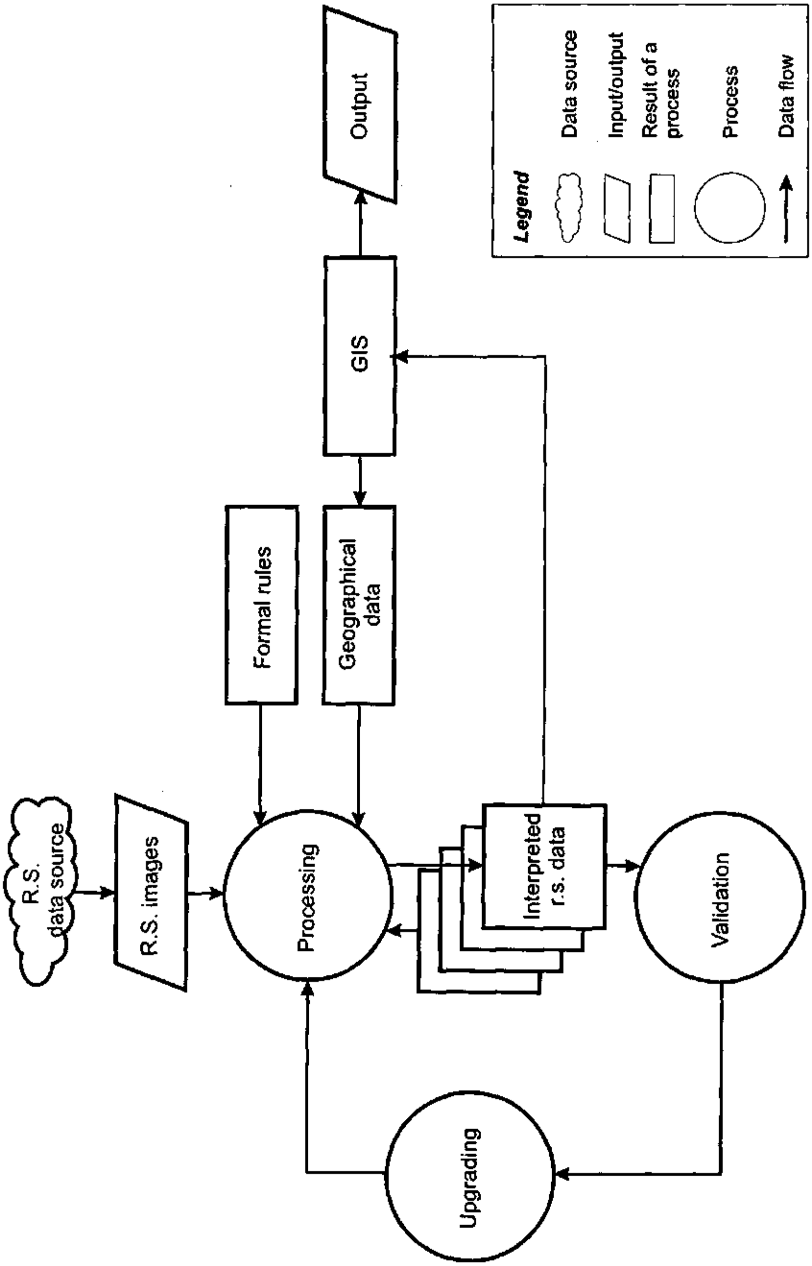


Figure 1.2: Sketch of the monitoring system. Images recorded by the satellite are processed using formal rules, geographical data and earlier interpretation results. The results are transferred to a GIS for combination with other data and output generation. Validation of the processing result may lead to upgrading of the processing algorithms.The notation is adapted from Forrester (1968).

Both projects are geared towards the global concern on climatic changes resulting from the disappearance of forests. Their contribution to actual forest management issues at a regional or local level is therefore limited. The TFAP operates through programmes at a national level. The research in this thesis has already served to validate low resolution TREES data. It could also make a contribution to the TFAP program of Colombia, called Plan de Accion Forestal Colombia (PAFC) or to the Amazonian part of the 'Ordenamiento Territorial', the nation-wide regional planning exercise currently being carried out in Colombia. Methods developed in a pilot area in this research can be used for larger areas within the regional planning process.

Methods

The *use of change models to predict the probability of certain changes and filter out unlikely changes* is new. Change models are models of the effect (or parts thereof) of the resettlement process on land cover. Starting with the land cover at a given time and the development of land use and related land cover common to the area, one can predict the probability of several types of land cover occurring the following year. For example, if a plot is covered by disturbed forest in 1990, it is very likely to be either disturbed forest or a maize or rice crop the following year; it is less likely but possible that it could be cassava or plantain, or pasture. It is unlikely that it will be either natural forest or secondary forest. This knowledge on change probabilities can be used to check the classification of images in subsequent years.

A simple sketch of the system is shown in Figure 1.2. Remote sensing images from a data source (satellite, ground station) are processed using formal rules, geographical data from a Geographical Information System (GIS) and any results from previous image interpretations. The GIS is updated with the new image interpretations, so that output (information on land cover and land cover change) can be generated. The image interpretations are also validated, which may lead to upgrading of the processing algorithms.

1.4. Contents of the thesis

Following the introduction, Chapter 2 gives a brief description of the area, its climate, geology, soils, vegetation, history, people and their use of the land. This serves as background information for the other chapters.

Chapter 3 outlines the monitoring system, describing the functional components of the system and the ways in which these are related. The development of the components of the system and the first results are described in the following chapters.

Chapter 4 explains the general methodology for field data collection and the analysis of field data and remote sensing data for developing rules for the processing of ERS-1 images. This methodology is applied to the study area in Chapter 5. The resulting rules for the classification of the ERS-1 images used in this study are based on the relation between image characteristics and vegetation structure.

In Chapter 6 another component of the monitoring system, a model of land cover change, is developed. This model expresses the effect of the land use in the settlement process on the vegetation structure. Possible changes in the structure of the vegetation over the timespan between two images can be calculated with this model. This knowledge can be used to exclude unlikely changes and hence improve the classification result in a time-series of images.

The results of image processing with formal rules based on image characteristics (Chapter 5) and possibilities in land cover change (Chapter 6) are presented in Chapter 7, focusing on two smaller areas. These results were evaluated with a control set of field samples and visually checked with images from the AIRSAR campaign.

Finally, in Chapter 8, the results are discussed in the perspective of the objectives of the study described in Chapter 1 and the outline of the monitoring system in Chapter 3. This discussion leads to the conclusions, more possible applications of the results, and the need for further research.

1.5. Institutional framework of the research

The research presented in this thesis started as a part of the Tropenbos-Colombia project 'Development of geographical information systems for land use planning and management in a tropical rain forest environment', in short 'Project 18'. In later years, the research was part of the projects 'Monitoring system Colombia, phase 1' and 'Monitoring system Colombia, phase 2', financed by the Netherlands Remote Sensing Board (BCRS) and with logistical support form Tropenbos.

The following institutes participated in these projects:
- International Institute for Aerospace Surveys and Earth Sciences (ITC, Enschede),
- Wageningen Agricultural University (WAU, Wageningen), Department of Water Resources,
- Tropenbos (Wageningen) and its Tropenbos - Colombia Program,
- Corporación Colombiana para la Amazonia - Araracuara (COA, Santafé de Bogotá, Araracuara and San José del Guaviare, Colombia), which was restructured and renamed SINCHI in 1994,
- Instituto Geográfico Agustin Codazzi (IGAC), Santafé de Bogotá, Colombia.

ITC gives international courses, carries out research and does consulting in the fields of aerospace surveys and earth sciences. Wageningen Agricultural University has a long history of research in the earth sciences, agriculture and natural vegetation. Research on radar remote sensing is concentrated in the Department of Water Resources. Tropenbos is a Dutch foundation that aims to stimulate research in developing the sustainable management of tropical forests. It has a number of local branches in countries around the world. One of these is located in Santafé de Bogotá, Colombia, with study sites in Araracuara and San José del Guaviare.

The COA concentrates on collecting knowledge of the characteristics and potential of the natural resources of the Amazon region and promoting the socio-economic development of the area in concordance with its basic objective of conserving the natural inheritance. According to these objectives the COA has carried out investigations and applied the results to the following fields: ecosystems, forestry, terrestrial and aquatic fauna, soils, agricultural and livestock systems, production systems, socio-economics, controlled management of livestock, and hydro-biologic resources.

The COA proposes development projects in the areas of: technical assistance for agriculture and livestock, extension and stimulation of forestry, supporting associations of producers, community organization and participation, improvement of the physical infrastructure, participating in and helping indigenous communities develop in order to improve the living conditions of people in settlements in the area under its jurisdiction, (COA, leaflet, 1992). The COA contributed to the research in this thesis with its knowledge on natural resources and land use in the area and by providing logistical support.

In 1994, the COA was transformed into the Instituto Amazonico de Investigaciones Cientificas SINCHI, and put under the umbrella of the Ministry of Environment. Their mandate is now less focussed on extension services and more on research into sustainable agricultural production systems. COA was the envisaged user of the monitoring system developed in this research. However, with the shifts of mandates that have occurred, the regional government of Guaviare might now be a more likely user, and it is already embarking on the use of the GIS for the area as developed within Project 18.

IGAC is the national geographic institute of Colombia, as well as a sister institute of ITC. It performs aerospace and other surveys and produces maps, e.g. on topography, soils and vegetation, as a base for land evaluation and planning.

2. DESCRIPTION OF AREA

2.1. Location

The study area is located on the northern fringe of the Department of Guaviare, extending from its capital San José del Guaviare south to El Retorno, between 2° 35' and 2° 20' north and 72° 47' and 72° 35' west. San José is located on the Guaviare river, which forms the boundary between the Amazon rain forest and the grasslands of the Llanos Orientales (see Figure 2.1). The Guaviare river is fed by the Ariari and Guayabero rivers, both rising in the Andes, and it drains into the Orinoco at the border with Venezuela. Caño Grande, near El Retorno drains into the Inirida river, which flows into the Guaviare river just before the Venezuelan border. The Unilla river, rising in the hills southwest of El Retorno and passing through Calamar, and the rivers to the south drain into the Amazon.

San José is connected by an unpaved road to El Retorno and Calamar in the south and via Concordia to Villavicencio in the north (and from there by paved road to Santafé de Bogotá). From this central road a number of smaller, unpaved roads run to the other villages. The settlement in this region spread from the central north-south road to the east and to the west (see Figure 2.1).

2.2. Climate

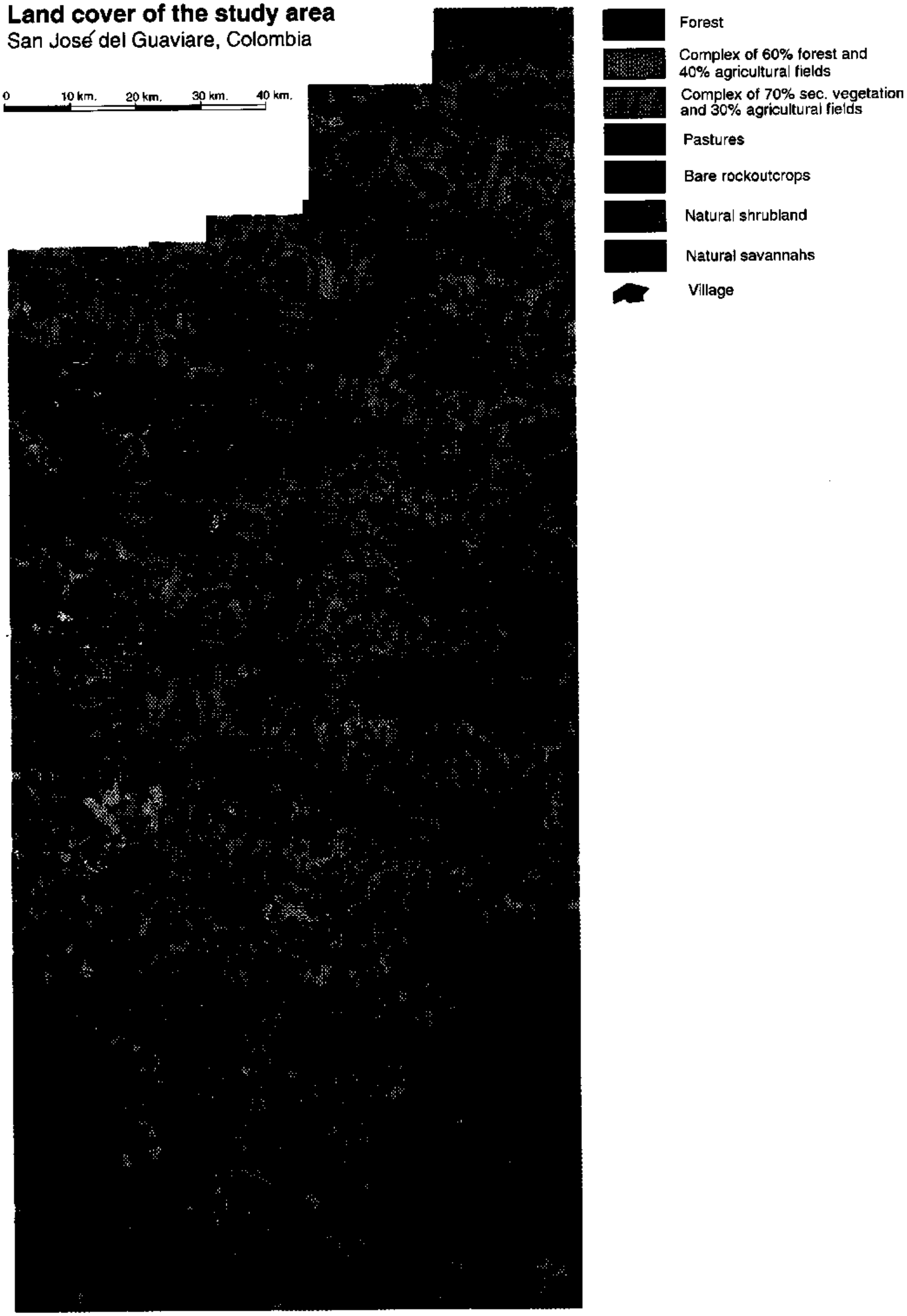
According to Köppen's classification, the area has a tropical seasonal climate (Am), with an average annual precipitation (in the period 1985—1991) of 2558 mm at the San José station and 2834 mm at the 'El Trueno' station, just north of El Retorno (Martínez, 1992). The mean annual temperature is 25.8°C, the mean maximum 30.7°C, and the mean minimum 20.4°C (Martínez, 1992). Most rain falls between April and November (see Figure 2.2). January and February are the driest months, when water shortages occur. During these two months, the maximum temperatures (35°C or hotter) and maximum oscillations occur (between 20° and 35°C), as well as strong northeasterly winds (Andrade and Etter, 1987).

The rainy season, between April and September is characterized by precipitation figures with an average of 250—300 mm/month, up to 450 mm/month (July). Short dry periods (two weeks) occur, usually during August or September; these are called 'veranillo' (i.e. little summer). These cause water shortages in some of the soils of the area, especially in the most clayey ones with limited effective depth (Andrade and Etter, 1987). The rainy season has the lowest average temperature (24—25°C) with minima between 10—15°C. The average number of rainy days per year is between 200—220, with about 25 rainy days in May, June and July (Andrade and Etter, 1987).

Next page:
Figure 2.1: Part of the land cover map from Andrade and Etter (1987), covering the study area between San José and El Retorno, as well as the area between El Retorno and Calamar. Legend translated by the author.

Land cover of the study area

San José del Guaviare, Colombia



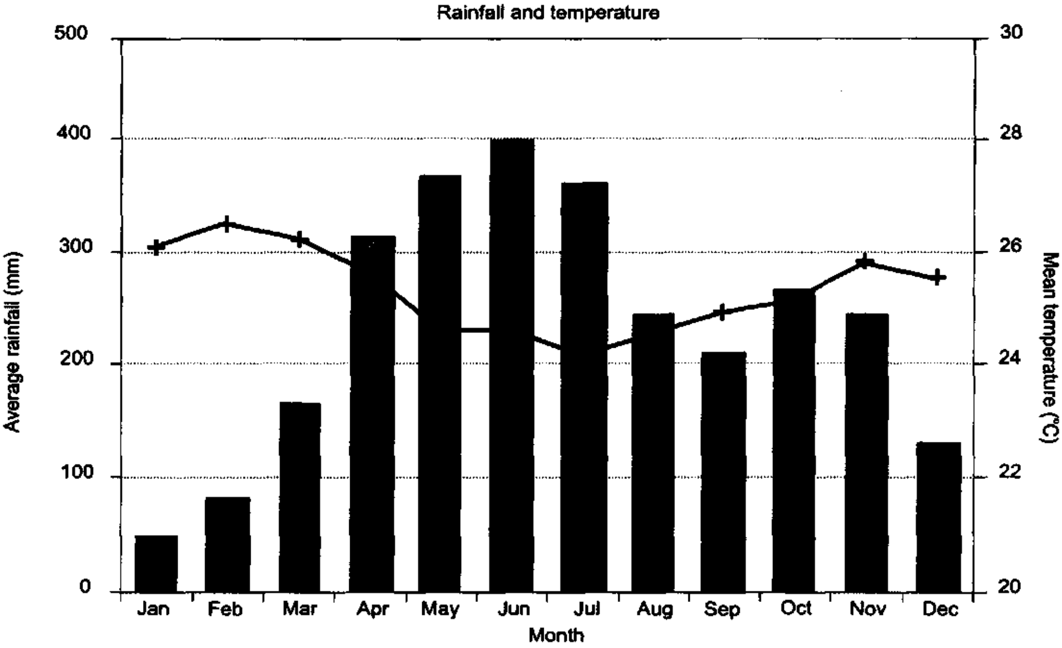


Figure 2.2: Monthly rainfall (bars) and monthly temperature (line) distribution measured at the "El Trueno" station, in the period 1985-1991 (after Martínez, 1992).

2.3. Geology and geomorphology

The area can be divided into two landscape units: the uplands or *tierra firme* and the alluvial plain or *vega*. According to Martínez (1992), the *tierra firme* is partly Paleozoic but mainly Tertiary in age and comprises a large undulating denudation surface, sandstone rocks and nepheline syenite rocks. The *vega* is of Quaternary age and comprises river terraces and flood plains. Figure 2.3 shows a geomorphological map of the area, after Andrade and Etter (1987).

The oldest sedimentary formation in the area is found in the Paleozoic rocks of the Serranía de La Lindosa, southeast of San José (Martínez, 1992). These quartzite sandstone rocks, forming mesas or cuestas with slightly dipping strata, belong to the Araracuara formation. The slopes of the summits vary from 3—12%, the scarp slopes from 12—75% (Martínez, 1992). Their mineralogy varies from sub-arkose to ortho-quartzite (Martínez, 1992).

The nepheline syenite of San José del Guaviare is an igneous rock, also of Paleozoic age, occurring in an intrusion in contact with the sandstone mesas and in small areas of isolated hills (Andrade and Etter, 1987, Martínez, 1992). The relief of these hills is irregular with slopes varying from 7—50% (Martínez, 1992). The mineralogy is mainly composed of alkali-feldspar and nepheline and may contain smaller amounts of biotite, magnetite, zircon and sphene (Martínez, 1992). Both the sandstone and the nepheline syenite rocks have piedmonts formed by their respective colluvial material (sometimes a mix of both) and younger alluvial material (Martínez, 1992).

The upper Tertiary in the Amazon is composed of large and heterogeneous deposits. The lower strata are more homogeneous over the area, while the upper strata vary greatly, presenting clays of different colors, with Miocene lignite lenses in some places as well as poorly consolidated sandstone in a clayey or ferruginous matrix in other places (Martínez, 1992). During the Plio-Pleistocene, the mainly unconsolidated sediments developed into what has been called "the Plio-Pleistocene Amazonian dissected plain" (Andrade and Etter, 1987), which is in fact a denudation surface, formed by erosion processes such as weathering, mass wasting and transportation, and resulting in various degrees of dissection. This denudation surface forms the largest part of the study area and comprises low hills with flat or slightly sloping surfaces and foot slopes (Martínez, 1992). To the east and north of the study area lies the Plio-Pleistocene dissected plain of the Llanos (Andrade and Etter, 1987), which was not included in this study but it is sometimes visible in the corners of the remote sensing images.

The Quaternary deposits mainly consist of fluvial sediments, and the type of deposits on the alluvial plain depends on whether they are formed by a sediment-rich 'whitewater' river rising in the Andes or a sediment-poor 'blackwater' river, rising in the region (Andrade and Etter, 1987, Martínez, 1992). The Guayabero, Ariari and hence the Guaviare too are meandering, whitewater rivers, transporting sediments from the Eastern Cordillera. There are several levels of terraces, which define the frequency and duration of their inundation. The alluvium is mainly sandy or silty, with coarse to fine stratifications (Martínez, 1992). The river system shows lateral erosion of the banks and the formation of river bars in several places. The older terraces may contain sediments of mixed origin (i.e. also reworked sediments of Tertiary origin) (Martínez, 1992). Caño Grande, near El Retorno, and the rivers Unilla and Itilla further to the south are blackwater rivers. They carry little sediment and are mainly erosive. They therefore have narrower and deeper channels than the whitewater rivers.

Next Page:
Figure 2.3: Part of the geomorphological map from Andrade and Etter (1987), with translated and adapted legend.

Geomorphology of the study area
San Jose del Guaviare, Colombia

2.4. Soils

Several soil surveys have been carried out in the area, with different levels of detail. An overview of these studies has been given by Martínez (1992). According to Martínez (1992), ultisols are dominant on the Tertiary denudation surface in this area, as well as in the whole Amazon of Colombia, while the alluvial plain and the sandstone mesas are mainly covered by inceptisols and entisols. On the hills and in the piedmont, coarse-textured and low fertility soils are derived from the sandstones (Martínez, 1992). Finer textured and more fertile soils developed on the nepheline syenite (Martínez, 1992. Soils on the denudation surface are characterized by low fertility and a high aluminum saturation. A layer of petro-ferric gravel near the surface is common on summits and upper shoulders (Martínez, 1992).

Along the whitewater rivers, the lowest level is flooded for about 1—2 months every year. Large amounts of sediment are deposited during the inundation. The soils have high water tables, medium textures, moderate fertility and are poorly drained (Martínez, 1992). The medium level is flooded less often and less sediment is deposited. Fertility is moderate to low, drainage moderate to poor (Martínez, 1992). On the highest level, both well drained and poorly drained soils can be found, depending on the micro/meso relief (Martínez, 1992). Flooding occurs here only once every 5—8 years (Martínez, 1992). The soils have low to moderate fertility and a medium aluminum saturation (Martínez, 1992). Along the blackwater rivers, soils have a low fertility and a medium to high aluminum saturation (Martínez, 1992). Drainage depends on the micro relief and is poor in concave areas.

2.5. Vegetation

Originally, the area was largely covered by tropical evergreen forest, of which only a part now remains. This forest is of lower wood volume than the forests of Araracuara, further to the south in the Colombian Amazon (G. Sicco Smit, personal communication). A large part of the forest has been cut and replaced by agriculture, pastures or secondary regrowth. The remaining forest has been partly disturbed by the removal of large, valuable trees.

Andrade and Etter (1987) distinguished the following four types of (natural) forest in the study area, based on density and height. The high dense forest has trees up to 40 meters high, generally emergent trees and the canopy is not very uniform. The forest is well stratified. The understorey has a low density. In general, these forests contain many lianas and epiphytes as well as disperse palms. Tree density (>10 cm dbh) is around 100 trees per hectare. This forest type can be found on the relatively higher parts of the alluvial plains of the Ariari, Guyabero and Guaviare rivers, the syenite hills and their piedmont, and on the relatively high parts of the Plio-Pleistocene Amazonian dissected plain (Andrade and Etter, 1987).

The medium-high, dense forest is around 30 meters high, with a uniform canopy and few emergents. The forest is well stratified and the understorey is dense (see also Figure 2.4.a). There are usually many palms, but few lianas and epiphytes. The tree density (>10 cm dbh) is around 90 trees per hectare. This is the most common forest type on the Plio-Pleistocene dissected plain (Andrade and Etter, 1987).

The low, dense forest is between 15 and 20 meters high, with occasional emergents till 30 meters and little uniformity in the canopy. This forest shows little stratification and has many lianas and palms. The density of the understorey varies. Tree density (> 10 cm dbh) is around 80 trees per hectare. The low, dense forest can be found on the wetter parts of the alluvial plains of both whitewater and blackwater rivers, and in the valleys of the Plio-Pleistocene Amazonian dissected plain (Andrade and Etter, 1987).

The low forest of medium density is between 15 and 20 meters high, with a uniform canopy. The forest shows little stratification and the understorey is dense (see also Figure 2.4.b). The forest contains many palms, lianas and (low) epiphytes. This is the (gallery) forest of the valleys in the sandstone plateau and its piedmont (Andrade and Etter, 1987).

According to Andrade and Etter (1987), areas covered mainly by palms and marsh vegetation are found in depressions with poor or imperfect drainage, mainly in the alluvial plains but also in some parts of the uplands. In the areas of permanent inundation, the vegetation is mainly herbaceous with some palms and shrubs, usually not higher than 3 or 4 meters. Inundated areas where the water level is lower are covered with an almost homogeneous vegetation of palms (*Mauritia flexuosa* and *Euterpe precatoria*).

Natural shrub lands, as described by Andrade and Etter (1987), are characterized by shrubs and low, stunted trees (2m), with low density and a somewhat xerophytic character. They are accompanied by a herb stratum with low density. They have similar characteristics to the cerrado in Brazil. These shrub lands can be found on the rock outcrops of the sandstone plateau.

High, dense savannah dominated by *Andropogon virgatus* and *Rhynchospora spp.* is found in the poorly drained areas of the old river terraces of the whitewater rivers, usually associated with areas covered with Mauritia flexuosa palms (Andrade and Etter, 1987). The herbaceous stratum may reach heights of more than a meter (Andrade and Etter, 1987).

Low- or medium-high savannah of varying density (see Figure 2.4.c) is found where drainage is good or excessive, on the high plains of the old terraces of the whitewater rivers and on the gently sloping parts of the sandstone plateau and its piedmont. The main herbaceous species are *Trachypogon spp.*, *Paspalum spp.* and *Bulbostylis spp.*(Andrade and Etter, 1987). Some stunted trees are present of *Byrsonima crassifolia*, *Bowdichia virgiloides* and *Curatella americana* (Andrade and Etter, 1987).

The savannahs are 'natural' in the sense that they are the natural cover for this landscape unit. However, the practice of burning to stimulate sprouting and improve the fodder quality of the grasses for the cattle must have an effect on the structure and the composition of the savannah vegetation. 'Semi-natural' might therefore be a better qualification for the savannahs in this area.

Part of the area is covered by dense secondary vegetation of varying age and succession stage (see Figure 2.4.d, e, f). Most of the secondary vegetation, however, is not more than 10 years old, because of the practice of reusing the areas of secondary vegetation for cultivation within a relatively short time span (Andrade and Etter, 1987).

The perennial crops found in the study area are: cacao, coca, plantain, cassava (Figure 2.4.h), sugarcane, fruit trees (Figure 2.4.g) and rubber. The annual crops are maize (Figure 2.4.i), (dryland) rice and sometimes cotton and sorghum. Few vegetables are grown in this area. The cacao, cotton and sorghum are found mainly on the more fertile soils along the whitewater rivers. The coca (Figure 2.4.g) grows on any well-drained site and is the only crop receiving mayor applications of fertilizers and pesticides (Andrade and Etter, 1987). Plantain (Figure 2.4.j) is cultivated on more humid soils, both on the alluvial plain as well as on the uplands (Andrade and Etter, 1987). Maize is the most common crop in the area; together with rice, sugarcane and cassava it is cultivated both on the alluvial plain as well as on the Plio-Pleistocene Amazonian dissected plain (Andrade and Etter, 1987, Martínez, 1992). Rubber is mainly grown on the Plio-Pleistocene Amazonian dissected plain.

The man-made pastures in the area are mainly planted with *Brachiaria decumbens*, but also with *Hyperrhenia rufa*. On a small scale, other varieties of *Brachiaria* have been introduced as well as the use of leguminosae in the pastures, to improve the protein content of the fodder. Usually, pasture is planted after a few years of cultivation of annual crops. Pastures are progressively invaded by weeds, (herbs as well as shrubs and palms). According to Andrade and Etter (1987), the cover of the planted grass species is reduced to 50% after 6—10 years, with the degradation being more severe in areas with fine-textured soils than in those with coarse-textured soils, because the former are more susceptible to compaction from the trampling of the animals. More details on the process of degradation of pastures can be found in Martínez (1992).

Figure 2.4.a: Medium-high, dense forest on the Plio-Pleistocene dissected plain.

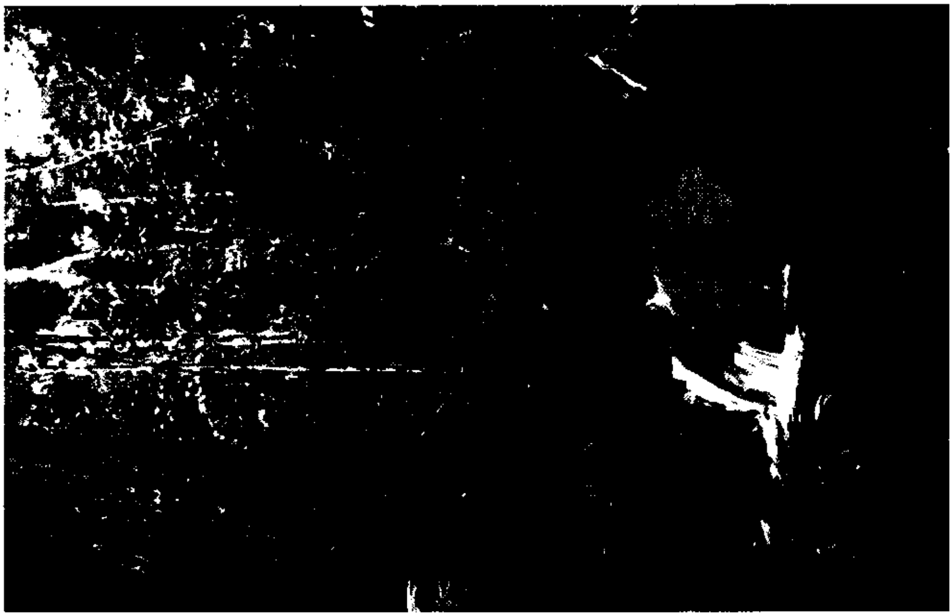


Figure 2.4.b: Low, medium dense forest in the valleys of the sandstone plateau.

Figure 2.4.c: Low- to medium-high savannah on the sandstone plateau.

Figure 2.4.d: Dense, young secondary vegetation after agricultural crops on the Plio-Pleistocene dissected plain.

Figure 2.4.e: Dense, young secondary vegetation (20 months old), after crops on the Plio-Pleistocene dissected plain. Note the high cover percentage of Cecropia trees.

Figure 2.4.f: Dense, older secondary vegetation (10 years old), on the Plio-Pleistocene dissected plain.

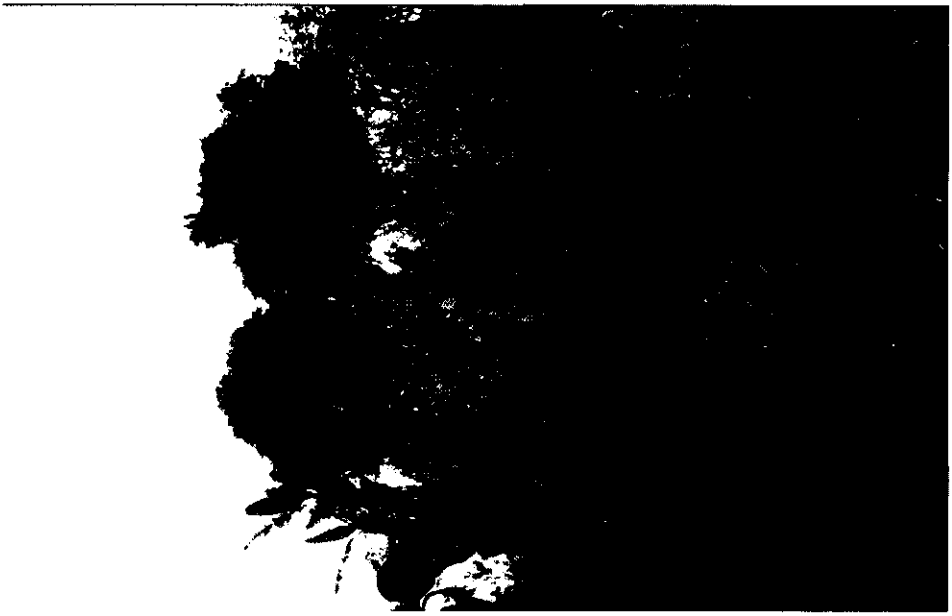


Figure 2.4.g: Coca shrubs and mango trees on soils from nepheline syenite rocks.

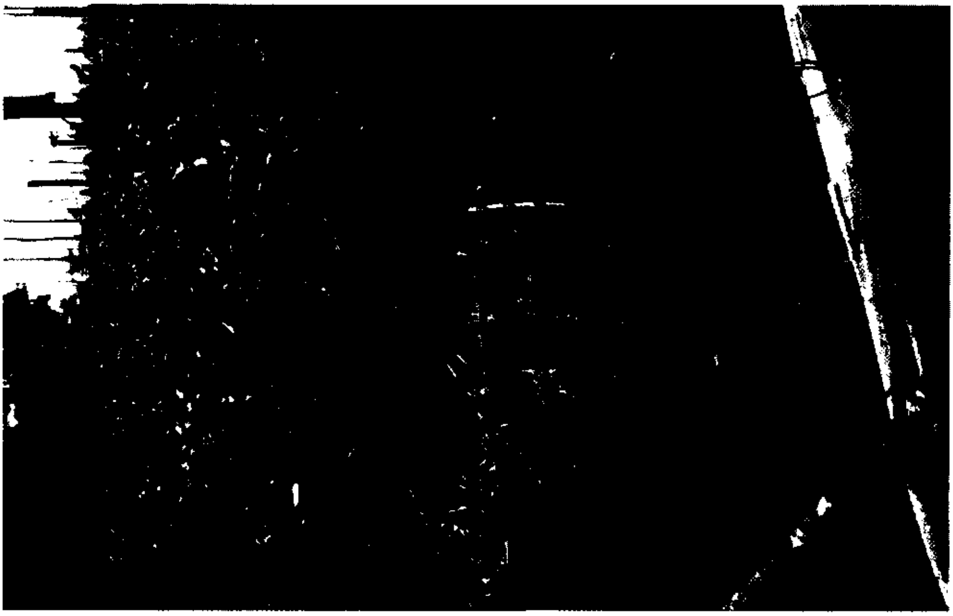


Figure 2.4.h: Maize after burning of secondary forest on the Plio-Pleistocene dissected plain.

Figure 2.4.i: Maize and cassava on the Plio-Pleistocene dissected plain.

Figure 2.4.j: Cassava and plantain on the Plio-Pleistocene dissected plain.

Figure 2.4.k: Pasture with Brachiaria decumbens and invasion of palms, on the Plio-Pleistocene dissected plain.

Figure 2.4.l: Pasture with Hyperrhenia rufa on the Plio-Pleistocene dissected plain.

2.6. History of the settlement in Guaviare

The movement of people from other regions to the Amazon, also called 'colonization' by some authors, was mainly caused by violence and the system of land tenure in the Andean region, which favored concentration of land ownership. At first, the movement to the Guaviare region was spontaneous, but later it was supported by the government. Non-indigenous settlements were first founded in about the middle of the 19th century, during the rubber and resin booms in San José del Guaviare, Calamar and Miraflores (Martínez and Vanegas, 1994a, also quoting Dominguez, without date, and Karremans, 1990a). According to these authors, the booms led to the exploitation and extermination of the indigenous people, most of whom belonged to the Guayabero group.

It took until 1968 before San José del Guaviare assumed some importance in the geography of Colombia (Acosta, 1993). Before the migration and settlement of people from the center of Colombia, the indigenous people of the Guayabero group lived on the banks of the Ariari river (Acosta, 1993, quoting Duran, 1979, and Chavez, 1987). They moved downstream to the Guaviare river in the 1950s, when the pressure of new settlers coming along the Ariari river increased; they settled mainly in the savannahs of La Fuga, near San José del Guaviare (Acosta, 1993, quoting Duran, 1979, and Chavez, 1987). The Guayaberos cultivated bitter cassava, and fished, gathered and hunted.

In the 1950s the 'colonization' of the banks of the Guaviare river by settlers from other departments fleeing the violence of the civil war began. The years of the civil war in Colombia, from 1948—1953, are better known as 'La Violencia'; it resulted in the death of over 200,000 people (Vaessen, 1991). The newcomers cultivated rice, maize and plantain, and did some fishing. Their plots were between 200—300 ha (Andrade and Etter, 1987). Another group of migrants settled in the savannahs of La Fuga and in the Serranía de San José and dedicated themselves to extensive cattle breeding, very similar to that undertaken in the Llanos Orientales (Andrade and Etter, 1987, quoting Andrade, 1985).

In the mid-1960's the construction of the road San José—Calamar was begun. Some 100 indigenous people of the Tukanos Orientales group were brought from the Vaupés to work as day laborers on this project (Andrade and Etter, 1987; Acosta, 1993). Upon completion of work, they returned to the Vaupés, but later came back to settle in Guaviare, near Caño Grande, far away from the 'colonists' in San José. They practiced a rotating cultivation of crops similar to those they had grown in Vaupés: bitter cassava, pineapple, chontaduro (a palmfruit), tree-grape etc., as well as hunting and fishing. Migration of the Tukanos to Guaviare continued until the end of the 1970s (Andrade and Etter, 1987; Acosta, 1993, quoting Chaves, 1987).

In 1968, the Colombian government started and supported a settlement project in the Guaviare region, centered on El Retorno, 30 km south of San José del Guaviare and along the Caño Grande and the road San José—Calamar. As described by Acosta (1993, quoting Ovden, 1986) and Martínez and Vanegas (1994a), this generated a new influx of migrants. The immigration in the period 1968—1971 is known as the 'colonization of El Retorno'. The political motivation for this program was to relieve the growing pressure for land in rural areas as well as the unemployment in the cities by stimulating the colonization of the 'empty' forest areas (Acosta, 1993).

The indigenous Tukanos who had settled in El Retorno moved east, downstream of Caño Grande, to what is now the reserve of 'La Asunción'. From this time on, there was permanent contact between the settlers and the indigenous Tukanos group who, from the beginning, were willing to participate and assimilate land use practices introduced by the settlers (Andrade and Etter, 1987). The lack of even a minimal infrastructure meant it was very hard for families to settle in this area and many gave up and left, until INCORA (Colombian Institute of Agrarian Reform) finally started to develop programs to stabilize the settlement process in 1970 (Acosta, 1993).

In 1969 INCORA asked INDERENA (Institute for the Development of Renewable Natural Resources and Environment) to take 181,200 ha from the forest reserve, officially initiating the settlement programs of El Retorno. INCORA started to supply credit and grant land ownership rights, requesting that at least two-thirds of the land should be opened up and planted (Andrade and Etter, 1987; Acosta, 1993). These settlers dedicated themselves mainly to the cultivation of maize and rice, in order to sell the surplus. Some cultivated sugarcane, plantain and beans or experimented with cotton, tomatoes and other crops. In areas where transport was difficult, surpluses of maize and rice were used to fatten pigs, which were sent by plane to Bogotá (Andrade and Etter, 1987; Acosta, 1993).

From 1971, different waves of settlers came to Guaviare but they did not have access to the INCORA programs. They settled outside the area taken from the forest reserve and assigned themselves plots of up to 300 ha (Andrade and Etter, 1987). IDEMA (a government institute for marketing of agricultural products) bought the local surplus of agricultural products (rice and maize), but was unable to sell this in the national market because of the bad infrastructure and the high transportation costs (Acosta, 1993). Initially, the new families had generated a small internal market for the surpluses, but they were soon able to feed themselves. Production increased so that in 1976, when maize production was at its peak at 14,000 tons (the equivalent of 8,500 hectares under maize), the IDEMA stores, with a capacity of 5,000 tons, were completely full, as were other public and parish buildings (Acosta, 1993). Prices collapsed, resulting in many bankruptcies. The economic crisis forced many settlers to leave, while others were reduced to a subsistence level of production (Acosta, 1993).

During this economic crisis in the mid-1970s, the production of marihuana (*Cannabis sativa*) was introduced to Guaviare, giving a strong but temporary impulse to the local economy (Acosta, 1993). The farmers who opted for the new crop abandoned the cultivation of food crops for self-sufficiency (Acosta, 1993). The drug traffickers supplied the farmers with seeds and organized transport and marketing (Acosta, 1993). A network of airports was constructed in the region, attracting new migrants who started to cut down large tracts of forest to cultivate the illegal crop (Acosta, 1993). As a result of the increased economic activity and the amount of cash flowing into the region, the town of San José developed into a centre of consumption and recreation (Acosta, 1993). But the marihuana boom was only temporary and although the infrastructure had improved, the region eventually lost a high income source (Acosta, 1993).

In 1977 the 'Commissaría especial del Guaviare' was created, covering an area of 54,847 km^2 and with San José as its capital. The settlement process was stagnating and in crisis at this time (Acosta, 1993). Subsistence agriculture continued on the alluvial plain, with the small-scale introduction of cacao in 1976 (Acosta, 1993). In the uplands, subsistence agriculture continued with extensive livestock on the natural savannahs and in other areas planted with grass by farmers with capital. Because of the high costs of labor and production, and the small profits made, intensive livestock was never an objective (Acosta, 1993). Pasture establishment was used as a way to obtain ownership rights to land, according to the rules of INCORA (Acosta, 1993).

The coca cultivation was initiated in Miraflores, to the southeast of Calamar, and slowly moved north, until it was recognized as a commercial product in the whole region in 1978 (Acosta, 1993). In the USA there was a growing demand for cocaine (Acosta, 1993, quoting Ovden, 1986). The settlement process took a sharp turn towards conditions generating the violence related to the illegal crop (Acosta, 1993, quoting Gonzalez, 1989). Coca production quickly became the most important economic activity in the region and the main source of income and accumulation of capital. The high profits made the farmers willing to take out loans to cover the high initial costs, as well as accept the violence related to the debt-collection (Acosta, 1993, quoting Ovden, 1986). Again the region's economy boomed, attracting a new surge of migrants, and the cutting of large tracts of forests (Acosta, 1993). Large numbers of laborers were hired to work in the cultivation and processing of coca. They were paid 4 or 5 times the minimum salary, so that labor became prohibitively expensive for other crops, and the area under food crops dropped to the level that a farming family could attend to themselves (Acosta, 1993).

Local inflation rose above the national level, San José became an economic island where prices bore no relation to those in the rest of the country (Acosta, 1993, quoting Baquero, 1983) which made the farmers become more and more dependent on the production of coca, as the only crop providing enough income to buy consumer articles (Acosta, 1993, quoting Ovden, 1986). There was an increasingly strong tendency to use the money earned from coca for luxury articles and to buy food instead of growing it. The indigenous Tukano adopted the colonists' cultivation schedule from the start of the coca crop and participated actively. They also started cattle farms with the help of INCORA (Acosta, 1993).

In 1982, the violence in the region reached a climax. Coca prices dropped below the production costs (Acosta, 1993, quoting Ovden, 1986) because of regional overproduction, competition with other coca-producing regions in the Amazon, and strong government control, causing difficulties in marketing and a surplus in supply (Acosta, 1993). Many farms were abandoned and the value of a day's labor dropped from 2,000 Colombian pesos to only 650 pesos in one year (Acosta, 1993, quoting Baquero, 1983). However, the farmers who had not dedicated themselves completely to the cultivation of coca were able to survive (Acosta, 1993, quoting Ovden, 1986).

During the crises, which lasted until mid-1984, the FARC guerrilla organization (the Revolutionary Armed Forces of Colombia) entered Guaviare, took over local and regional power, and restored peace and order. The FARC encouraged the farmers to organize themselves into community action boards, unions and cooperative societies (Acosta, 1993,

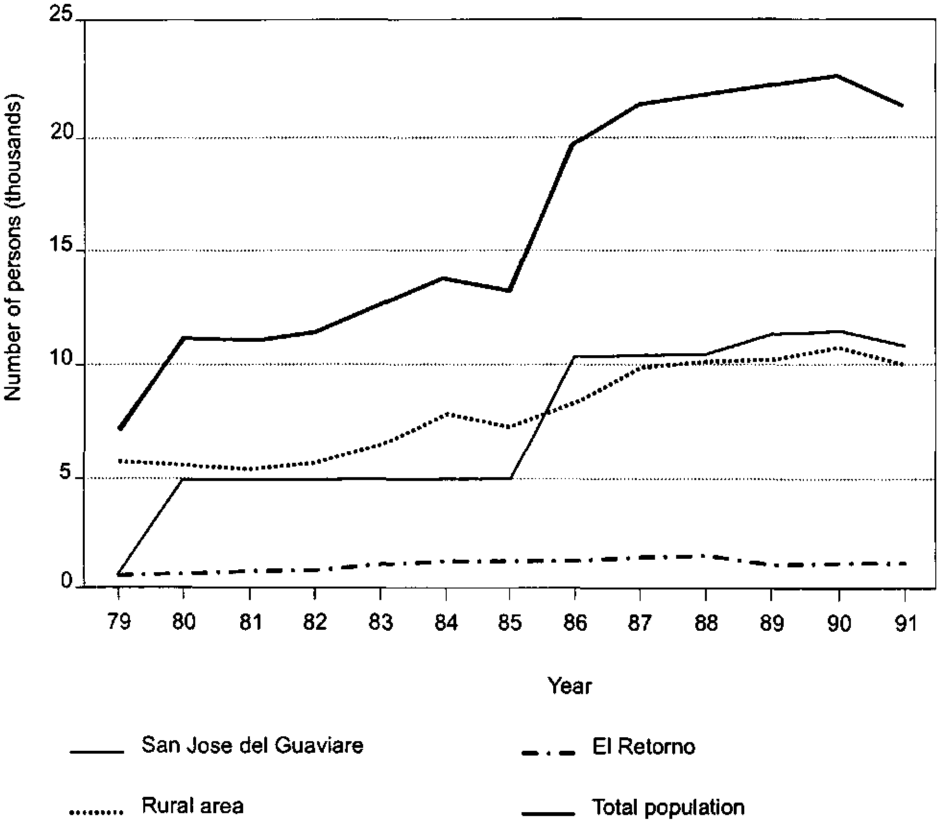


Figure 2.5: Graph showing the population increase between 1979 and 1992 for the towns of San José del Guaviare and El Retomo and the rural area around these towns, study area is approximately the same as for this research. Figure adapted from Martínez and Vanegas, 1994a, data used with kind permission of D.E. Vanegas Reyes.

2.7. Actual land use

Land use should not to be confused with land cover, nor with vegetation. Land use is the way in which people use the land, e.g. cattle breeding, shifting agriculture, cash-cropping are all land use types. Land cover is what one sees in an area: pastures, maize fields, savannahs, cities, anything that covers the surface of the earth. Some of this land cover will consist of vegetation. Of course,land cover, land use and vegetation are related. When the type of land use is (extensive) cattle breeding, the associated land cover could be pastures or savannahs. These pastures and savannahs each have a typical vegetation that comprises a number of species and their distribution. However, not every pasture and savannah belongs to a system of cattle breeding (some pastures are not used for cattle).

Cattle breeding is the dominant land use on the uplands or *tierra firme* in the area, although cattle breeding on the natural savannahs is also very widespread. On the Plio-Pleistocene Amazonian dissected plain, the process is as follows: after cutting and burning the primary or secondary forest, annual and perennial crops are planted (maize, rice, cassava, plantain) and finally forage grasses (mainly *Brachiaria decumbens* and to a lesser extent *Hyperrhenia rufa*). A smaller part of the area is planted with more permanent crops, like rubber, fruit trees, sugarcane and coca. Fruits are for own consumption or the local market. The sugarcane is processed into 'panela', brown sugar loaf, in several mills in the area. The coca leafs are processed on the farm to a halfway product called 'base', which is usually bought at the farm by specialized salesmen and processed to cocaine in specialized (illegal) laboratories.

If annual crops are planted in the first year after clearing the forest, maize is often sown first and cassava and plantain are planted in the maize crop directly after clearing the weeds, so they can start producing when the maize is harvested (see also Figures 2.4.h, i, j). In other cases, the field is burned between two crops. The number of years a field is used for crops varies, but after a while it will be left fallow or turned into pastures. According to Karremans (1990b), in 45% of the cases, the sequence in land cover is from primary forest, to crops, to pasture. In 35% of the cases, the sequence is from primary forest to crops, to fallow (secondary forest), followed by crops and finally pasture. In the remaining 20%, there are two or more fallow periods followed by crops before the plot is turned into pasture. The same author also stated that a field under pasture remains under pasture, although it may degrade. During fieldwork it became clear that pastures sometimes may be left fallow and develop secondary regrowth. This regrowth is different from the type of regrowth after crops. After crops, the first years of regrowth are characterized by a large number of *Cecropia spp.* trees (sse Figure 2.4. e) and other fast-growing, large-leafed species. After several years under pasture, the regrowth shows almost no Cecropia trees and the species there are have smaller leaves. The color of regrowth after pasture is also less green, lighter in tone, than after crops (Carlos Hernando Rodriguez, personal communication, 1993). This could be the effect of nutrient shortage.

Production focusses on beef cattle in the majority of farms, with a minor proportion of dairy cattle. Technical input is low and management semi-extensive. Zebu types and crosses with local breeds are predominant in the area (Martínez, 1992).

Agriculture is the main land use in the more fertile soils of the alluvial plain. Cacao, bananas, maize, soybean, sesame, cotton, cassava and sugarcane are the main crops. Crop yields are higher than on the uplands. For maize, two harvests per year are possible. The first is in August and September, at the same time as the maize harvest on the uplands. The second harvest, 'maíz traviesa', is in February and March (Andrade and Etter, 1987). There are also pastures although flooding and bad drainage can be a problem (Martínez, 1992; Andrade and Etter, 1987). Figure 2.6 shows the cropping calendar for the area, both uplands and alluvial plain, after Andrade and Etter (1987).

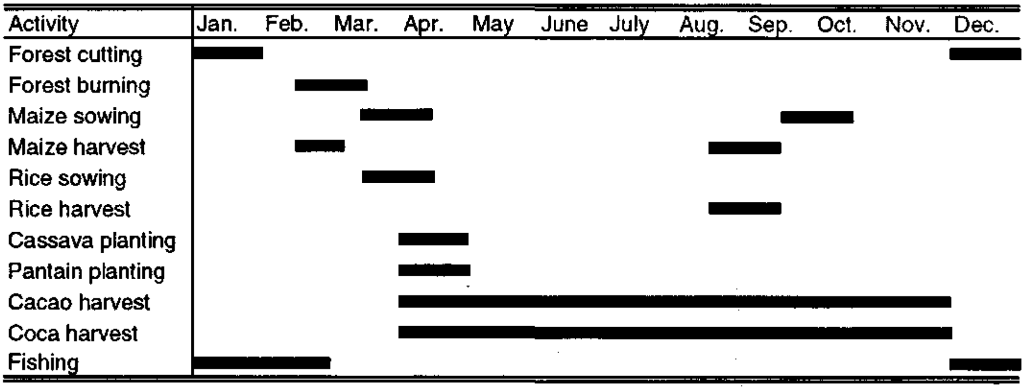


Figure 2.6: Cropping calendar for the area around San José del Guaviare, showing the main agricultural activities (after Andrade and Etter, 1987).
▬ Period in which the activity takes place.

3. OUTLINE OF A MONITORING SYSTEM

3.1. Introduction

The outline of a monitoring system, based on (radar) remote sensing (see also Bijker and Hoekman, 1994), is presented in this chapter. Components of this type of monitoring system will be explored and applied to the settlement area of San José del Guaviare, Colombia, in Chapters 5, 6 and 7. The monitoring system should be linked with a geographical information system (GIS) in such a way that the data from the GIS can be used for the interpretation of the images, and the output of the monitoring system can be used to update the data on land cover in the GIS. The combination of both systems provides planners and decision makers at local and regional levels with a powerful tool. The systems can provide current and accurate data for decisions affecting land use, for building scenarios and for monitoring the effect of such decisions on the land cover in the area. Moreover, monitoring of the settlement process will give a better insight into this process. It is expected that similar systems will be built for other areas once its usefulness has been proven in Guaviare.

The development of an operational monitoring system for Guaviare is important for local applications as well as for improving the understanding of such systems for monitoring tropical land use in general. Consequently, the objective is to design a generic architecture in which some components use generally applicable models and other components use site-specific models. The site-specific models can then be replaced if necessary, for applications at other locations.

With a generic approach, a generalization of the monitoring system concept as well as a high flexibility is pursued. The latter is illustrated in the operationalization strategy. A pre-operational system with limited functionality can be built using simple models for the system's functional components. This prototype system can supply users with relevant information and the users can supply useful feedback for the further development of the system. This approach may, therefore, be characterized as a *developing while working* approach.

As a first step in the development of the system, an inventory of functional components and the relations and interactions between them has to be made. These ideas should be reflected in the system design or architecture. The system can be designed to combine models and techniques in such a way that they mutually support and reinforce each other. With the introduction of some new techniques and functional components that are only meaningful within the environment being monitored, the system can acquire some characteristic properties. One of the most challenging possibilities is that the system's functionality can be enhanced with *self-learning capabilities*.

3.2. Basic system architecture

3.2.1. Structure

The basic architecture is represented in Figure 3.1. This figure shows the relation between functional components, data and information flows and time. It also shows the three shells that will be discussed hereafter: the core, the peripherals and the externals.

In the core of the system, the remote sensing images are processed. Around this core is a shell of peripherals, necessary for the validation and upgrading of the system. The third, outer shell of the externals presents the input and output relations of the system with the "world outside".

3.2.2. Core

Remote sensing data, in the form of digital images, enter the system via the remote sensing data source. The main supplier of the data is the ERS-1 radar satellite, although other (e.g. optical) remote sensing data may also be used. For the Guaviare area, as well as for many other areas in the tropical rain forest, optical/NIR satellite images are scarce and only available erratically, due to the high percentage of cloudy days. These images are not therefore suitable as the basis for a monitoring system. All the images used in the monitoring system are stored in an archive.

An image of a certain date is processed into interpreted remote sensing data. For this interpretation, data from the geographical database, formalized knowledge and image interpretations of earlier dates are used. The geographical database is related to the geographical information system (GIS) for the area. The new interpretations are accumulated for future processing in the GIS and can be used to produce system output products.

3.2.3. Peripherals

The monitoring system has a core and external parts necessary for validation and upgrading. There are three conceptual levels (types) of validation, i.e. system validation, classification validation and model validation. The system validation component evaluates the functioning of the system as a whole. It should indicate the accuracy of the changes detected by the monitoring system (at $t = t_n$). A land cover survey is required (at $t = t_n$). The classification validation component evaluates the performance of (multi-temporal) classification procedures. A certain short series of interpretations ($t = t_i$ .. t_j), corresponding to a certain sequence of phenological stadia during a single growing season, is compared with in situ observations of the actual development of vegetation growth.The third level of validation is performed in the model validation component. All system models, including land cover change models, are evaluated using all the interpreted results ($t = t_0$ .. t_n) and recordings of actual observations of land cover succession and spatial change.

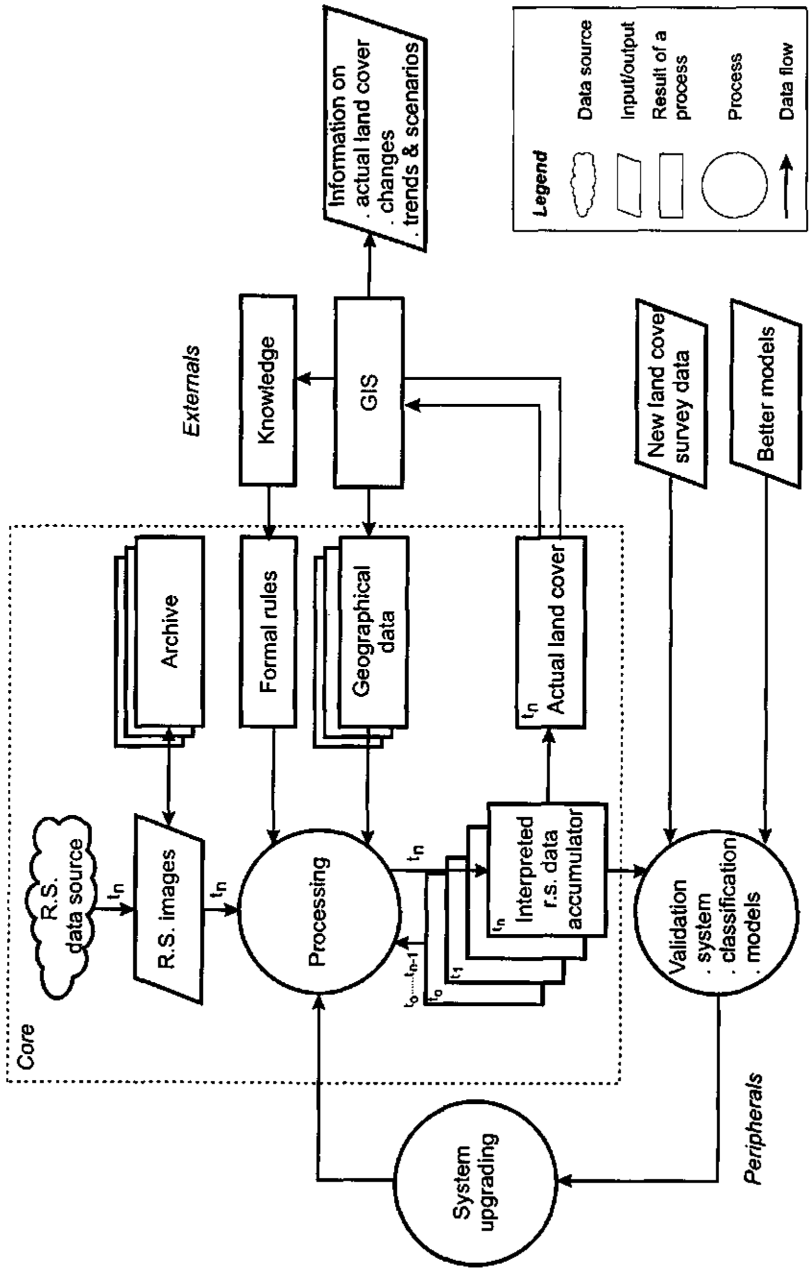


Figure 3.1: Basic architecture of the monitoring system, based on remote sensing, developed in this thesis. (Adapted from Bijker and Hoekman, 1994).

System upgrading can be performed in various ways (see also section 3.5). As a result of field survey and system validation, a portion of the interpreted data stored in the system's accumulator can be substituted for 'correct' data (i.e. labeled at the 100% accuracy level). The performance of the system's models and techniques can be evaluated from the classification and model validations. Modifications of the models and techniques, or even completely new models and techniques (with the same functionality), can also be evaluated. System upgrading can now be achieved by substituting more appropriate models and techniques for those used by the system's processing component.

3.2.4. Externals

External inputs, necessary for the functioning of the system, are: a GIS, 'local' knowledge, field surveys, vegetation growth models and land cover change models. The GIS supplies the monitoring system with a geographical database. The monitoring system supplies the GIS with up-to-date information on land cover that can be combined with other information in the GIS for analysis and building scenarios on various themes.

Field survey enters the monitoring process in several ways. It is used: (1) to establish empirical relations between remote sensing observables and the objects, (2) to develop the vegetation growth and land cover change models, and (3) to validate backscatter, vegetation growth and land cover change models and the monitoring system as a whole. The empirical relation and the models are the knowledge used for the formulation of the formal rules used in processing (see Figure 3.1).

Field survey is performed most intensely at the beginning of the monitoring process, when the initial situation of the land cover has to be defined and the models need to be calibrated. Later, field surveys continue in a more extensive way for validation of the system and its models. Apart from a general check on accuracy, some areas might need more detailed surveys because of classification problems or because the need for accuracy is higher in these areas. People working in the area can use their own knowledge of the field or do the checking along with their other fieldwork, for example, extension workers or census surveyors can carry out checks when they visit the farmers.

3.3. Processing module

The processing module of the basic architecture is depicted in detail in Figure 3.2. This module contains image processing leading to object delineation, and object processing leading to object classification. Object delineation and object classification are closely related. There is some classification necessary for object delineation but once the objects are identified and delineated, the final classification per object can take place.

Segmentation of the remote sensing images by means of segmentation algorithms based on heterogeneity and texture and/or a priori boundary information leads to object delineation. This object delineation has to be done repeatedly, as the shape, size and location of objects may change with time. A plot can be divided up to grow two different crops or several agricultural plots can be merged into one plot with pasture. When a plot is burned, part of the adjacent forest might also be burned and then be added to the plot. A river displaces itself over the years by sedimentation and erosion. These are just some examples of the multitude of changes that can occur.

The probability of changes in size, shape or location of objects clearly depends on the class of the objects and on their location relative to other objects. Displacement is typical for a river, while area growth is more typical for a town or a pasture. The size of pastures in the older part of the settlement area is not very likely to change, whereas on the settlement front, plots are more likely to be changing in size and shape. A city is more likely to grow along main roads or on dry land than towards a site without any infrastructure or with swampy conditions.

Expert knowledge is expressed in formal rules that act on the four different components of the object processing block:

1. Knowledge of the phenological stages of the vegetation in a land cover type and their *physical relations* to remote sensing observables, expressed either in empirical relations or in a theoretical model, formed by a combination of vegetation growth models with backscatter and reflection models.

2. Knowledge of the succession of land cover as part of the settlement process is formalized in a land cover change model that generates either a land cover change probability matrix or a set of decision rules. This matrix or set of decision rules express *temporal relations* between land cover types.

3. Knowledge of the spatial displacement of objects (e.g. the rate of displacement of the river at certain points) is formulated in a spatial displacement probability matrix, expressing *spatial relations* between objects.

4. Other knowledge of the processes in the area are formulated in (fuzzy) logical operators. These operators describe *semantic relations* between objects.

In the image processing block, knowledge of the relation between land cover and image characteristics is used to delineate objects. This involves knowledge about the texture, internal heterogeneity, or typical size, shape and location of certain land cover types. The use of knowledge of temporal relations (phenological stages as well as succession) in land cover for object classification is elaborated in the next section.

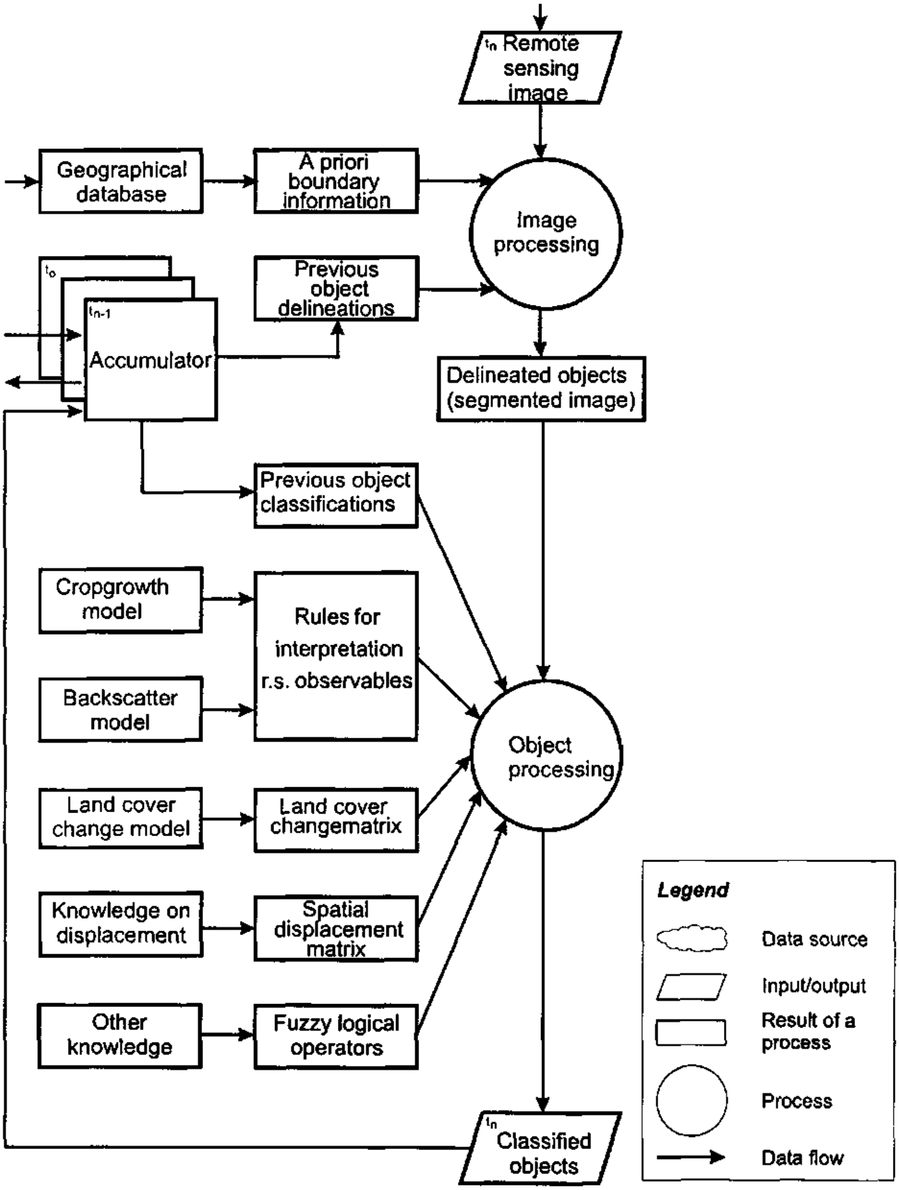


Figure 3.2: Elaboration of the processing module of the basic system architecture of Figure 3.1.

3.4. Temporal models of land cover change

The monitoring system contains two models that formalize the knowledge on the relation between land cover and time so that this knowledge can be used for the object classification (see Figure 3.3). The first model covers the changes within one growing season. Within one season, the land cover type does not usually change, although the backscatter level changes due to growth and development. This is especially true for annual agricultural crops. The second model covers changes over several growing seasons. The land cover type may change, but the changes that are possible depend on the initial land cover type and time. Both models are related to a backscatter model to predict the influence of calculated changes on backscatter.

Starting with the seasonal changes, it is clear that the growth and development of vegetation, such as crops and grasses, has its effect on the backscatter. Existing vegetation growth models can be used to estimate the growth and development stage of the vegetation on a certain date. Based on this estimation, the expected backscatter of the land cover can be calculated with backscatter models. For the area around San José del Guaviare, the seasonal changes in the natural forest are not expected to influence its backscatter properties. The river and the built-up area are also not expected to cause seasonal changes in backscatter. The savannah will have seasonal changes in vegetative cover and in soil moisture conditions and hence in backscatter. But as the location and extent of the savannah is already known and is not expected to change, it is not necessary to model these changes for classification. Backscatter can be calculated for several land cover types (including agricultural crops) and several phenological stadia during the growing season. If vegetation growth models and backscatter models are not available, an empirical relation between land cover and backscatter can be used instead. Relations between land cover, time (phenological stage) and backscatter can be stored in a land cover signature matrix. This matrix can be used for the classification of multi-temporal images (a set of images of different dates within one growing season). *Classification is then a matter of matching, i.e. finding the best fit between observed backscatter (as a function of time) and predicted signatures. In this way, it might be possible to separate land cover types that cannot be separated on a single image.*

Knowledge and understanding of the settlement process facilitate the interpretation of the remote sensing data. This knowledge is formalized in a land cover change model, used to generate a set of formal rules or a land cover change matrix. Starting with the land cover on a certain date, the land cover change model calculates the chances of a certain land cover occurring on later dates. This relation between initial land cover and possible land cover types on later dates can be stored in the land cover change matrix. This is a probability matrix used for the interpretation of the remote sensing data over several years.

From the accumulated probabilities at various dates, the most likely land cover type succession for a certain object (e.g. an agricultural field) can be derived. These land cover change probabilities can be matched with the classification probabilities resulting from seasonal variations. This evaluation may result in the adaptation of the classification results on one or more dates to fit into the logic of the settlement process, i.e. *not only knowledge about the land cover on an earlier date $t = t_{k-1}$, but also knowledge about the land cover on a later date $t = t_{k+j}$ is used to find the most probable land cover on a date $t = t_k$.*

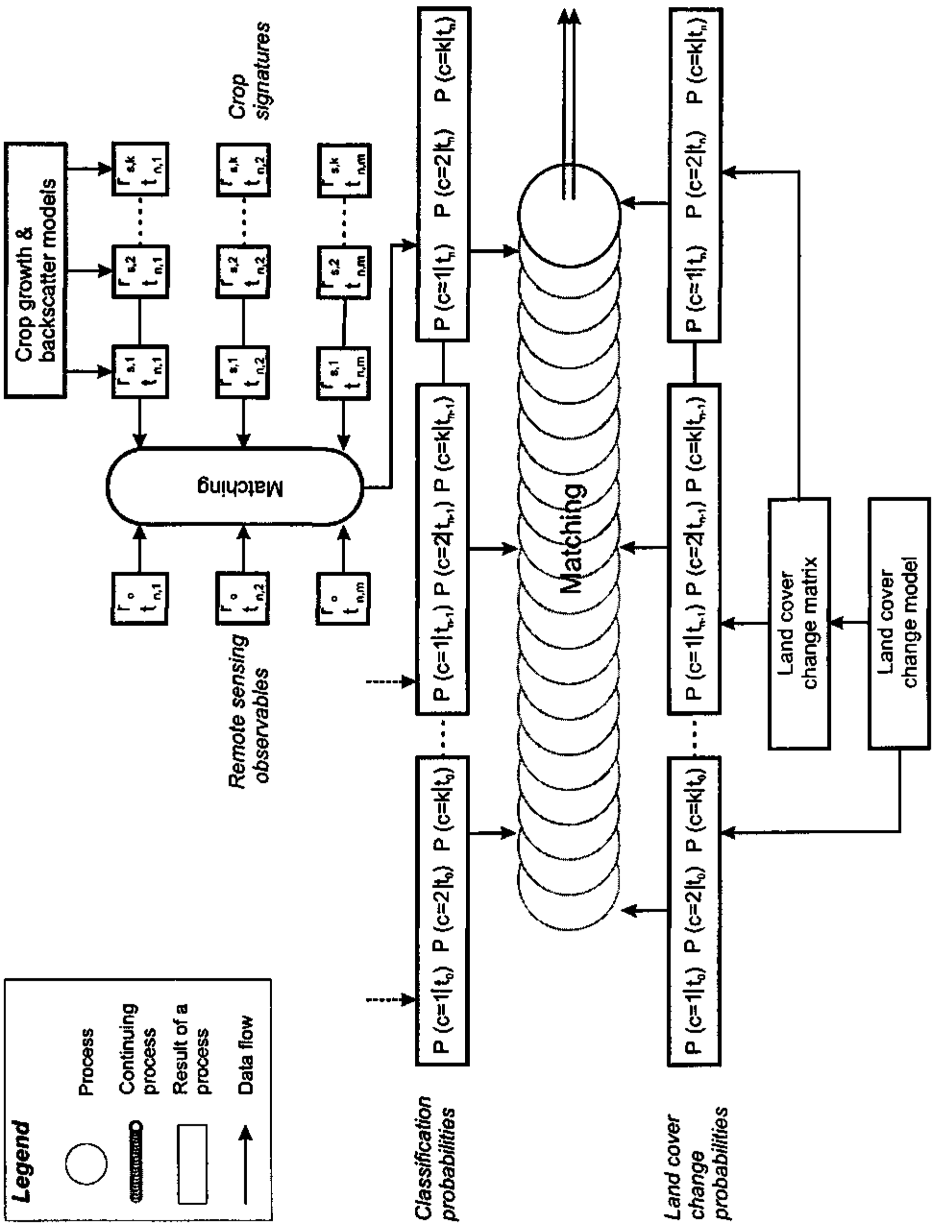


Figure 3.3: The functioning of temporal models in the processing module. The upper block shows observed image characteristics (remote sensing observables) r_o and simulated image characteristics r_s for k land cover classes for m times of observation during the n-th growing season. The lower block shows classification probabilities (upper row) for a certain object in all n growing seasons, to be matched with land cover change probabilities (lower row) resulting in classification (not shown in the figure).

3.5. System characteristics

For processing and interpretation of remote sensing data many, conceptually different, tools have been developed during the past decades. The monitoring system presented here comprises many of these 'classical' components, along with some new ones. The system combines these tools in such a way that they can support each other.

One of the most crucial components in the system is the *accumulator.* Results in the form of land cover classification probabilities are accumulated over time. This is not only relevant for interpretation of new remote sensing data, but also for evaluation of the 'internal' models. For example, land cover statistics (cover type sequences and acreages) can be assessed for the whole area of observation and for the whole period of observation. Thus, *land cover change models can be corrected for initial biases and, even more important, to gradual changes in land use.* The system, in principle, can be designed to make the upgrading of the model by itself, i.e. *it can have self-learning properties.* One of the possible techniques to acquire these properties is the application of adaptive fuzzy logic (IEEE, 1992).

Improving models, either through (internal) adaptation or by explicit (external) upgrading, is expected to improve interpretation of new remote sensing data. In a monitoring system with an accumulator, there is a second consequence for model improvement. Previously made interpretations can be adapted, which in turn will be used to improve interpretations of later data, and so on. Adapting all interpretations will cause adaptation of, for example, land cover statistics, which in turn can be used to adapt the models again. In fact, the system has entered a state of *re-organization through iteration.* The dynamics of the processes of re-organization and (internal) adaptation have to be studied in much more detail to assess system stability and self-learning capabilities.

The system can be upgraded externally by the peripherals (introduced in Section 3.2.3), the results of field survey and model developments. Results of the different types of validation can be evaluated by a human interpreter before upgraded models and rules are fed into the appropriate components of the system. The same applies to developments in the local GIS and the local 'knowledge'. This results in upgrading of the system's geographical database and set of formal rules, respectively. After feeding the system with updated models and rules it can be triggered to re-organization, in the way discussed above.

The initial state of the system is of great importance to its performance, especially in the beginning, when the number of remote sensing observations is still low. The land cover change model, for example, cannot support interpretation when preceding cover types are unknown, or not known accurately. Segmentation algorithms will perform poorly when a priori data on boundaries, or accurate previous results of segmentation, are absent. Because of the relatively low spatial resolution of the ERS-1, *the complementarity of other sensors may be exploited and a one-off extensive field survey is very useful.* SPOT and Landsat-6, if available, may be used for their high spatial resolution in the panchromatic bands and the good possibilities they offer for classification; JERS-1 is good for discrimination between forest and non-forest types. Once the system's accumulator contains an accurate land cover classification, exploiting the high reliability of ERS-1 data may supply sufficient data to enable land cover changes to be traced as well.

Interpreted images can be processed to produce land cover maps. As discussed, several remote sensing and GIS data sources can be used in the land cover classification procedures. The number of data sources and the accuracy and precision of the data sources may not be equal for all parts of the area. Furthermore, the classification of some land cover types and some terrain units are known to have a lower accuracy than others. A land cover map should therefore be accompanied by a map showing the spatial distribution of the data sources and the overall accuracy.

3.6. Development strategy

As a first step a pre-operational system with limited functionality can be built using simple models for the system's functional components. In the following chapters, such models will be described for the Guaviare area, for the relation between land cover and backscatter, and for land cover change. This first version of the monitoring system may in fact be capable of performing the differentiation between forest- and non-forest cover. In a later stage, forest as well as non-forest might be specified in a number of different subclasses, e.g. forest types, crops, pastures, etc. The prototype system can supply users with relevant information and useful feedback for further system development may be obtained: a *developing while working* approach. As the system has been developed to be used by institutions involved in land use planning, the influence of the user on the development of the system is crucial. The system should supply the user with spatial information on land cover and the location, extent, direction and speed of the changes in this land cover in a 'language' and a format that is adapted to the further process of planning.

The system should not be a black box. The assumptions used in the vegetation growth and land cover changemodels should be made clear to the user, who should also have the option of entering his or her own knowledge to adapt or refine the assumptions. This can be realized by adapting the model parameters interactively, and/or by using one's own models. This is possible because *the system design is generic, i.e. the structure is general and should be applicable in places other than Guaviare.* For each application of the system, a number of models, assumptions and parameters should be adapted to the specific situation.

3.7. Conclusions

A monitoring system, with a GIS, is a tool to be used in land use planning, together with other tools. Land use planning is usually, and should be, done by an interdisciplinary team. Before a monitoring system is built, the need for spatial planning should be evident, for example, because the present development of land use is causing social and/or environmental problems. It should also be evident that the spatial planning need generates a demand for information on the land cover, that can, at least partially, be satisfied by a land cover monitoring system. The monitoring system provides the opportunity of acquiring actual information about land cover. Conclusions can then be drawn about whether the land cover is as expected or as desired, and the impact of measures in a changing human and physical environment can be followed in the land cover development.

4. GENERAL APPROACH TO THE DEVELOPMENT OF DECISION RULES

4.1. Introduction

In Chapter 3 the use of formal rules for the classification of time series of remote sensing images was shown to be an important building block of the monitoring system. This leads on to a description here in Chapter 4 of the general approach to the development of decision rules based on image characteristics and our knowledge of the process of land cover change. An overview of the approach is given, followed by a description of the different steps in the process. In Chapter 5 the approach is applied to the Guaviare data set.

Figure 4.1 illustrates the general approach to data collection and analysis, and the development of the decision rules. Two data sources are shown in the upper part of the figure: field surveys and remote sensing. Land cover data are collected during field surveys and the structure of any vegetation comprising part of the land cover is described. Analysis of these data provides insight into the *spatial* variability of the land cover in the area, with emphasis on the variation in vegetation structure. It reveals the internal structure of the land cover data.

Analysis of the land cover data also provides information on the *temporal* variation in land cover and especially in vegetation structure, which is mainly caused by changing land use. The temporal variation of vegetation structure is formalized in a land cover change model, which is then used to generate the decision rules based on land cover change. Any unlikely changes can be excluded or re-evaluated using these rules and knowledge of land cover at earlier dates.

Analysis of the remote sensing data shows the variation in image characteristics both within an image and between corresponding parts of different images. Image characteristics can be backscatter level (or its averages in space or in time), texture, patterns and temporal variation in backscatter. Furthermore, the images can be divided into objects by image segmentation.

Rules for the classification of remote sensing images, based on image characteristics, are developed by integrating the results of the analyses of the land cover data with those of the remote sensing data. This is an empirical way of describing the relation between land cover and image characteristics. The empirical relation can be checked by a theoretical model (and vice-versa), for example, one of the existing models for backscatter simulation. Simulation of backscatter departing from the land cover parameters measured in the field is also part of the integration of results from the land cover data and the backscatter data.

Both sets of decision rules, based on image characteristics and on the land cover change model, are used to classify the segmented images, resulting in a time series of classified images showing the spatial distribution of land cover and its changes in time.

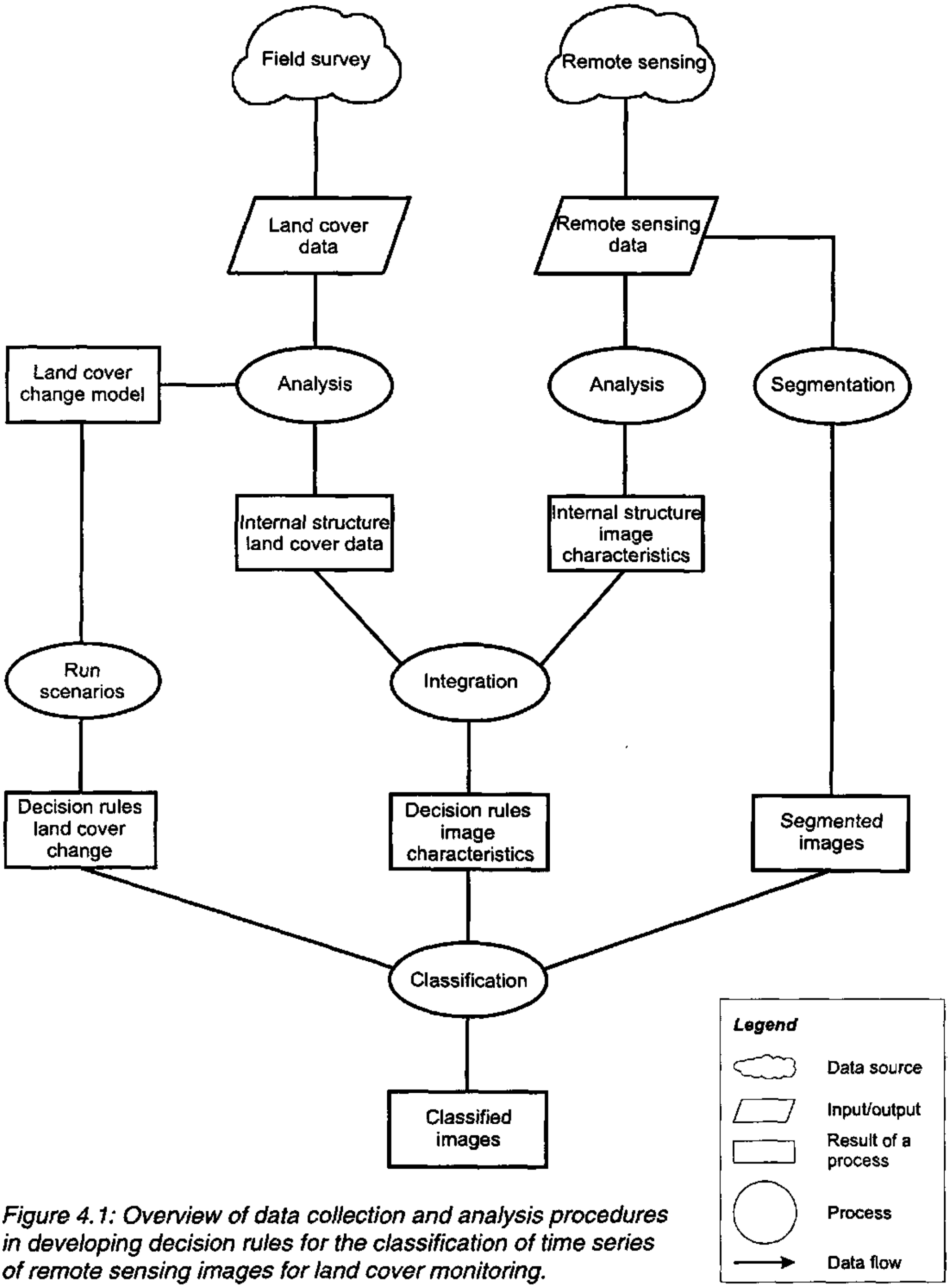


Figure 4.1: Overview of data collection and analysis procedures in developing decision rules for the classification of time series of remote sensing images for land cover monitoring.

4.2. Field surveys

4.2.1. Objective of field surveys

Land cover data are collected during field surveys. The term "land cover" refers to "the vegetational and artificial constructions covering the land surface" (Burley, 1961). Land cover data derived from field surveys are needed for image interpretation in order to relate image characteristics to land cover characteristics. Field data should therefore include those characteristics of the land cover that influence radar backscatter and hence the image characteristics. These land cover characteristics include vegetation and soil parameters.

However, in this study, it is not only the relation between land cover and image characteristics that has to be understood. The other important function of field data collection is to characterize land cover in a way that is meaningful for land use and spatial planning, and also comparable with land cover studies in other regions. Thus, the collection of land cover data in the field has to be based on both user requirements and image characteristics:

User <—> Land cover <—> Image

In this thesis, classes defined by the user of the monitoring system are called "user classes" and are recorded for each sample, together with other field data. If the objective is to make a land cover map, the land cover classes must be meaningful to the users of the map. The users' objectives result in criteria like vegetated versus non-vegetated areas, natural vegetation versus crops, crop type, species, etc. The sensor might be sensitive to other characteristics, like roughness or soil humidity. The roughness of land cover, revealed for example by differences in the number of shrubs in pasture land, might not be very interesting to a user, as long as it is not a sign of soil degradation. However, for the radar signal, variation in shrub cover in pasture land can have a significant influence on the backscatter. (Hoekman et al., 1994a).

In addition to spatial structure, radar is mainly sensitive to the dielectric properties of the objects. These dielectric properties depend largely on the water content of the vegetation and soil. Vegetation can therefore be modelled as a cloud of water droplets in order to predict the radar backscatter (e.g. cloud model as formulated by Attema and Ulaby (1978) and quoted by Hoekman (1990)).

It is very difficult to measure moisture content and its distribution in soils and vegetation. The moisture content and its distribution in the topsoil depend on the weather, internal and external drainage, and soil properties such as texture, mineralogy and the amount, size and distribution of the soil pores. The moisture content and its distribution in the vegetation can be approximated by measuring or estimating the amount and distribution of living biomass. In practice this means estimating the amount and distribution of green vegetation. It is assumed that there are no water droplets on the surface of the leaves (e.g. as directly after a rainstorm) and that the influence of the amount of moisture in dead vegetation is negligible. The latter factor has been confirmed for C-band (but not for large branches and trunks in P-band) by Hoekman et al. (1996).

4.2.2. Methods for describing vegetation structure

The amount and distribution of vegetation, regardless of its floristic composition, is commonly called the vegetation structure and it is usually described by the spatial distribution of structural elements. For this study, we needed a system to describe the structure of all the vegetation present in an area, forest as well as non-forest.

Well-known systems for describing vegetation structure are those by Küchler (1967), UNESCO (1973) and the ITC system of rural land use and land cover classification (LUCC) as described by Van Gils et al. (1991). The UNESCO classification is not suitable for regional or local scales (1:200 000 and larger). The ITC LUCC classification does not provide enough tools for describing structure at the level of detail required for this study. Elements of Küchler's Life Form System were adapted for use in this thesis.

Other systems for describing vegetation structure are dedicated to a particular geographical area or vegetation type, for example Van Wijngaarden's (1985) system for savannah, which stratifies the savannah vegetation into grasses, shrubs and trees. Classification is based on the cover percentages of these strata. Van Wijngaarden's system is not suitable for use in tropical rain forest without adaptation.

A large number of dedicated systems have also been developed for describing the structure of temperate and tropical forests. A good overview of these systems is provided by Tomlinson (1983) and Bourgeron (1983). Forest structure is usually described by the spatial distribution of structural elements, such as life forms, growth forms or synusiae. These terms are not used consistently in the literature. Barkman (1979) defined life form as "the morphological expression of the adaptation of organisms to their environment". He also considered that "growth forms are based on those morphological characters that control the general architecture of the organisms". According to these definitions, Küchler's Life Form System is actually based on growth forms rather than life forms. Synusiae are aggregations of taxa with a common life form (Tomlinson, 1983).

The definition of structural elements can also be based on more or less detailed descriptions of the architecture of individual trees, for example the 23 architectural tree models of Hallé and Oldeman (1970). Such a concept is too specific to be used in other vegetation types and it is therefore unsuitable for this study.

For the spatial aspects of the structure of the forest, i.e. the spatial distribution of the structural elements, the concept of stratification is widely used. Although the concept is widely used, the existence of strata in a forest is much debated. Bourgeron (1983) concluded: "As a result of the complexity of the phenomenon and the lack of comparability of definition and methods, there is no definitive answer to the question of the existence of stratification of the tropical rain forest". In the same article Bourgeron even writes: "Moreover, it very often appears that the recognition of stratification is a conceptual choice, an 'act of faith', made prior to working in the forest (...)".

4.2.3. Description of vegetation structure for monitoring land cover with ERS-1

None of the existing systems for describing vegetation structure completely meets the objectives of this study. The systems for describing tropical rain forest cannot be used in secondary vegetation and pastures since they are based mainly or solely on the architecture and the spatial distribution of trees. Other, more general systems, do not provide enough tools for describing the forest's structure. A new method was therefore developed for describing vegetation for mapping and monitoring with spaceborne radar remote sensing. This method incorporates parts of existing methods described in Section 4.2.2 and provides links to the land cover classes defined by the users as well as to image characteristics.

For all vegetation types, structure is described as the spatial distribution of structural elements. In this study, these structural elements are formed by the structural plant groups, defined as aggregations of taxa based on their growth form. The structural plant groups used for describing the vegetation structure in Guaviare are listed in Table 4.1. Most of them are similar to Küchler's "life forms". The plant group "Stem *Musaceae*" is new and introduced as a separate category for the large *Musaceae*, which are quite numerous in the rain forest; they have an architecture that is very different to the other forbs and also to the shrubs and trees, which might influence their image characteristics. The term "structural plant group" was chosen to avoid confusion with existing classifications based on growth forms, life forms or synusiae.

The structural plant groups can be used in other areas with similar land cover. If the land cover is very different and Küchler does not provide additional "life forms" (structural plant groups) for this situation, other plant groups can be added to suit the situation, without changing the overall concept of the method. For certain forests in Indonesia, for example, a separate structural plant group can be introduced for the giant aroids or "talas" (*Colocasia spp.*).

The concept of stratification is used for describing the spatial distribution of these structural plant groups. Vegetation is described by dividing it into horizontal layers (strata). A vegetation stratum is a horizontal slice of the vegetation, with a lower and an upper boundary. In this study, the stratification is based on differences in leaf mass and the presence of structural plant groups. In order to keep to as close as possible to reality, the number of strata and their dimensions were chosen according to the dimensions seen in the field. There were no pre-set stratum dimensions, in contrast to Küchler's system, in which vegetation is divided into strata according to pre-set height boundaries.

Per stratum the total cover percentage is estimated as the percentage of the horizontal plane that is covered by the vegetation of that stratum. The dominant structural plant group and a number of additional parameters like leaf size are also recorded per stratum. If any species are recognized by the field surveyors, these are recorded as well. The dominant structural plant group is the one that makes up the largest part of the stratum's cover. Table 4.2 shows the general scheme for field data collection.

Table 4.1: Structural plant groups for describing vegetation structure. The term "graminoids" comprises the grasses (Poaceae) and the grass-like families such as Cyperaceae. Zingiberaceae and Costaceae are included in the structural plant group "forbs".

Plant group	Description
Trees	Woody plants taller than 5 m
Palms	Palm trees with stems
Stemless palms	Palms (almost) without stems
Stem *Musaceae*	Large members of the *Musaceae* family, having a stem, mainly *Phenacospermum guianensis* (tarriago)
Shrubs	Woody species less than 5 m high
Forbs	Herbaceous plants excluding graminoids
Tall grasses	Graminoids taller than 50 cm
Short grasses	Graminoids 50 cm and shorter
Vines	Lianas and other climbing plants

Table 4.2: General parameters to be recorded during field survey

General parameters:
- reference number
- location; GPS-measured coordinates and/or place on the image
- physiographic unit and position in the landscape
- drainage
- user class
- phenological development stage (for grass and crops)

For user classes with vegetation:
- horizontal vegetation strata to be discerned

Each horizontal vegetation stratum is characterized by:
- dimensions (upper and lower height limits of the stratum)
- cover percentage of the vegetation in the stratum
- dominant plant group
- species, if known
- dominant leaf size
- presence/relative abundance of palms
- presence/relative abundance of epiphytes
- presence/relative abundance of lianas, pseudolianas and other climbers
- presence/relative abundance of dead trees (still standing and fallen) and stumps.

The dominant leaf size (in terms of cover percentage) was recorded per stratum. Leaf sizes were estimated in the Raunkiaer-Webb categories described by Givnish (1984) with some minor adaptations. Table 4.3 shows the categories with the maximum surface as defined by Raunkiaer and Webb and the maximum surface used in this study. Givnish follows Webb in assuming that leaves are about twice as long as they are wide and that they have an area of roughly two-thirds of leaf length times width. In this study it was assumed that leaves have an elliptical shape. The leaf size categories used here have also been described in Hoekman et al. (1996).

Table 4.3: Original Raunkiaer-Webb (R-W) categories of leaf size (from Givnish, 1984) and the adaptations used in this study.

Raunkiaer-Webb category	Maximum surface defined by R-W (cm^2)	Maximum surface in this study (cm^2)	Maximum leaf length (cm)	Maximum leaf width (cm)
Nanophyll	2.25	2.26	2.4	1.2
Microphyll	20.25	20.36	7.2	3.6
Notophyll	45.00	45.80	10.8	5.4
Mesophyll	182.25	183.22	21.6	10.8
Macrophyll	1640.25	1684.68	65.0	33.0
Megaphyll	> 1640.25	>1684.68	>65.0	>33.0

Based on the physical theory of the propagation of waves, leaf size in relation to wave length is expected to influence backscatter. A relation between vegetation type and leaf type is known from the literature (e.g. Givnish, 1984). Fast-growing pioneer species usually have big leaves with little structural material (and a high moisture content) per square meter of leaf surface, while slow-growing species of the upper canopy of mature forest have smaller leaves with more structural material and a lower moisture content. Slow-growing species tend to invest more in their leaf structure. We tried to gain an indication of leaf moisture content in three classes (scleromorph, meso-scleromorph and non-scleromorph), but the correlation between these classes and the leaf moisture content as measured by weighing and drying was not sufficient to justify further use of the method.

Figure 4.2 shows an example of the description of vegetation structure based on vegetation strata and structural plant groups. The description of pastures and natural grasslands is fairly simple. Note that the strata do not overlap in the horizontal plane. The strata are separated by differences in dominant structural plant group. Where trees or (stemless) palms are present, there might be some overlap between the trees or palms and the grasses, in which case the sum of the vegetation cover of all strata will be over 100%. In higher vegetation types like forest, strata do overlap in the horizonal plane, resulting in a sum of the vegetation cover of far more than 100%, because the tall trees allow shorter trees and other vegetation to grow under them. Tree strata are distinguished by changes in density of the leaves.

A vegetation stratum with "trees" as the dominant structural plant group may contain a reasonable number of palms, in which case this should be recorded. The same is true for a stratum dominated by "shrubs" that also contains stemless palms. As the structure of palms is very different to that of trees or shrubs, a relatively large number of palms in a stratum influences the backscatter.

Epiphytes can contain a large amount of water. If a forest contains many epiphytes in the upper canopy of the trees, this influences the moisture content and its distribution in the canopy, and hence the backscatter. Moreover, the relative abundance of epiphytes can be an indicator of differences in forest type. Montane forest, in particular, might contain many epiphytes. Abundant lianas and other climbers affect the distribution of biomass in the forest and can also be characteristic of certain forest types.

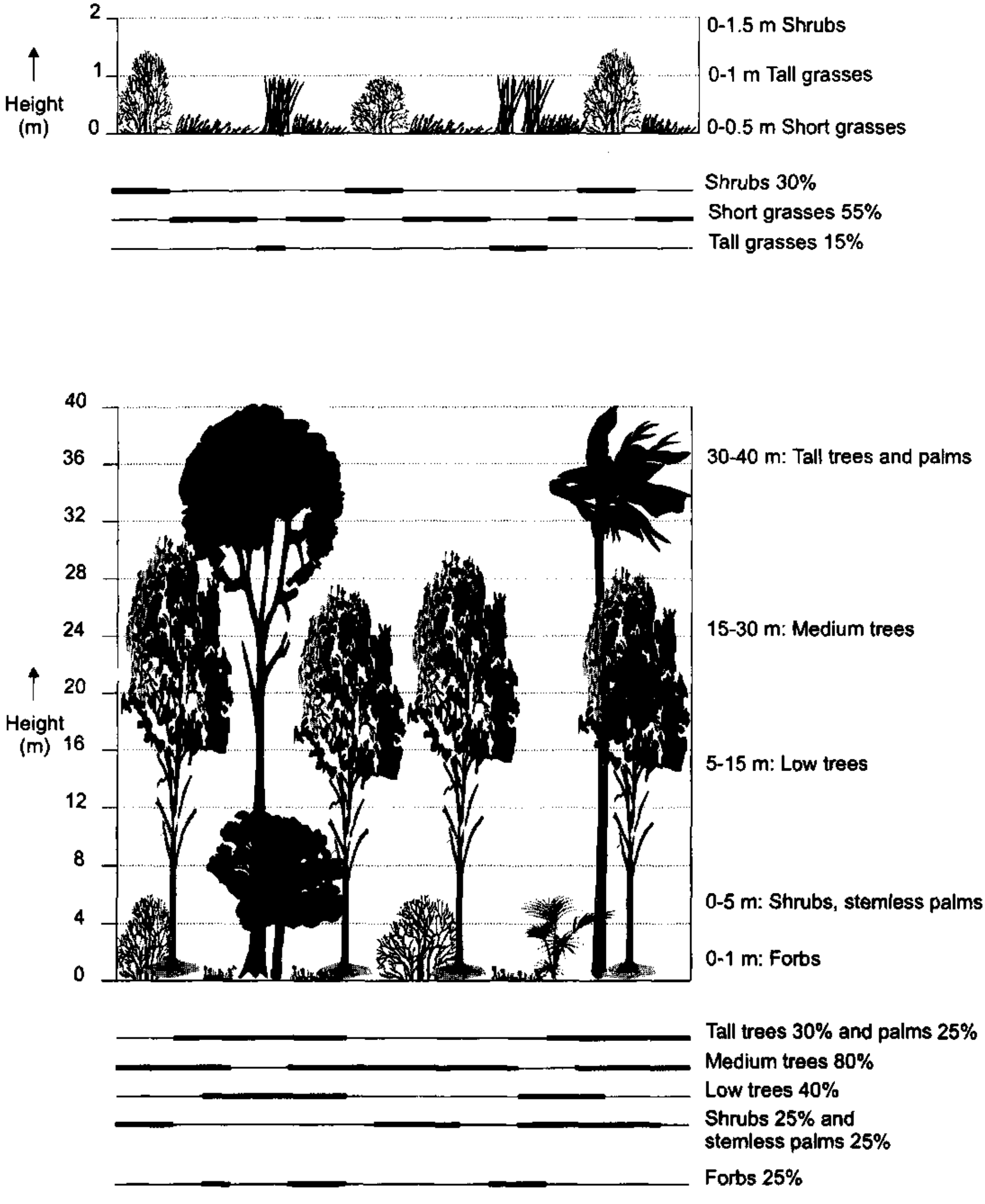


Figure 4.2: Examples of the description of vegetation structure using vegetation strata and structural plant groups for grasslands (sum of cover of strata <= 100%) and forest (sum of cover of strata >100%).

In addition to the strata characterized by plant groups, there are also strata characterized by litter (dead leaves and twigs), dead trees (still standing, including stumps), dead wood (fallen trunks and branches) and bare soil. An abundance of dead trees and stumps indicates the human influence (cutting) in the forest and the history of non-forested parts, since stumps and burned trees in pastures indicate that the field was originally part of a forest. The amount of dead wood in pastures decreases with the age of the pastures because of repeated burning and decay.

4.2.4. Additional measurements for backscatter simulation

The backscatter simulation used a theoretical model in part of the analysis of the relation between vegetation structure and image characteristics. The simulation required data from biomass and soil moisture measurements. Biomass was measured by cutting and weighing samples from a number of plots on pastures and natural grasslands. We used the method of selective sampling, using ranked sets as described by McIntyre (1952). Tree points were randomly selected in a plot and at each of these points three adjacent squares, each of one square meter, were marked. For each set of three squares, we estimated which of the three squares in the set had the highest, the intermediate and the lowest biomass. In the first set of three squares, all grass and herbs were cut and weighed from the square with the lowest biomass. From the second set, the vegetation in the square with intermediate biomass was cut and weighed. From the third set, the vegetation in the square with the highest biomass was cut and weighed. This method of measuring gives a better indication of the variation in biomass per square meter than simply weighing the vegetation of three randomly chosen squares. Basal areas and tree heights were measured by Quiñones (1995) to estimate the biomass in a number of forest plots with a plot size of 1000m^2.

Volumetric soil moisture content of the upper ten centimetres of the soil was measured in several plots for at least eight locations within the plot. Plot size was in the order of 0.5 ha. When possible, measurements were carried out twice, in the morning and in the afternoon, to see whether the soil moisture content changed during the day and in order to get a better impression of the range of soil moisture content for backscatter simulation.

4.3. Spatial variability of the land cover data

Analysis of land cover data almost automatically leads to classification: samples with similar land cover are grouped together. There are many ways of making this classification, which is always based on certain criteria, although these are not always explicit or used consistently. According to the criteria chosen, samples will be grouped into classes with a minimum of intra-class variation and a maximum of inter-class variation. A multitude of criteria can be used to group samples into classes, but not all will be equally significant. For example, if vegetation has to be classified, the classification can be based on the different shades of green. Usually, the criterium "shade of green" will not result in significant classes, as one rarely wants to know whether the vegetation at a certain spot is light green or dark green. It is only interesting if the shade of green is related to more interesting parameters like species or health (e.g. nutrient deficiencies). So classes should be chosen based on the research objective.

In the previous Section (4.2) it was explained that the land cover parameters to be collected depend both on the user and on the sensor characteristics. The same is true for the choice of which of these parameters will be used as criteria for dividing the land cover data into classes. The different land cover classes perceived by the user in the field may not have different image characteristics, and aspects with different image characteristics do not necessarily belong to different user classes.

The land cover data can easily be grouped into classes according to the user class, which can be related to certain image characteristics, resulting in a list of image characteristics per user class. This procedure is common to most studies distinguishing land cover classes by remote sensing techniques. The disadvantage is that it obscures the direct relation between land cover structure and image characteristics by imposing classes that are based not only on the structure of the vegetation, but also on floristic composition, land use and history. It may force samples with very different vegetation structures into the same user class, because of similar land use or history, while samples with similar vegetation structures are grouped into different user classes because of differences in floristic composition.

To illustrate the above, let us consider a field with two meter high cassava plants and a field with two meter high shrubs, e.g. a plot left to regenerate after cultivation. Both samples are very similar with respect to vegetation structure: a two meter high dense shrub cover with no emerging trees and with little or no herbs or grasses as undergrowth. Yet because of the differences in floristics and use between cassava, a food crop, and the other shrubs, regarded as weeds or natural vegetation, the first sample is grouped in the user class "crops" and the second sample is grouped in the user class "secondary vegetation". Of two samples in the user class "secondary vegetation", one sample could have shrubs and herbs but no trees, while the other could have many low trees or even some high trees, presenting a considerable difference in structure.

It might therefore be worthwhile to reconsider the simple and straightforward approach of grouping samples into user classes and to consider methods that do not require grouping the data into classes before the analysis. Such methods have been developed in vegetation sciences and a good overview of the methods most commonly used nowadays was provided by Jongman et al. (1995). Usually, vegetation data analysis starts by exploring the data with descriptive statistical analysis. This approach studies the variation in a data set, looking for patterns and trends. Multivariate statistical methods are used for classification and ordination. In this study, these methods are used to group samples into clusters based on their vegetation structure characteristics, so that the variation in vegetation structure within clusters is small compared to the variation in vegetation structure between clusters. Classes based on differences in vegetation structure are expected to show a clearer relation to image characteristics than classes based on floristic composition, land use or history. The procedure is shown in Figure 4.3.

The first step in the analysis of the vegetation data is to standardize the vegetation strata. When looking at the data set the dimensions of strata characterized by grasses, shrubs, trees, etc. all vary closely around certain height values. This fact is used to define a number of standardized dimensions for strata, typical for the vegetation types present in the area. The vegetation descriptions of the samples are now re-ordered in such a way that they fit the standardized vegetation strata. Table 4.4 gives an example of the standardized dimensions of the vegetation strata for the Guaviare area.

In general, the cover percentage of stemless palms is small compared to the cover percentage of shrubs in the same height range. Therefore, stemless palms are included in the shrub-stratum. Similarly, palms are included in the corresponding tree-stratum, as are stem *Musaceae*. The presence or absence of palms, stemless palms or stem *Musaceae* becomes a separate parameter. The cover of lianas and other climbers is also included in the stratum of corresponding height, with an indication of their presence or absence.

When graminoids are flowering, the plants are much higher than those without flowers. Although flowers add significantly to the height of the plant, they add little to the cover, which is mainly composed of leaves. The flowers are therefore excluded from the short grasses and from the tall grasses and put into a new, separate stratum: flowers of grass.

Short grasses, tall grasses, forbs, shrubs and stemless palms supply their cover from the soil upwards. Therefore the lower limit of the strata formed by members of these plant groups is set at zero. Stem *Musaceae* and the groups with trees and palms have crowns accounting for the major part of the cover. The lower limit for the strata formed by these plant groups is therefore set at the lower limit of the crowns.

It certainly saves time if it is possible to set standardized dimensions for strata before going into the field. These standards can be based on previous field surveys in the same or a similar area, or on one of the systems for structural description providing standard dimensions for strata (e.g. Küchler, 1967). However, care should be taken that rigid standard dimensions imported from elsewhere do in fact coincide with the dimensions of the structural components (plant groups) of the vegetation in the study area to avoid artifacts.

The vegetation structure data, with cover percentages of strata with standardized dimensions, can now be clustered as described above, grouping samples with a similar structure together and separating samples with a different structure. The resulting groups are vegetation structure clusters (see Figure 4.3).

The clustering is carried out using the program TWINSPAN (Two-way indicator species analysis) (Hill, 1979). According to Kent and Coker (1992) TWINSPAN is the most popular method for community classification (cluster analysis) in Britain and North America. It is commonly used for the analysis of the presence and abundance of species. Verweij (1995) also used it for her analysis of the structure of paramo vegetation, based on the cover percentage of plant groups or vegetation strata. However, the application of TWINSPAN to the analysis of mixed vegetation (forests, grasslands and shrublands), using the cover percentages of the standardized vegetation strata, as shown in this thesis, is new.

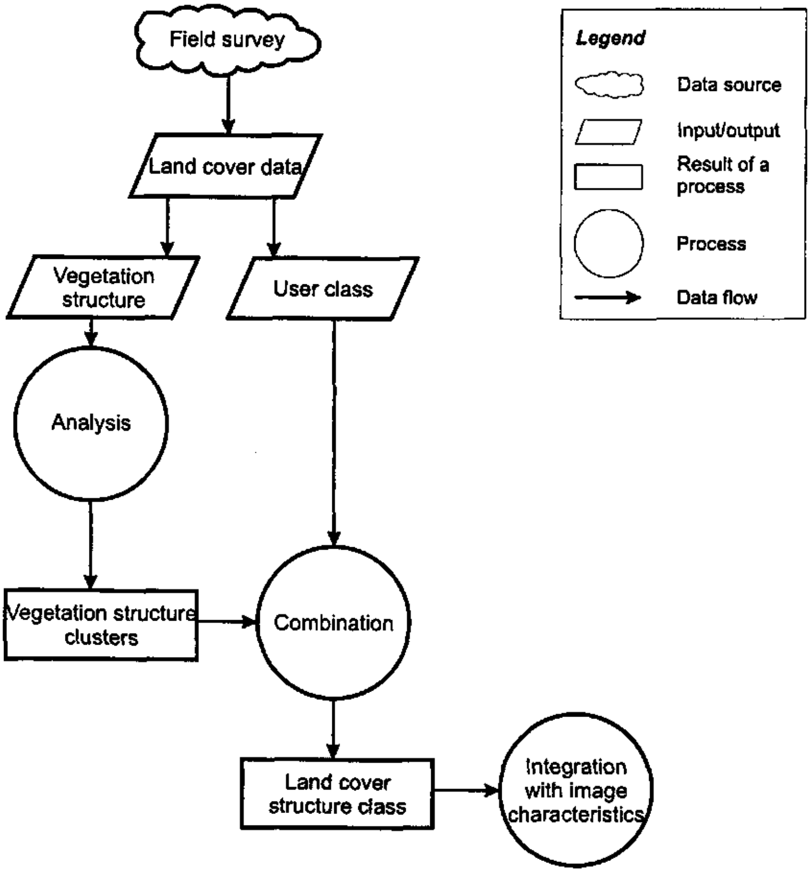


Figure 4.3: Analysis of the spatial variability of land cover data.

The user requires information expressed in user classes and not in vegetation structure clusters. The vegetation structure clusters were therefore compared with the user classes. Each combination of a vegetation structure cluster with a user class results in a so-called land cover structure class. User classes without vegetation (built-up area, open water, rock outcrops) cannot of course be subdivided by vegetation structure and were transferred to the land cover structure classes. The land cover structure classes form the link between the user classes on the one hand and the vegetation structure clusters and image characteristics on the other.

If there was no relation between vegetation structure clusters and user class, the number of land cover structure classes would be very large. However, in general, this is not the case and the structure of the vegetation is one of the criteria the users employ to define their land cover classes. This relation between vegetation structure and user class limits the number of combinations between vegetation structure clusters and user classes and hence the total number of land cover structure classes.

Table 4.4: Standardized strata with the structural plant groups they comprise and their lower and upper limits

Structural plant group forming the stratum	Lower- and upper limit of stratum (m)
Short grasses	0—0.5
Tall grasses	0—2
Flowers of grass	0—3
Forbs	0—2
Shrubs and stemless palms	0—5
Low trees and palms and stem *Musaceae*	5—15
Medium-high trees and palms	15—30
Tall trees and palms	>30

4.4. Temporal variation in land cover data

Analysis of the changes in land cover and in particular, vegetation structure with time, shows relations between land cover structure classes over time and the possibility of transitions from one land cover structure class to another. This relation can be formalized in a land cover change model, which can calculate the possible changes (in vegetation structure) for every land cover structure class over a certain period. The calculations on the possibility of changes between land cover structure classes result in a set of decision rules; these rules are used to exclude unlikely changes in land cover structure classes during classification of the images.

The changes caused by human intervention are usually abrupt: the slash and burn of primary forest or secondary vegetation and the planting of crops, cleaning of pastures by burning or cutting the shrubs are examples. Several factors can induce such an intervention. The chance that a primary forest will be cut decreases with its distance from settlements and infrastructure. At farm level, it depends on the relative areas of primary forest, secondary vegetation, pastures and crops and the objectives of the farmer. The wider political, economic, social and juridical setting also influences the fate of the forest. From a cultural point of view, a farmer might want to open up land, not only because it is needed for crops or pastures but also because this is seen as land improvement and will increase the value of the farm.

Whether a secondary forest will be cut and burned depends on the age of the secondary forest and the need for extra land for cropping or pastures. Whether a pasture will be cleaned depends on the number of shrubs and the maximum amount of shrub invasion tolerated by the farmer.

This wider setting can be very difficult to model. The easiest way to account for the influence of the wider setting is to leave the resulting influence of all these factors to the evaluation of the user. The user can introduce the net effect into the model via switches, which can be used to trigger deforestation at a certain location, or to trigger shrub cleaning in pastures if the shrub limit, as set by the user, is reached.

Natural processes of regeneration after cultivation and shrub invasion of pastures are gradual and depend on the rate of growth of the plants. The speed of shrub invasion and the growth rate of trees and other plants during regeneration is derived from analysis of the field data and from the literature. According to the growth rates, the amount of time needed for the change from one land cover structure class to another can then be calculated. One example of such a land cover change model is the BOSTOS model for Guaviare described in Chapter 6.

4.5. Remote sensing data source

The monitoring system as it is designed now, is based on radar images of the ERS-1 and ERS-2 satellites. One could also use optical images from Landsat or SPOT, which would provide more possibilities for the discrimination of various cover classes. But they lack one important aspect that is crucial for monitoring: optical/NIR satellite images are only infrequently and erratically available for most areas of tropical rain forest due to the high percentage of cloudy days, as shown by Table 4.5.

Table 4.5 shows the availability of Landsat-MSS images for four different frames of the San José del Guaviare area, from the launch of Landsat-1 in July 1972 to March 1991. Few images have been collected and of those, most have a very high cloud cover. If images with 0—20% cloud cover are considered as acceptable for mapping and monitoring purposes, one frame has only one useful image in nineteen years, one frame has two useful images and the other two frames have three useful images, which is not enough for a land cover monitoring system in an area where the land cover changes rapidly. Moreover, in images with nearly 20% cloud cover, at least 25% of the area cannot be mapped or monitored because of clouds and shadows of clouds. Radar images from the ERS-1 satellite have no cloud problems and are, at least in theory, available every 35 days.

Table 4.5: Number of available Landsat MSS images of the San José del Guaviare settlement area and their percentage of cloud cover, from July 1972 to March 1991.

Frame	Cloud cover classes (increments of 10%)										Total
	0—10	10—20	20—30	30—40	40—50	50—60	60—70	70—80	80—90	90—100	
6-58	0	2	0	1	6	1	2	1	4	15	32
7-58	0	3	0	4	0	5	5	0	2	16	35
6-59	1	2	0	2	3	1	1	3	5	24	42
7-59	0	1	4	1	4	2	0	2	6	17	37

4.6. Analysis of image characteristics

The available images were co-registered to each other. The sampled fields were delineated by polygons and within the polygons the image characteristics per sample per image were extracted (Figure 4.4). Image characteristics in this study include average and standard deviation of the backscatter per sample (polygon) per image, average backscatter of a sample over subsequent images and variation in backscatter over subsequent images. This variation was calculated as the difference between the highest average σ^0 and the lowest average σ^0 of the same area in three subsequent images. It should be noted that this variation of average backscatter with time is also time-dependent. If the three subsequent images include seasonal differences, the variation will generally be larger than when all the images are taken in the same season.

There is a large variation in field size in the area, from small clearings in the forest of a few tenths of a hectare (10—20 pixels in an ERS-1 image) to very large pastures covering several hectares. The classification of the small fields is less reliable than the classification of large fields because the average backscatter per sample (field or object) and its variation over time can be assessed less accurately with fewer pixels. Smaller plots also have a higher relative number of "border pixels", whose backscatter value is a mixture of the backscatter of both neighbouring objects. Texture measurements cannot be calculated for these small plots and are therefore not used in this study. In other areas with larger fields (objects), texture measurements might be a useful image characteristic for classification.

Analysis of the image characteristics of these samples shows the variation of each characteristic in the sample set and hence its potential for classification. An image characteristic that is more or less constant for all samples in an area cannot be used for distinguishing between land cover classes in that area. An image characteristic with high variation should give a better classification, as long as this variation is related to a parameter relevant to the classification of land cover.

The vegetation structure data from the land cover data set have been analyzed by clustering. Looking for the internal structure of these data, it would seem logical to use some kind of clustering for the analysis of the internal structure of the remote sensing data as well. However, the same method does not give satisfying results for the analysis of backscatter level data. The clusters based on backscatter level of the samples on the nine images show only a very vague relation with the user class, because other parameters, like soil moisture content, can have a large influence on the backscatter. These parameters are not known when the images are recorded and therefore the samples are not grouped into clusters based on their image characteristics, but are related directly to the land cover structure classes.

4.7. Relation between land cover and image characteristics

The integration of the analysis of the land cover data and the analysis of the image characteristics is shown in Figure 4.4. The data set with image characteristics per sample per image is subdivided according to the land cover structure classes described in Section 4.3. Analysis shows the extent of different image characteristics in different land cover structure classes, leading to which land cover structure classes can be separated during classification of the remote sensing images and which image characteristics can best be used.

The criteria for classification of land cover structure classes are described in terms of image characteristics and organized in a decision tree. This tree represents the set of decision rules for the classification of time series of images based on image characteristics.

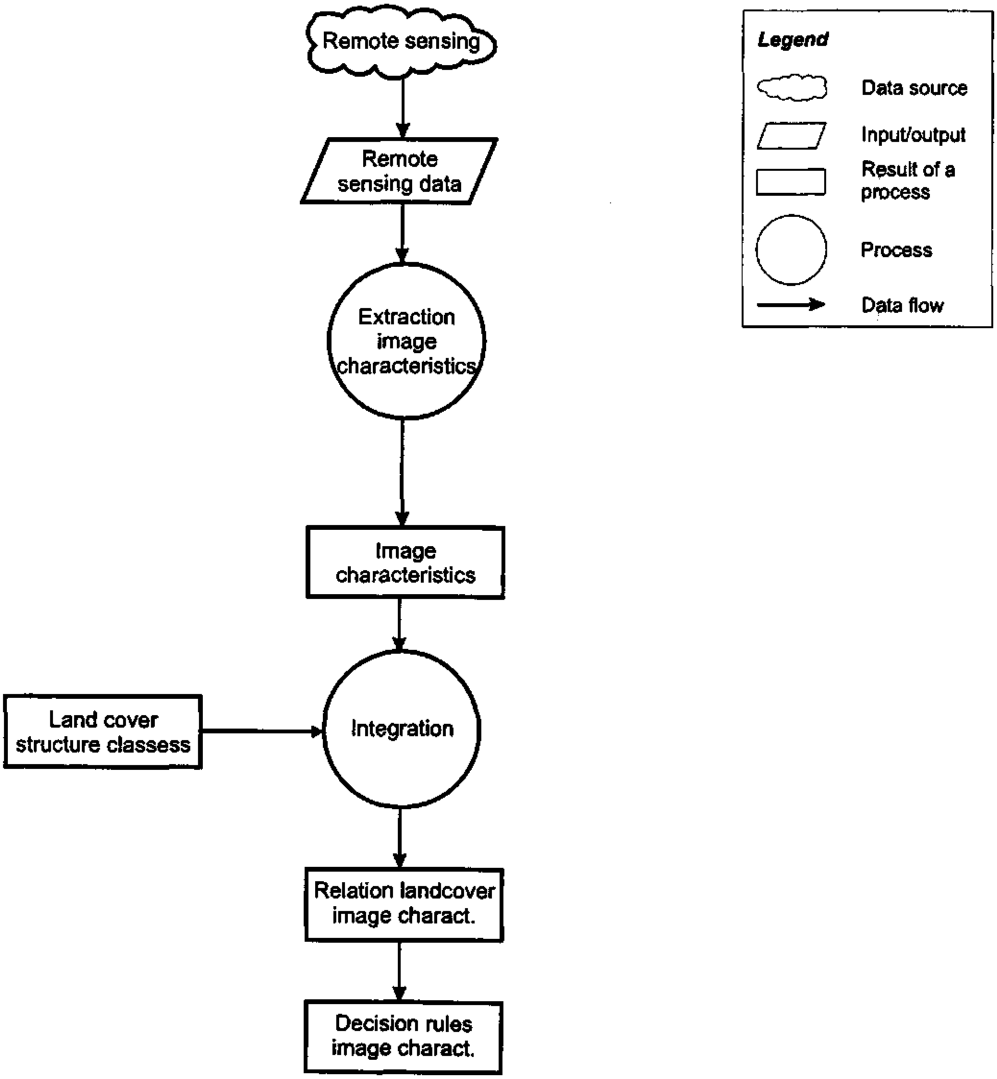


Figure 4.4: Analysis of remote sensing data and relation with land cover structure.

An understanding of the relation between radar backscatter and the individual vegetation structure parameters is necessary to explain why only some land cover structure classes can be separated, based on their image characteristics. Describing this relation in a model also helps to understand the intra-class variation in image characteristics in the land cover structure classes.

One way to arrive at such a model is to use a multiple regression technique like canonical analysis to describe the relation between the vegetation structure parameters and the radar backscatter. This results in an empirical model. With the present data set, canonical analysis does not give useful results. There are several reasons for this. Many vegetation structure parameters can influence radar backscatter and the values of these parameters often vary widely. In most cases, the vegetation structure is not described at the moment of recording the image and this difference introduces an error in the statistical description of the relation between vegetation structure and backscatter, especially for rapidly changing parameters like cover percentage of grass in pastures. Finally, variation in backscatter may be due to a parameter that was not measured, like soil moisture content. Moisture content of the topsoil changes rapidly with the weather and no data exist on the moisture content of the topsoil in the plots at the moment the images were recorded.

Another way to arrive at a model of the relation between vegetation structure and backscatter is to use physical relations to explain the relation between vegetation characteristics and backscatter. Theoretical models usually need more input parameters, requiring complicated measurements in the field. If measuring is not possible, estimations or parameters from the literature can be used. The advantage of a theoretical model is that it is easier to apply it to a new situation, as long as the physical relations are still valid. An empirical model only holds true for the situations for which it was made. In the study of the land cover in Guaviare, a theoretical model was used to simulate backscatter, based on land cover parameters. The outcome was used to understand why certain land cover structure classes can be separated on the images. The model can also be used to predict the possibility of detecting a land cover type not yet known to be present in the area.

4.8. Image segmentation

For classification based on backscatter level, image segmentation prior to classification improves the results. Due to the random speckle, characteristic of radar images, it usually gives better results to calculate the average backscatter of an object and use this for object-wise classification instead of classifying individual pixels. Segmentation is also important when using texture features for classification. When fields (objects) are large in relation to the image spatial resolution, texture features can be calculated using a spatial window, similar to most filters. However, when objects are relatively small this procedure does not work and segmentation is imperative. When objects are very small, texture measurements cannot be calculated with sufficient accuracy even after segmentation.

Segmentation splits the image up into objects (e.g. plots or fields) whose image characteristics can be calculated and compared to those of the training samples. Segmentation of an image by hand, either by drawing on the screen using a mouse, or by drawing on a hard copy and digitizing the result, is tedious, time consuming and subjective work. It is not easily reproducible; no two persons will segment an image in the same way, which causes problems in monitoring, as new images have to be segmented continuously. Not only the classes of the objects change, but also the limits between two objects (plots) tend to change; they may be divided into two plots, or enlarged by cutting adjacent forest or merged with other plots. Segmentation therefore has to be carried out repeatedly.

Digital image segmentation is a field of science that is still developing. Most existing segmentation algorithms perform poorly on radar images, due to speckle which blurs edges. Segmentation algorithms based on pattern recognition become prohibitively complicated and time consuming if objects (fields) do not have regular shapes. A promising algorithm has been developed by extending the single segmentation algorithm RCSEG into a multi-channel segmentation algorithm (Caves and Quegan, 1995). This algorithm can be used for the segmentation of images before classification.

The RCSEG algorithm is based on an iterative process of edge detection and segment growing. The detected edges are used to limit segment growing, the resulting segmentation is used to generate a more accurate edge map, which leads to improved segmentation, etc. The iteration process is controlled by measuring the average contrast, which is an (area) weighted average of the contrast within segments. The average contrast decreases with ongoing segmentation. Segmentation is halted when the average contrast reaches a minimum.

The simplest way of segmenting multi-temporal imagery is to segment each image separately (or "channel", as it is called by Caves and Quegan, who treat multi-temporal imagery as multi-channel images). However, this leads to registration problems and does not use correspondence between images to improve feature detection. Caves and Quegan therefore redeveloped the RCSEG algorithm to segment a multi-channel image (multi-temporal imagery) as a single entity.

The multi-channel segmentation algorithm aims to produce a single region labelling from the multi-channel input. Each segment should represent a homogeneous region that differs statistically from adjacent segments. These differences may be present in some or all of the channels. Post-processing techniques are used to detect in which images (channels) the differences occur and to generate boundary maps representing these differences. Thus, in one image (channel) the boundary between two segments can be deleted, because in this image there is no difference between the two, while in another image (channel) the boundary is retained. This approach is useful for detecting changes in multi-temporal imagery. To summarize, one can say that the multi-channel segmentation algorithm of Caves and Quegan provides segmentation with good registration of edges without wiping out structural differences between channels or images.

4.9. Role of the analysis in the operational monitoring system

In this chapter, the methods and analysis necessary for the development of the monitoring system have been presented, which means that they have to be carried out only once, during the development of the system. However, some methods and analysis that have been described here are also part of the operational system.

In the operational monitoring system, the remote sensing data source is also present, supplying data for the monitoring system (see Figure 3.1). Field survey is also present in the operational system, although with a slightly different function. In the procedures depicted in Figure 4.1, field data are used as a basis for making decision rules, whereas in the operational system, field surveys are needed to check the output of the monitoring system (present land cover, land cover changes) and to check whether the assumptions on which the decision rules are based are still valid. The function of the rules in the operational monitoring system is shown in Figure 3.2, depicting the image processing module of the monitoring system.

The analysis of the land cover data and of the relation between land cover characteristics and image characteristics are not part of the operational system. The analysis is carried out once, in the initialization phase of the monitoring system and then the results of this analysis are available to the system in the form of decision rules. These analyses have to be repeated only when the system is transferred to another area, when a completely new land cover type is introduced into the area, when a new sensor is used or when new parameters for the backscatter modelling become available.

Land cover change modelling has to be repeated if the process changes, for example because of new land use practices or new regulations. The model can be adapted or even replaced by a new model, depending on the outcome of the field checks.

The segmentation and classification of images using decision rules based on image characteristics and land cover change are part of the operational monitoring system: in Figure 3.1 it is part of "processing", in Figure 3.2 it is part of image processing/object delineation.

4.10. Conclusions

Data on the spatial variability of land cover structure can be analyzed with cluster analysis to derive structure classes. These structure classes can be related to image characteristics, which leads to the formulation of rules that can be used in image classification.

Data on the temporal variability of land cover can be analyzed and used for the modeling of land cover change. The model can be used to formulate rules for the classification of time series of images.

Prior to classification with the rules based on image characteristics and those based on land cover change, an algorithm can be used for segmentation of the remote sensing images, thus

Table 5.9: Available airborne data

Type	Date	Source
B&W aerial photograph, prints	1986	Andrade & Etter (1987)
B&W aerial photograph, prints	1990	IGAC-photo-library
X-band single polarization SLAR, prints	1973	PRORADAM, 1979
C-, X-band polarimetric SAR, digital	29-04-'92	SAREX-campaign (ESA)
C-, L- and P- band polarimetric. SAR, digital	31-05-'93	AIRSAR campaign (NASA)

The SAREX- and AIRSAR images were studied to get a better understanding of the backscatter behaviour and the possibilities of future (polarimetric) spaceborne sensors with longer wavelengths. For a description of these results see Hoekman et al. (1994a,b,c), Quiñones (1995) and Hoekman et al. (1995, 1996).

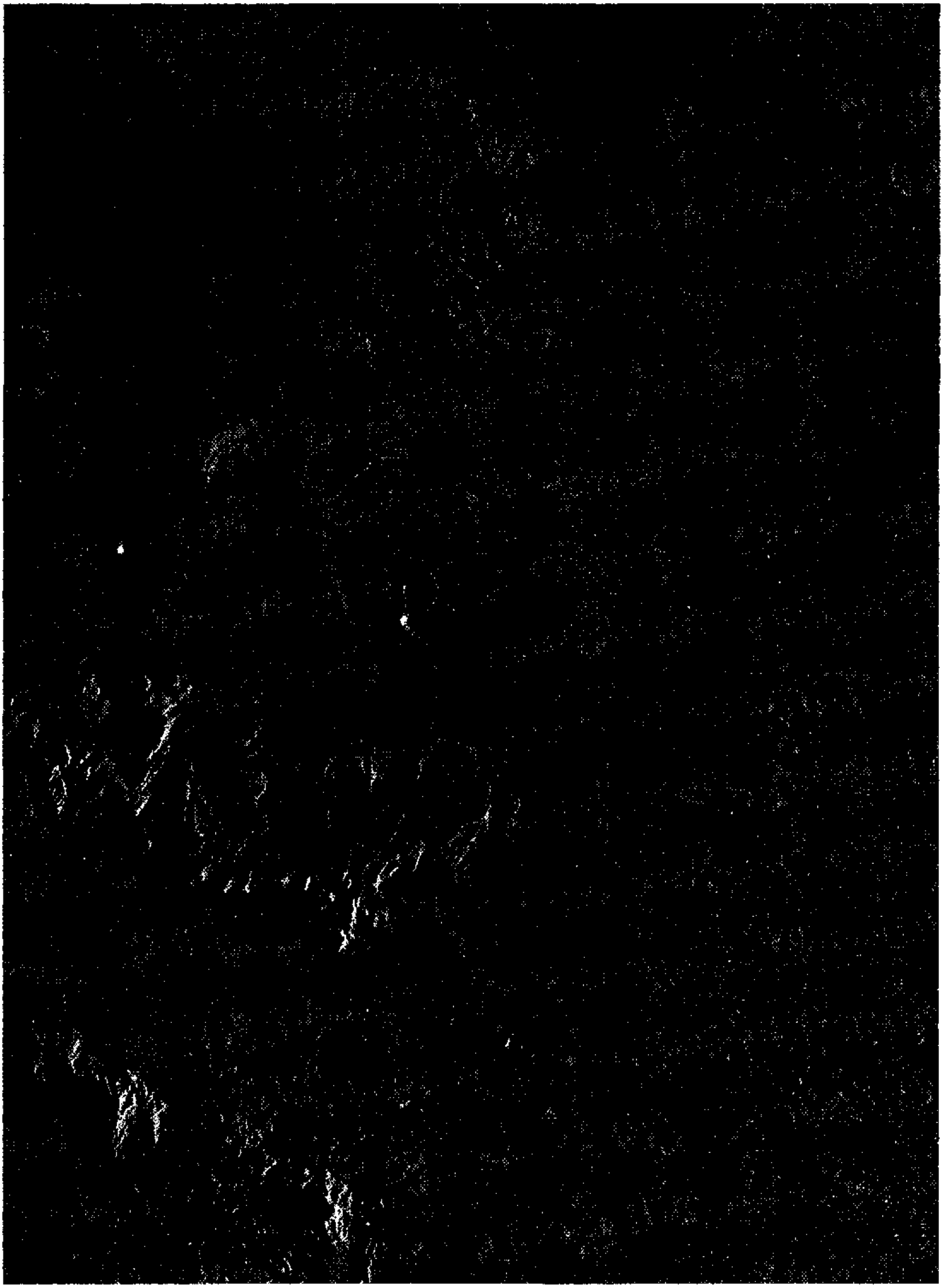
5.4. Analysis of image characteristics

All nine ERS-1 images of 1992 were co-registered. A multi-temporal composite (Figure 5.1) was created from the images of May, August, and December 1992. This combination gives good possibilities for visual discrimination. The composite was first enhanced by filtering with a gamma-map filter (Lopes et al., 1993) to reduce speckle effects. This resulted in a blurry image. The filtered image was therefore averaged with the original image to restore the edges. This procedure of image enhancement was developed by M.A.M. Vissers and gives visually attractive results: sharp edges with reduced speckle.

Polygons were drawn on this composite to delineate the fields that were surveyed during fieldwork. For locating the fields on the image, the coordinates measured with a Global Positioning System (GPS) receiver were useful, as well as the SPOT images used for orientation in the field. Nevertheless, some fields were impossible to locate accurately on the ERS-1 image. The polygons were transferred to the nine original, unfiltered images for the extraction of the mean backscatter value (average σ^0 per polygon) and its variation with time.

Clustering the samples on the basis of image characteristics did not give good results: the resulting clusters showed only a vague relation to user classes. Samples showing similar image characteristics on the four 1992 images, showed differences when the 1993 and 1994 images were looked at. Therefore, image characteristics were analyzed after the samples had been classified into the land cover structure classes, as explained in Chapter 4.

Next page:
Figure 5.1: Detail of the 1992 multi-temporal composite of ERS-1.
Red: 22nd December, green: 4th August, blue: 26th May.



5.5. Relation between land cover structure and image characteristics

5.5.1. Empirical relation

Of the samples for which image characteristics were extracted, those belonging to the miscellaneous land cover types or to the lower, temporarily flooded terraces of the Guaviare river were excluded. The remaining samples were split into two groups: for one of which only the user class was known and for the other the vegetation structure was also recorded. The former serve as a control group for the classification algorithm, while the latter permit analysis of the relation between land cover structure class and image characteristics.

The samples with both image characteristics and vegetation structure data were grouped according to their land cover structure class (see Table 5.7 for land cover structure classes). Table 5.10 gives a summary of the average σ^0, one of the image characteristics, per land cover structure class. Table 5.11 shows the minimum and maximum average σ^0 per land cover structure class (σ^0 averaged per plot per image).

Table 5.10: Summary of image characteristics per land cover structure class: average σ^0 (dB) per image per land cover structure class

Land cover structure class	Avg. im1	Avg. im2	Avg. im3	Avg. im4	Avg. im5	Avg. im6	Avg. im7	Avg. im8	Avg. im9
1 Closed, high primary forest	-5.66	-6.75	-5.76	-6.25	-6.68	-6.16	-6.36	-5.82	-6.46
2 Closed, medium primary forest	-6.10	-6.43	-6.49	-6.53	-6.58	-6.28	-6.25	-6.57	-5.85
3 Open, low forest	-6.16	-6.03	-6.58	-6.64	-6.69	-6.84	-6.64	-6.41	-5.79
4 Forb land with shrubs & trees	-6.74	-6.91	-6.95	-7.23	-7.14	-7.05	-6.59	-6.36	-5.61
5 Shrubland with trees	-6.70	-7.38	-7.24	-8.05	-7.16	-6.98	-7.24	-6.95	-6.79
6 Shrubland	-6.83	-6.12	-6.10	-6.42	-6.28	-6.82	-6.17	-6.71	-5.97
7 Rough short grass pasture	-8.10	-7.47	-8.23	-8.76	-7.78	-7.60	-8.42	-7.32	-7.72
8 Smooth, closed short grass p.	-9.19	-8.00	-8.66	-9.38	-8.05	-8.46	-8.92	-7.50	-8.60
9 Smooth, open short grass p.	-8.05	-6.68	-7.51	-8.76	-8.00	-7.81	-9.32	-5.97	-7.47
10 Rough tall grass pasture	-9.19	-8.82	-9.52	-9.09	-8.52	-8.21	-8.88	-8.19	-7.71
11 Smooth tall grass pasture	-8.78	-7.59	-8.31	-8.99	-8.42	-8.48	-8.55	-8.87	-8.75
12 Semi-natural tall grassld. -dry	-9.91	-9.98	-9.85	-11.36	-9.79	-9.43	-9.50	-8.82	-9.37
13 Semi-natural tall grassld. wet	-6.21	-9.92	-6.21	-8.05	-8.59	-6.94	-6.86	-7.44	-6.93

In Table 5.10 biomass decreases from land cover structure class 1 to 12 and the general trend in backscatter is to decrease in the same direction. Land cover structure class 13 is expected to have a biomass between 11 and 12. In this land cover structure class, wet semi-natural tall grassland, the influence of large variations in soil moisture content is very pronounced and causes large changes in backscatter.

As can be seen in Table 5.11, the ranges in average σ^0 per land cover structure class show considerable overlap. This can also be seen in Figures 5.2.a and 5.2.b, showing the average σ^0 of each sample per image. The legend of these figures shows the corresponding land cover structure classes. Moreover, the variation in backscatter between plots in the same land cover structure class is still quite large, although user classes were subdivided on the basis of cover percentage of strata of the vegetation. This is particularly true for the non-forest land cover structure classes. The highest backscatter values, between -3.0 and -5.0 dB,were found for two plots of shrubland (land cover structure class 6), both of which contain a substantial number of the large-leafed *Cecropia spp.* and also stem *Musaceae*. The other three shrublands of land cover structure class 6 contain no, or very few, *Cecropia* trees and are mainly covered by herbaceous climbers. Backscatter of these plots ranges between -5.0 and - 8.4 dB. Low values of -9.4 and -10.1 dB most probably coincide with the period of bare soil before the plot was left to regenerate.

Table 5.11: Average, minimum and maximum of average σ^0 (averaged per plot per image) per land cover structure class over all 9 images.

Land cover structure class	Average σ^0 (dB) over 9 images	Minimum σ^0 (dB) over 9 images	Maximum σ^0 (dB) over 9 images
1 Closed, high primary forest	-6.21	-8.07	-4.14
2 Closed, medium primary forest	-6.34	-7.73	-4.74
3 Open, low forest	-6.42	-8.31	-4.76
4 Forb land with shrubs & trees	-6.73	-8.81	-4.56
5 Shrubland with trees	-7.17	-9.77	-4.66
6 Shrubland	-6.38	-10.11	-3.35
7 Rough short grass pasture	-7.93	-11.40	-5.62
8 Smooth, closed short grass past.	-8.56	-11.65	-5.56
9 Smooth, open short grass past.	-7.73	-9.75	-5.52
10 Rough tall grass pasture	-8.68	-10.30	-7.22
11 Smooth tall grass pasture	-8.53	-10.20	-5.25
12 Semi-natural tall grassld. -dry	-9.78	-12.96	-8.42
13 Semi-natural tall grassld. -wet	-7.46	-10.46	-3.23

The forests of land cover structure classes 1, 2 and 3 oscillate between -5.0 and -7.5 dB, with only a few exceptions. Sample #140, one of the two secondary vegetation plots in cluster III that were excluded from land cover structure class 3 (see Section 5.2.3), shows backscatter values within the range of class 3, no backscatter data were available for the other secondary vegetation plot. The secondary vegetation of class 4 (forbs, shrubs and trees) mainly shows values between -5.0 dB and -8.0 dB. It is typical that the spread between the values seems to become smaller from image 1 to 9. This could be because all these plots were only described in 1994, so actual land cover structure in previous years is not known accurately. Land cover class 5, shrubland with trees, shows values mainly between -6.1 and -8.6 dB.

For the pastures of class 7, rough grassland of short grasses, backscatter ranges mainly between - 6.5 and -9.5 dB. The smooth, closed grasslands of class 8 show backscatter values mainly between -6.5 and -11.0 dB. The two smooth, open grasslands of class 9 range between -5.5 and -9.8 dB. For the rough, tall grasslands of class 10, most values are between -7.5 and -10.0 dB. The smooth, tall grass pastures of land cover structure class 11 have

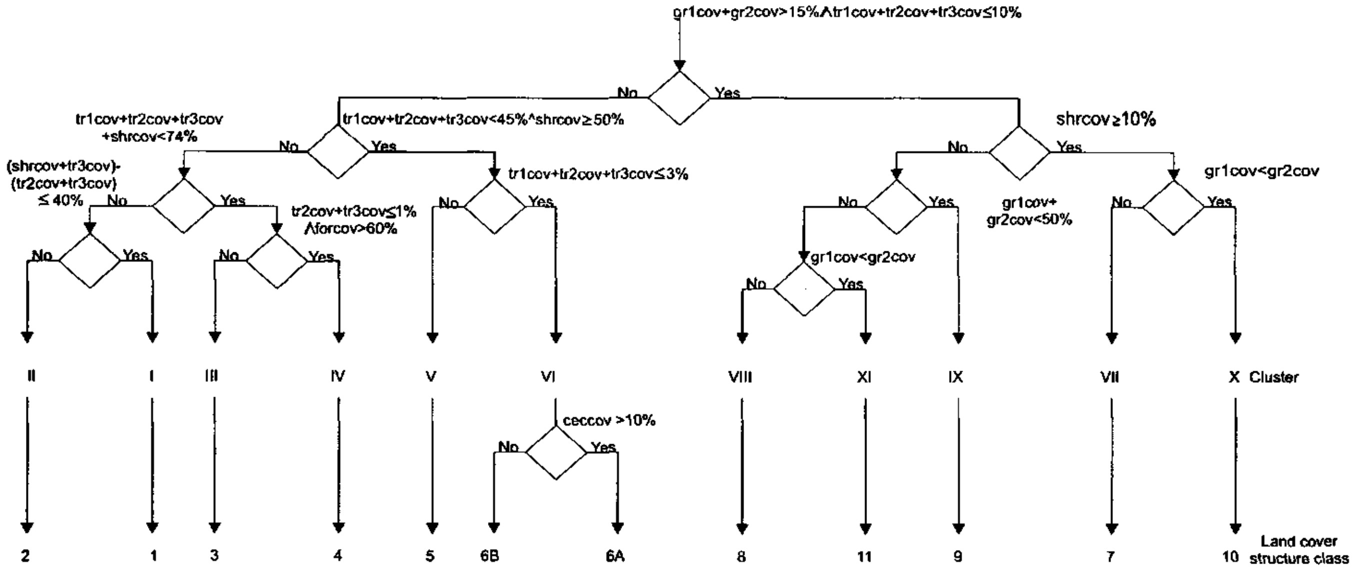


Figure 5.8: Classification tree for vegetation structure clusters and land cover structure classes. Land cover structure classes 12 and 13 (dry respectively wet natural grassland), also belonging to vegetation structure cluster XI in Table 5.5, are not shown here as they will not be included in the BOSTOS.

5.8. Conclusions

For the Guaviare region, 7 main land cover types, termed "user classes" were identified. Clustering of the vegetation structure data, as collected in the field, resulted in 11 vegetation structure clusters, which, when used to subdivide the user classes, resulted in 13 land cover structure classes.

The cover percentages of green vegetation in the following strata: tall trees, medium-high trees, low trees , shrubs, forbs, tall grasses and short grasses, were decisive in the clustering of vegetation data. Dominant leaf size, as reflected by a high cover percentage of large-leafed *Cecropia spp.*, contributed to the sub-division of the land cover structure class of shrublands. The percentages of bare soil, dead wood, presence of palms, vines, *Musa spp.* or epiphytes contributed little or nothing to the clustering for the vegetation structure data in this area.

A decision tree, based on cover percentages of green vegetation in predefined strata, was made for the classification of new vegetation structure data, like those generated by the land cover change model (Chapter 6) in the land cover structure classes.

Analysis of the remote sensing data showed which land cover structure classes could be separated with two image characteristics: average backscatter per segment and maximum difference in this average backscatter over nine subsequent images. Calculations of the expected backscatter with a theoretical model supported the empirical findings.

Image segmentation was performed by the multi-channel version of the RCSEG algorithm, performed on all images of the same year. Subsequent images showed large differences in the result of the segmentation. As different segments can be classified in the same class, the classification result is much more stable than the segmentation result. Dividing the images into smaller subsets, because of computing capacity, caused artifacts in the form of lines where the subsets were rejoined. These artifacts disappeared almost completely after classification (see Chapter 7).

6. CHANGE MODELS

6.1. Introduction

The dynamic land cover model described in this chapter (see also Bijker and Van Wijngaarden, 1994) was developed to assess land cover changes as part of the land cover monitoring system presented in Chapter 3. Monitoring and change detection involves the interpretation of multi-temporal images. We want to exclude unlikely changes in this process by making use of existing knowledge on the nature and speed of changes. This knowledge is formalized in models that describe the possible temporal changes in land cover.

Changes in the vegetation structure of crops are not related to changes in land cover structure class, but are part of their growth and development cycle. Such changes can be modelled by dynamic crop production models such as WOFOST (Diepen et al., 1988).

A special model was developed for changes in vegetation structure that are related to changes in land cover structure class. It describes the dynamics of the cover of different layers in the vegetation on the clearing of forest for arable fields or pastures, and the regeneration to forest.

Social, economical and political circumstances change with time and influence the settlement process. The physical conditions in the area may also show important spatial variation. Despite all these variations, previous studies have shown that some generalizations about the settlement process and its effect on the land cover can be made; these are summarized in the description of land use in Chapter 2. These generalizations were checked in interviews with farmers and COA extension officers, and by field observations.

6.2. Modelling

The objective of the BOSTOS (BOSque-pasTOS) model is to describe the medium term (one year to several decades) dynamics of the structure of the land cover under various human interventions or management practices. The dynamics of the vegetation structure have already been successfully modelled in savanna and paramo ecosystems, e.g. by Van Wijngaarden (1985) and Verweij (1995). The dynamics of the vegetation are also modelled only for the vegetation structure in BOSTOS. Vegetation structure is described as the percentage crown cover for the different strata, as defined in Sections 4.2, 4.3 and 5.2. For the purpose of modelling, some small changes were made to the standardized strata as described in these sections. The two grass strata were put into one stratum with a maximum height of 1 m, flowers of grass were neglected. The maximum height of the forbs was also set to 1 m. The cover by *Cecropia spp.* is described in a separate stratum, because of the special role these tree species play in the regeneration of the vegetation after disturbance.

The BOSTOS model is a deterministic model, following the state-rate variable approach. The model was implemented in the simulation language PCSMP (IBM, 1975, Janssen et al., 1988, and Leffelaar, 1993). The cover percentages of the vegetation strata are the state variables. Table 6.1 shows the strata used for modelling with their height limits and structural plant groups.

Table 6.1: Vegetation strata used as state variables in the BOSTOS model

Code	Name	Height (m)	Dominant structural plant group
TR3	Tall tree stratum	> 30	Tall trees
TR2	Medium-high tree stratum	15—30	Medium-high trees
TR1	Low tree stratum	5—15	Low trees
SHR	Shrub stratum	0—5	Shrubs
CEC	*Cecropia spp.* stratum	0—15	Low trees
GRA	Grass stratum (total graminoids)	<1	Short & tall grasses
FOR	Forb stratum	<1	Forbs
DWO	Dead wood stratum	<1	-
BAS	Bare soil and litter stratum	<1	-

A stratum can reach maximum cover if it is not covered by another, higher stratum. Maximum cover percentages for strata, if not covered by other strata, are listed in Table 6.2. The values are based on field observations. In most cases, however, the maximum cover a stratum can reach when fully developed is limited by the cover of the strata above, (competition for light, space, water, etc.). The maximum cover percentages in a structure, limited by the cover of the strata above, are also listed in Table 6.2.

Table 6.2: Maximum cover of the strata used as state variables in the BOSTOS model. The absolute maximum cover is the maximum cover percentage a stratum can have when on its own. However, when a stratum appears in a structure with other strata, its maximum cover can be limited by the cover of the other strata. This is the maximum cover percentage in a structure.

Stratum	Absolute maximum cover (%)	Maximum cover in structure (%)	Maximum cover percentage in structure depends on
TR3	60	60	N.A.
TR2	80	50	-0.5*TR3
TR1	90	35	-0.5*(TR3+TR2)
SHR	100	10	-0.5*(TR3+TR2)-TR1
CEC	100	0.1	-1.0*(TR3+TR2+TR1)-0.3*SHR
GRA	100	0.1	-1.0*(TR3+TR2+TR1+CEC+SHR+DWO)
FOR	100	0.1	-0.5*(TR3+TR2+TR1+CEC+SHR)-1.0*(GRA+DWO)
DWO	20	20.0	N.A.

It is assumed that without human interference the vegetation develops towards a primary forest with a 'stable' maximum structure. In this maximum structure, the cover percentage of a layer depends only on the cover of the layers above. The most complex structure found during field observations was considered to be the maximum structure. The maximum cover percentages of strata in a structure are based on these observations.

The rate variables are the rates of change with which the cover percentage of the strata can change. There are two groups of growth rates: the natural regeneration rates and the growth rates after a management intervention. The natural regeneration rates are: death rate, growth rate, move-up rate and appearance rate. These rates are listed in Table 6.3, together with the related variables 'average lifespan' and 'time to grow to next stratum'.

The death rate is the fraction of the stratum cover that disappears due to plants dying; it depends on the average lifespan of the plants in the stratum. The growth rate is the average increase in plant height in one year. The time to grow to the next stratum is the time a plant needs to grow from the lower limit to the upper limit of the stratum; this depends on the difference between the lower and the upper limits and on the growth rate. The move-up rate is the fraction of the stratum cover that disappears per year because of plants exceeding the stratum's upper limit. The appearance rate is the fractional increment in cover per year due to plants entering the stratum by passing the lower limit. The appearance rate of a stratum is equal to the move-up rate of the underlying stratum.

Few quantitative data are available on the growth and death rates of woody plants in tropical rain forest. A death rate was calculated based on the estimated average lifespan of the woody plants. Growth rates were estimated in the field, based on the age and the height of the vegetation. For the tree strata, the appearance rate depends on the cover percentage in the underlying stratum. For herbaceous and shrub strata, it was assumed that the appearance rate is inversely proportional to the actual cover, with a maximum growth rate equal to doubling the cover in one year at low cover percentages and the rate reducing to zero as the cover percentage approaches the maximum possible.

Table 6.3: Natural growth rates of plants per stratum. These growth rates are used for the regeneration of the vegetation.

Stratum	Average lifespan (years)	Death rate (fraction of cover)	Growth rate (m/year)	Time to next stratum (years)	Move-up rate (fraction of cover)	Appear rate (fraction of cover)
TR3	100	0.01	N.A.	N.A.	N.A.	0.02*TR2
TR2	50	0.02	0.3 m/yr	50	0.02	0.04*TR1
TR1	33	0.03	0.4 m/yr	25	0.04	0.10*SHR
SHR	25	0.04	0.5 m/yr	10	0.10	1.0*AC*(1-AC/MC)
CEC	20	0.05	N.A.	N.A.	N.A.	1.0*AC*(1-AC/MC)
GRA	N.A.	N.A.	N.A.	N.A.	N.A.	1.0*AC*(1-AC/MC)
FOR	N.A.	N.A.	N.A.	N.A.	N.A.	1.0*AC*(1-AC/MC)
DWO	10	0.10	N.A.	N.A.	N.A.	0.2*DRT

* AC = actual cover; MC = maximum cover; DRT = death rate trees

In the case of human interference, the vegetation cover can change abruptly in one year. The effect of the various management activities are presented as the cover one year after the event. Thus, where the forest has been cleared for cultivating an annual crop, the cover after one year is not the cultivated crop, but a young fallow vegetation consisting mainly of shrubs and *Cecropia spp.*

The main human interventions in the land cover in the area, as described in Chapter 2, are the following:

a. Clearing primary forest and cultivation of an annual crop
b. Clearing secondary forest and planting grass
c. Burning and/or clearing shrubs in pastures
d. Abandoning a previously cultivated field
e. Degeneration and abandoning pasture.

The last two practices lead ultimately to the regeneration of the forest.

The effects of these five activities on the vegetation structure are modelled in BOSTOS. Table 6.4 shows the effect of particular management activities on the cover of the different strata one year after action was taken. The total growth rate is the sum of the natural plus these managed growth rates.

Table 6.4. Growth rates of plants per stratum for various management activities

Stratum	Cultivation	Grass planting	Burning of pasture	Clearing of shrubs
TR3	-0.98*TR3	-0.6*TR3	-0.4*TR3	0.0
TR2	-0.98*TR2	-0.8*TR2	-0.6*TR2	0.0
TR1	-1.0*TR1	-0.9*TR1	-0.8*TR1	-0.2*TR1
SHR	-1.0*SHR+50	-0.95*SHR	-0.9*SHR	-0.98*SHR
CEC	-1.0*CEC+35	-1.0*CEC	-1.0*CEC	-1.0*CEC
GRA	-1.0*GRA+10	-1.0*GRA+80	+0.5*GRA	0.0
FOR	-1.0*FOR+20	-1.0*FOR	+2.0*FOR	0.0
DWO	-0.5*DWO+DRT	-0.2*DWO+DRT	-0.2*DWO+DRT	0.0

In order to be able to predict whether a certain management activity will take place in any particular year, an analysis was made of the farming practices in the area. It appeared that farmers have certain criteria for deciding when to cultivate a crop, to plant grass, burn a pasture, etc. Based on a number of interviews with farmers, the criteria listed in Table 6.5 were found to be relevant to this modelling exercise.

Forest (primary or secondary) can be cleared and burned for the cultivation of annual crops only when total tree cover exceeds 45%. This excludes the burning of young secondary vegetation. Not all forest with total tree cover over 45% is cleared, but the forest considered for slash and burn will only effectively be cleared if this criterion is met.

Grass is planted only if the total dead wood cover is less than 5%, grass cover is less than 20% and tree cover is less than 10%. If there is too much dead wood, the cattle find grazing difficult. If there is already sufficient grass cover, extra planting is unnecessary. Too many trees give too much shade for the development of the grass. Moreover, many farmers like their pastures 'clean', i.e. without trees, as this was the custom in their region of origin (e.g. the Andes).

The pastures, once established, have to be maintained. This involves the burning and/ or clearing of emerging shrubs, and the burning of old, unpalatable grass. If the grass cover becomes too low, it is no longer considered as pasture but young secondary vegetation, which is left to regenerate for clearing and burning some years later.

Table 6.5: Criteria for management interventions, as used in the BOSTOS model.

Management intervention	Criteria for intervention
Cultivation	Only when total tree cover is more than 45%
Grass planting	Only when dead wood cover is less than 5% - and grass cover is less than 20% - and tree cover is less than 10%
Pasture burning	Only when grass cover is more than 50% - and shrub cover is more than 20%
Shrub clearing in pastures	Only when shrub cover is between 10 and 20% - and grass cover is more than 50%

6.3. Simulation

The land cover class in the initial situation, derived from a previous mapping or classification, was translated into cover percentages for the various vegetation layers using Table 5.14. Subsequently, BOSTOS was used to calculate the possible cover percentage of different vegetation layers at a later date. These cover percentages can be translated back into land cover classes with the classification tree for land cover structure classes presented in Figure 5.8. In Chapters 4 and 5, *Cecropia spp.* were included in the shrub and tree strata, whereas for BOSTOS they have a stratum of their own. The criteria in Figure 5.8 can also be used for classification when the cover percentage of *Cecropia spp.* is excluded from the shrub and tree strata. When applied in this way to the data in TWINSPAN (Table 5.5), one misclassification detected in Section 5.7 disappears but another is added. Figure 5.8 can therefore be used without adaptation for classifying the simulation results from BOSTOS.

Several simulation runs were made, using different initial conditions or management options. Three examples of simulation results are given in Figures 6.1, 6.2 and 6.3 showing the changes in cover percentages of the different vegetation strata and the resulting land cover structure class, according to the classification scheme in Figure 5.8.

Figure 6.1 depicts the situation where a closed, medium-height forest is cleared to cultivate annual crops, and where the conditions are right, grass is planted. It shows that after the cultivation of a crop, regeneration of shrubs and *Cecropia spp.* takes place and that, after about 6 years, the conditions are right to cultivate again. This repeats itself, but after the second cycle, the conditions are right to plant grass, i.e. the dead wood cover (tree trunks and large branches on the ground) is less than 5%. The pasture is invaded by shrubs, and every 7 years the shrubs are removed by burning and/or clearing. In reality, annual crops are usually cultivated for two or three consecutive years (see also Section 2.7). The time allowed for regeneration varies between 4 and 7 years, so the 6 years shown by the simulation run is not unrealistic. Shrub clearing every 7 years might be an underestimation — although exact data are unavailable, 2 or 3 years might be more realistic. However, this also depends on the age of the pasture, as new pastures suffer more shrub invasion.

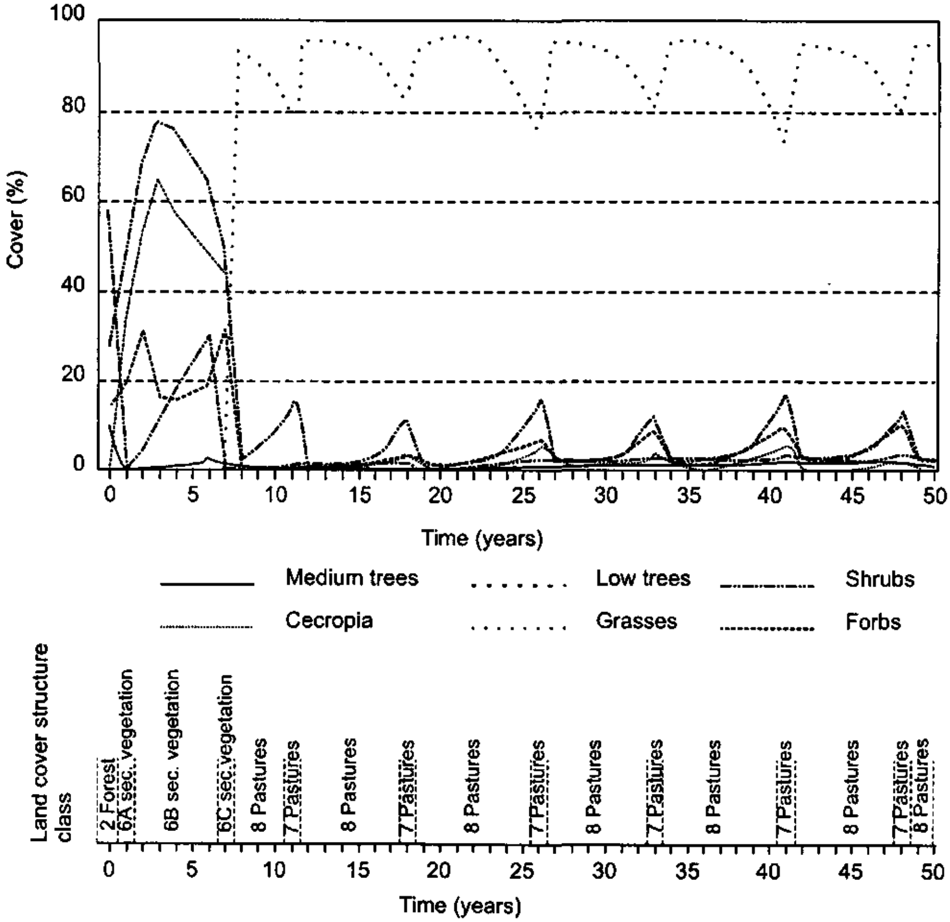


Figure 6.1: BOSTOS simulation of cutting and burning of closed, medium-height forest, followed by cultivation of annual crops, regeneration, again cultivation of annual crops and finally planting of pastures.

In some cases, the crops planted after clearing are not annuals (e.g. maize, cassava) but perennials like sugarcanes, banana, coca and tree crops, leading to longer periods of cultivation, or even permanent cultivation.

Figure 6.2 depicts the regeneration of a pasture after it was abandoned. From a smooth, open, short grass pasture (class 9) for example (a pasture that has recently been grazed by cattle), grass and shrub cover increase, resulting first in a closed, short grass pasture and, without clearing or burning the regenerating shrubs, it soon develops into a rough, short grass pasture. It takes only 4 to 5 years for the pasture to become so invaded by shrubs that the grass cover is reduced to almost zero, and trees also start appearing. According to the model, it takes more than 20 years before large trees start appearing. After 30 years, the structure starts to resemble the primary forest of land cover structure class 1.

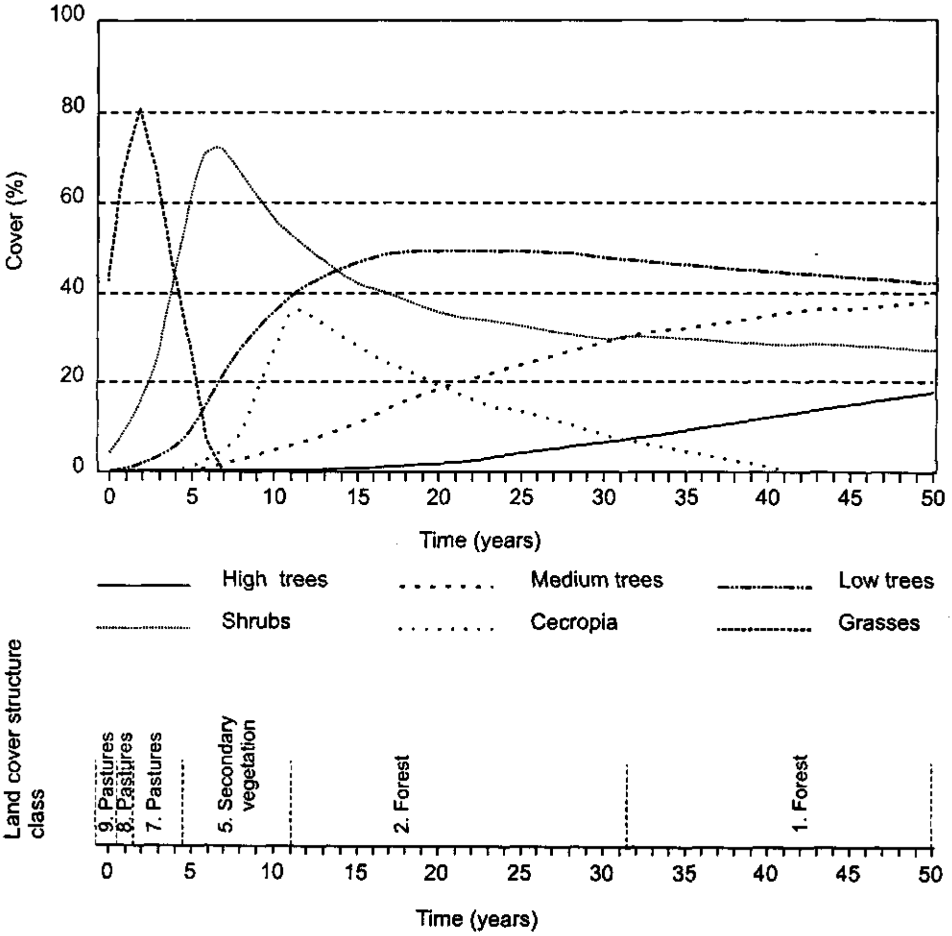


Figure 6.2: BOSTOS simulation of regeneration of an open, short grass pasture.

have been taken out. In both cases, it is not an intermediate step in the regeneration of pastures or crops.

Figure 6.5 shows an adapted version of Figure 6.4, and both class 6B and class 4 have been placed where they most likely belong according to field observations.

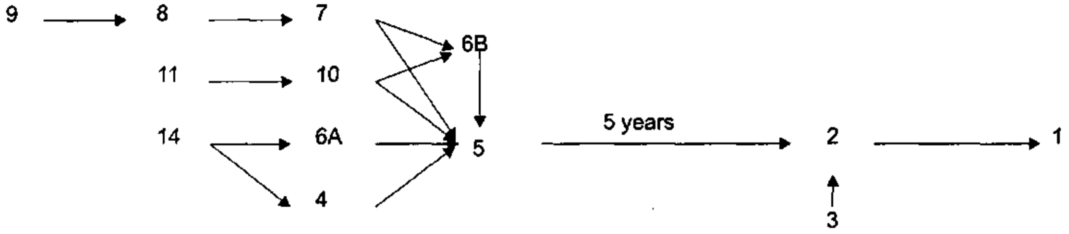


Figure 6.5: Sequence of land cover structure classes during regeneration, as calculated by BOSTOS, with adaptations for situations that could not be simulated yet. The land cover structure classes are identified by numbers (see Table 5.7).

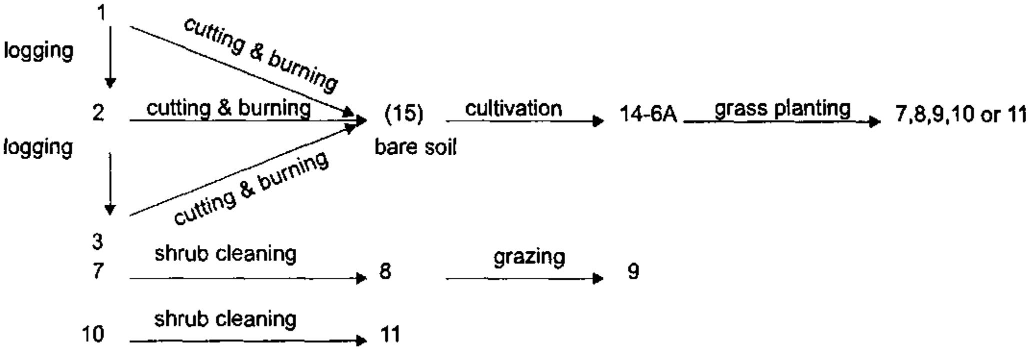


Figure 6.6: Changes in land cover structure classes that result from management interventions. The land cover structure classes are identified by numbers (see Table 5.7).

6.4. Conclusions

The simulation runs with the BOSTOS model, presented in the previous section, show that the approach is promising in predicting potential changes in land cover over a specified time period. This is essential information for the monitoring system, as will be demonstrated in Chapter 7. Not all the possible transitions between land cover structure classes are fully understood yet, as shown in the previous section by the discussion on the place of land cover structure classes 4 and 6B in the regeneration. Further development and improvement of the BOSTOS model should concentrate on two main aspects.

(1) Improvement of the present parameters and constants through field observations, and comparison with other studies. Especially the rates of change of the various layers need confirmation. A problem here is that in most other studies on the growth and regeneration of tropical rain forest, the vegetation is described in terms of species composition and structural aspects like biomass and diameter at breast height of the woody species (e.g. see Saldarriaga et al., 1988, Torro and Saldarriaga 1990). These data have to be translated into cover of the various strata as used in this study.

(2) Introduction of the spatial variation. The present version of BOSTOS assumes that the area is homogeneous in every aspect but land cover, or at least that the spatial variation in other factors does not influence the land cover. It therefore excludes all spatial variation in soils, water availability and vicinity of roads, markets and services, etc., and their influence on the land cover. If data on soils, water, roads and population were available in a Geographical Information System (GIS), these could be used to calculate spatially dependent regeneration rates and the chances of a forest area being cleared for cultivation.

At the moment BOSTOS is based on the natural vegetation growth rates and the effects of a limited number of agricultural practices. However, these agricultural practices tend to adapt quite rapidly to changes in the socio-economic circumstances or in land use policies. These factors should continuously influence the assumptions made in future versions of BOSTOS. This is a good reason for making a general, generic structure with a number of parameters (and eventually algorithms) that the user can change interactively to adapt the model to new circumstances. In this respect, a two-way interaction with the monitoring system could also be interesting, as the monitoring system could give clues on whether the assumed agricultural practices are still occurring.

The importance and direction of further development of BOSTOS has to be seen in relation to further development of the monitoring system as a whole. The task of BOSTOS in the system is to guide the classification process in the right direction, i.e. towards accurate classification of time series of ERS-1 and -2 images. Use of a model like BOSTOS is more important when the classification of images, based on image characteristics, is not very accurate, as is the case with ERS-1 and -2 images. With other sensors, which permit more accurate classification of land cover, a land cover change model will contribute less to the overall system accuracy.

vegetation with forbs, shrubs and trees, shrub land with trees, and shrub land with no or very few *Cecropia spp.*, respectively*)*. At range 4, the land cover structure classes with short grasses (7, 8 and 9) are added to the classes with forest (1, 2 and 3) and the classes with secondary vegetation (4, 5 and 6B) already present in range 4. At range 5, the classes with forest (1, 2 and 3) are no longer present. Classes 4, 5 and 6B with secondary vegetation and classes 7, 8 and 9 with grassland with short grasses are now joined by the land cover structure classes with tall grasses (10 and 11). At range 6 only classes with short grasses (7, 8 and 9) and with tall grasses (10, 11 and 12) are present.

Table 7.1: Land cover structure classes grouped per backscatter range

Range	Min. σ^0	Max. σ^0	Land cover structure class														
1	-3.0	>-3.0															15
2	-5.0	-3.0						6A									
3	-6.1	-5.0	1	2	3	4	5		6B							13	
4	-7.5	-6.5	1	2	3	4	5		6B	7	8	9				13	
5	-8.5	-7.5				4	5		6B	7	8	9	10	11		13	
6	-13.0	-8.5								7	8	9	10	11	12	13	
7	<-13.0	-13.0															15

Class 13, the wet semi-natural grasslands, is spread over ranges 3 to 6, so it might be confused with many other land cover structure classes. However, the location of these grasslands is known and not subject to change. The few grasslands of land cover structure class 9 present in range 3 are not accounted for here. These are not outliers in the sense of presumably rare cases of high backscatter values caused by an exceptional land cover structure. As could be seen in Figure 5.5, such high backscatter values for pastures are likely if the topsoil has a high moisture content. However, these pastures will probably show lower backscatter values on other images, recorded during drier field conditions. When applying decision rules based on land cover change in monitoring, they will come out sooner or later as pastures, as will be shown in Section 7.5.

At range 7, below -13 dB, there is no vegetation present. The surfaces with such low backscatter values, like quiet open water and rock surfaces not facing the sensor, show strong specular reflection of radar waves, so no signal returns to the sensor.

The backscatter ranges are subdivided by using a measure for the variation in backscatter with time: the difference between the maximum and minimum backscatter of the same area over three subsequent images. A sequence of three images was chosen because, in the Guaviare study, it was likely that there would be sequences of three images in one year taken in different seasons (and hence showing maximum differences over a growing season).

At the backscatter ranges 3 and 4, it is not possible to separate land cover structure classes 1, 2 and 3 (different forest types) from each other, either by backscatter level or by differences in backscatter variation with time. The same is true for the land cover structure classes with secondary vegetation (4, 5 and 6B). However, it is possible to separate the forest (classes 1, 2 and 3) from the secondary vegetation (classes 4, 5 and 6B) at these backscatter ranges, using temporal variation in backscatter. In almost all forest samples (classes 1, 2 and 3) the variation in backscatter over three subsequent images was less than 1.5 dB. The variation was mostly between 1.5 and 2.5 dB for samples with secondary vegetation (classes 4, 5 and 6B). The backscatter simulations in Section 5.5.2 also showed that the expected backscatter of secondary vegetation and forest are (almost) the same, but that the backscatter of secondary vegetation is slightly more dependent on the moisture content of the topsoil, and hence less constant over time than the backscatter of forest.

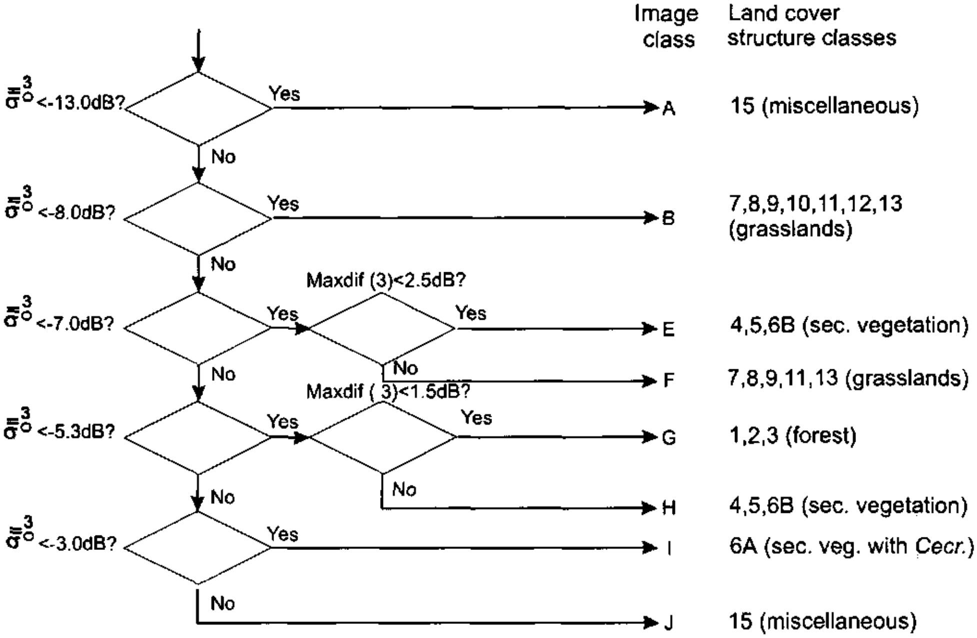
At range 4 no distinction can be made between the grasslands of classes 7, 8 and 9, but these grasslands as a group can be distinguished from the forests (classes 1, 2, 3) and the secondary vegetation (classes 4, 5 and 6B). This is possible because grassland samples often show variations of more than 2.5 dB over three subsequent images, while the forests and the secondary vegetation show less variation in backscatter with time.

At range 5, the few samples of secondary vegetation classes (4, 5 and 6B) cannot be separated by backscatter variation from the man-made and natural grasslands (classes 7, 8, 9, 10, 11 and 13). Knowledge of the sample's history has to be used to decide which class is most likely. Distinguishing between the different grassland classes at ranges 6 and 7 is not possible on the basis of either backscatter level or backscatter variation with time. The above observation leads to the first decision tree (Figure 7.1). The classes resulting from the classification are called image classes and indicated with capitals A—J.

7.2.2. Decision rules for averages of subsequent images

Looking at Figure 5.3 in Section 5.5, it is clear that the averages of the backscatter per sample over 9 images show far less overlap between classes. This led to the idea of basing the decision tree (set of formal rules) for image classification on averages over a number of images. Two additional decision trees were made, based on averages of nine and three images. The decision tree in Figure 7.2 is based on Figures 5.3 and 5.4, using the averaged backscatter over nine images and the maximum difference in backscatter over these images. Note that the limits between the image classes are at different backscatter levels. This also causes a small change in the land cover structure classes corresponding to the image classes: land cover structure class 11 (grasslands with tall grasses) is also present in image class F, although in Figure 7.1 only the grasslands of land cover structure classes 7, 8, 9 and 13 were present. The disadvantage of the decision tree in Figure 7.2 is that, when all nine images are used for the classification, no monitoring and change detection is possible, and no decision rules based on land cover change can be applied. Moreover, if the sample's cover has changed between the first and last image, this might go unnoticed because of the averaging.

backscatter over three subsequent images. For the classification of the first three images, the maximum difference over images 1, 2 and 3 was used, for image 4 the maximum difference over images 2, 3 and 4, for image 5 the maximum difference over images 3, 4 and 5, etc. The results are presented in Table 7.2 for the training set and in Table 7.3 for the control set. In these tables, the samples classified correctly are given as the percentage of the total number of samples in that land cover structure class. Some land cover structure classes contain only a few samples, thus causing large variations in the percentages of correctly classified samples between the images.



$\overset{3}{\bar{\bar{\sigma}}}{}^{o}$ = average $\bar{\sigma}^{o}$ per segment, averaged over three subsequent images
Maxdif (3) = maximum difference in $\bar{\sigma}^{o}$ over three subsequent images

Figure 7.3: Decision tree for the classification of sets of ***three images****. The decision tree is based on average backscatter level over three subsequent images and maximum difference in backscatter level over the same three images.*

There were good results for the classification of the forests of land cover structure classes 2 and 3, although the forest samples of land cover structure class 1 showed more misclassifications, mainly due to secondary vegetation in image classes H or I, and to a lesser extent E.

The results for the classification of secondary vegetation, land cover structure classes 4, 5, 6A and 6B, were not good. The samples classified incorrectly were classified either as forest (D or G) or as pasture (B). Furthermore, about half of the samples with secondary vegetation considered to be classified correctly, were classified in the mixed class C, containing both secondary vegetation and pasture. The secondary vegetation and pastures in class C will be separated with the decision rules based on the possibility of land cover change (see Section 7.4).

The results for the classification of the smooth pastures (land cover structure classes 8, 10 and 11) and the dry natural grassland (land cover structure class 12) were good. The classification of the rough pastures (land cover structure classes 7 and 9) was more difficult because the rougher surface and higher biomass of these pastures results in a higher backscatter, similar to secondary vegetation or forest (see also Section 5.5.2). The difference in classification result between smooth pastures and rough pastures cannot be accounted for by moisture differences, since no relation was found between the cover percentage of shrubs in a pasture and the topsoil's moisture content in the field. So the difference in classification results is caused by the higher roughness and the higher biomass of the rough pastures. On the ERS-1 images, these grasslands resemble the secondary vegetation (image class E) or even the forest (image class D) more than the smooth pastures.

The misclassifications of the wet natural grasslands of land cover structure class 13 was most likely due to an increase in backscatter caused by the high water content of the topsoil rather than by an increase in biomass. Misclassifications were towards forest classes (D and G) as well as secondary vegetation classes (E, H, I). As the location of these grasslands is already known and does not change, these misclassifications can be corrected easily.

The training and control sets in Tables 7.2—7.5 contain no samples with crops. Classification of the crop samples using the decision tree in Figure 7.1 puts these samples in a large variety of image classes. This demonstrates that the backscatter levels of crops show a lot of variation, depending on the type of crop, the phenological stage, the density, the amount of bare soil, the humidity of the topsoil and the amount of weeds. It will be almost impossible therefore to classify crops based on image characteristics alone. However, at least some of the crops can be detected by using the knowledge that after clearing the forest, one or two years of annual crops will normally follow.

Secondly, the rules for the classification of averages of three images (Figure 7.3) were applied, using the average backscatter per polygon, averaged over three subsequent images and the maximum difference in average backscatter over three subsequent images. The results are presented in Table 7.4 for the training set and in Table 7.5 for the control set. In Table 7.4, the samples classified correctly are given as the percentage of the total number of samples in that land cover structure class.

Comparing Tables 7.2 and 7.3 with 7.4 and 7.5, it becomes clear that for both the training and control sets, the overall classification result is better for classification of individual images than for the classification of averages of three images. For secondary vegetation, the results were better when classifying averages of three images. However, this is at the expense of the classification results for forests, pastures and (semi-) natural grasslands, for which the classification of individual images gave better results.

Thirdly, the decision tree in Figure 7.2 was applied to the averages and maximum differences over nine images of both the training and control sets. The results are shown in Tables 7.6 and 7.7. The total classification results for the training set are better than those for individual images and averages of three images, while the results for the control set are intermediate. However, it should be noted that the classification results for individual images and for averages of three images are expected to improve after application of the decision rules based on the knowledge of land cover change (see Section 7.4).

Table 7.2: Percentage of samples of the ***training set*** *classified correctly with the decision tree for* ***individual images*** *(Figure 7.1), based on backscatter level and maximum difference in backscatter level over three subsequent images. Correct classification means that the land cover structure classes 1, 2 and 3 (forests) are classified as D or G, classes 4, 5 and 6B (secondary vegetation) in C, E or H, class 6A (secondary vegetation with Cecropia spp.) as I and classes 7—13 in B, C or F.*

Land cover structure class	Total number of samples	Percentage of samples classified correctly per land cover structure class per image									Average percentage correct
		Image 1 May '92	Image 2 Aug. '92	Image 3 Nov. '92	Image 4 Dec. '92	Image 5 Jul. '93	Image 6 Sep. '93	Image 7 Apr. '94	Image 8 Jul. '94	Image 9 Sep. '94	
1	4	50	50	50	50	75	100	75	50	75	64
2	10	90	90	80	100	90	90	90	100	90	91
3	4	75	75	75	75	100	100	75	100	50	81
4	4	25	50	25	50	50	25	50	50	50	42
5	5	40	60	60	60	80	60	20	40	20	49
6B	3	33	0	33	0	33	33	33	33	66	30
6A	2	50	100	100	50	50	0	100	0	0	50
7	9	67	33	78	78	78	67	89	44	56	65
8	14	100	64	100	86	71	86	86	64	86	83
9	2	50	0	50	100	50	50	100	0	100	56
10	3	100	100	100	100	100	100	100	100	33	93
11	2	50	50	50	100	100	100	100	100	100	83
12	3	100	100	100	100	100	100	100	100	100	100
13	3	33	100	33	100	100	33	0	67	33	56
Total	68	71	63	74	78	78	74	75	65	66	71

Table 7.5: Percentage of samples of the ***control set*** *classified correctly with the decision tree for* ***averages of three images*** *(Figure 7.3), based on average backscatter level over three subsequent images and maximum difference in backscatter level over the same three images. Correct classification means that user class forest is classified as D, user class secondary vegetation in E, H or I and pastures and dry and wet natural grasslands in B or F.*

User class	Total number of samples	Percentage of samples classified correctly per user class per average of three images							Average% correct
		Image 1,2,3	Image 2,3,4	Image 3,4,5	Image 4,5,6	Image 5,6,7	Image 6,7,8	Image 7,8,9	
Forest	15	73	67	73	67	60	73	57*	67*
Sec. veg.	21	38	29	38	43	43	33	43	38
Pasture	30	67	80	87	70	60	57	52*	67*
Dry nat. grassld.	7	100	100	100	100	100	57	71	90
Wet nat.grassld.	3	0	0	0	0	33	0	0	5
Total	76	61	62	68	62	58	51	50*	59*

* One forest sample and one pasture sample were outside the area covered by the image taken in September 1994, because the orbit was different for this image.

Table 7.6: Percentage of samples of the ***training set*** *classified correctly with the decision tree for* ***averages of nine images*** *(Figure 7.2), based on average backscatter level and maximum difference in backscatter level over all nine images. Correct classification means that the land cover structure classes 1, 2 and 3 (forests) are classified as D, classes 4, 5 and 6B (secondary vegetation) in E or H, class 6A (secondary vegetation with Cecropia spp.) as I and classes 7—13 in B or F.*

Land cover structure class	Total number of samples	Percentage of samples classified correctly per user class per average of nine images
1	4	50
2	10	90
3	4	50
4	4	75
5	5	80
6B	3	33
6A	2	100
7	9	67
8	14	86
9	2	100
10	3	100
11	2	100
12	3	100
13	3	67
Total	68	78

Table 7.7: Percentage of samples of the ***control set*** *classified correctly with the decision tree for* ***averages of nine images*** *(Figure 7.2), based on average backscatter level and maximum difference in backscatter level over all nine images. Correct classification means that user class forest is classified as D, user class secondary vegetation in E, H or I and pastures and dry and wet natural grasslands in B or F.*

User class	Total number of samples	Percentage of samples classified correctly per user class per average of 9 images
Forest	14*	64*
Sec. veg.	21	43
Pasture	29*	72*
Dry nat. grassld.	7	100
Wet nat. grassld.	3	0
Total	74*	62*

* Of the original 76 samples, one forest sample and one pasture sample were outside the area covered by the image taken in September 1994, because the orbit was different for this image.

7.4. Decision rules based on the possibility of land cover changes

In Section 6.3 possible transitions between land cover structure classes were simulated with the BOSTOS model and the results were presented in Figures 6.4, 6.5 and 6.6. Based on these figures, a matrix can be drawn to evaluate the differences between two classification results of the decision rules for individual images or for averages of three images (Figures 7.1 and 7.3). Such a matrix is shown in Figure 7.4. In this matrix, possible transitions between the land cover structure classes have been translated into possible transitions between the image classes from Figures 7.1 and 7.3.

	Image class second classification	J	I	H	G	F	E	D	C	B	A
Image class first classification	Corresp. Land cover structure class v >	15	6A	4, 5, 6B	1, 2, 3	7, 8, 9, 13	4, 5, 6B	1, 2, 3	4, 5, 6b, 7, 8, 9, 10, 11, 13	7, 8, 9, 10, 11, 12, 13	15
J	15	J	I	H	J	F	E	J	C	B	A
I	6A	J	I	H	I	F	E	I	C	B	A
H	4, 5, 6B	J	H	H	G*	F	E	D*	H	B	A
G	1, 2, 3	J	I	H	G	F	E	D	C	B	A
F	7, 8, 9, 13	J	F	H	F	F	E	F	F	B	A
E	4, 5, 6B	J	E	H	G*	F	E	D*	E	B	A
D	1, 2, 3	J	I	H	G	F	E	D	C	B	A
C	4, 5, 6b, 7, 8, 9, 10, 11, 13	J	C	H	G*	F	E	D*	C	B	A
B	7, 8, 9, 10, 11, 12, 13	J	B	H	B	F	E	B	B	B	A
A	15	J	I	H	A	F	E	A	C	B	A

*Figure 7.4: Matrix of possible changes between image classes over a timespan of one year. An * indicates an additional condition to be met, e.g. regarding the history of the sample. The underlined occasions are unlikely transitions, where the original image class is maintained. For details: see text.*

An area can always remain in the same land cover structure class and hence also in the same image class. All land cover can be turned into "miscellaneous" (land cover structure class 15, image class A or J), e.g. by building houses or roads, or by clearing all vegetation (bare land). If an area is classified as land cover structure class 15, it can be planted with crops (this will be discussed in more detail later) or pasture (land cover structure classes 7, 8, 9, 10, 11, image classes B, C, F) or regenerate into land cover structure class 6A or 4 (image classes I, C, E, or H), with or without a (short) period of cultivation before regeneration. Land cover structure class 6A/image class I can regenerate into land cover structure class 5 (image classes C, E, H), or be converted into pasture (image classes B, C, F).

The forest of land cover structure classes 1, 2, and 3 (image classes D and G) can either remain within those two image classes (with or without transitions between the forested land cover structure classes within these image classes), be cleared for cultivation (land cover structure class 14) and/or grass planting (image classes B, C, F) or be cleared and regenerate (with or without cultivation first) into land cover structure class 6A or 4 (image classes I, C, E, or H). 'New' forest can only result from regeneration of land cover structure class 5, i.e. from image classes C, E or H. BOSTOS simulations show that the sample should have been in land cover structure class 5 at least six years before it can regenerate to forest land cover structure class 2, i.e. it should have been in image classes C, E, or H at least six years before it can get into D or G again. (Note: image classes C, E and H also contain other land cover structure classes, so six years in image classes C, E or H does not mean automatically six years in land cover structure class 5.) The image classes C, E, and H can also be converted into pasture (image classes B, C, F). Pasture remains either as pasture or regenerates into land cover structure class 6B or 5 (image classes C, E, H).

Areas of dry or wet, natural grasslands (classes 12 and 13, respectively) are regarded as stable. Once their location and area are established, e.g. with ancillary data from the GIS already made for Guaviare (Martínez and Vanegas, 1994a,b), these areas can be masked and discounted from further classifications.

Cultivation of crops (class 14) can take place after any land cover structure class where total tree cover is over 45%; this means after the forest classes 1, 2 or 3, (image classes D or G), or on previously cleared land (image classes I and J). After cultivation, there can be a second cropping cycle (class 14), grass planting (class 7, 8, 9, 10 or 11), or the plot can be left to regenerate (class 6A).

When we applied this matrix to the results of the classifications of individual images or averages of three images, it turned out that many pasture samples, after having been classified as pasture first, were classified as secondary vegetation in later images. Presumably, this was due to an increase of backscatter caused by higher soil moisture or an increase of biomass and roughness of these pastures. Only a few of these pastures will really have been left to regenerate and develop secondary vegetation, since this is not common practice. A new change matrix was therefore made (see Figure 7.5) in which it was impossible for a sample classified earlier as pasture or (semi-) natural grassland to change into secondary vegetation. As settlement in the area only started in the 1950's, there can be very little secondary vegetation old enough to be classified as forest again, so changes from secondary vegetation to forest were also excluded in Figure 7.5.

	Image class second classification	J	I	H	G	F	E	D	C	B	A
Image class first classification	Corresp. Land cover structure class v >	15	6A	4, 5, 6B	1, 2, 3	7, 8, 9, 13	4, 5, 6B	1, 2, 3	4, 5, 6b, 7, 8, 9, 10, 11, 13	7, 8, 9, 10, 11, 12, 13	15
J	15	J	I	H	J	F	E	J	C	B	A
I	6A	J	I	H	I	F	E	I	C	B	A
H	4, 5, 6B	J	H	H	H	F	E	H	H	B	A
G	1, 2, 3	J	I	H	G	F	E	D	C	B	A
F	7, 8, 9, 13	J	F	F	F	F	F	F	F	B	A
E	4, 5, 6B	J	E	H	E	F	E	E	E	B	A
D	1, 2, 3	J	I	H	G	F	E	D	C	B	A
C	4, 5, 6b, 7, 8, 9, 10, 11, 13	J	C	H	C	F	E	C	C	B	A
B	7, 8, 9, 10, 11, 12, 13	J	B	B	B	F	B	B	B	B	A
A	15	J	I	H	A	F	E	A	C	B	A

Figure 7.5: Matrix of possible changes between image classes over a timespan of one year, corrected for additional conditions. The underlined occasions are unlikely transitions, where the original image class is maintained. For details: see text.

7.5. Application of decision rules based on the possibility of land cover change

In this section, the decision rules of the matrix of possible changes between image classes over a timespan of one year (Figure 7.5) will be applied to the classifications of Section 7.3, resulting in a classification based on the application of decision rules based on both image characteristics (Figure 7.1 or 7.3) and on knowledge of land cover changes (Figure 7.5). The results are shown in Tables 7.8—7.11. When comparing the classification result of the rules based on image characteristics (Tables 7.2—7.5) to image at $t = t_n$ and the classification result of the combination of these rules with those based on land cover change to all images between $t = t_0$ and $t = t_n$, the latter shows a better result for most classes.

However, the decrease in accuracy for classification of forest (land cover structure classes 1, 2 and 3) with time is dramatic and affects the overall classification result. An increasing number of forest-pixels was classified as non-forest. This was due to the fact that, with the rules as shown in Figure 7.5, if a forest is misclassified once as a pasture or secondary vegetation because the backscatter level is a little too low or too high, or the maximum difference in backscatter over three images is a little too large, it can never be classified as forest again, so the error propagates. This can be mitigated by adding the rule that a sample can still be (re-)classified as forest after it has been classified as non-forest for no more than one consecutive time. Adding this rule improves the classification accuracy of the forest, with very little effect on the accuracy of the classification of the other classes (see last columns of Tables 7.8—7.11), so the overall classification result after application of the rules based on land cover change is indeed better than without these rules. With the addition of the extra rule, the overall classification accuracy stabilizes at 74% for the training set and 69% for the control set.

Another possibility could be to add an extra image class K, containing a small range of backscatter values just outside the "forest" image classes D and G. If a sample is classified as D or G in image at $t = t_n$, and as K in image at $t = t_{n+1}$, it depends on image at $t = t_{n+2}$ what the final classification will be. If at $t = t_{n+2}$ the sample does not belong to D or G, the sample is considered non-forest since $t = t_{n+1}$, if at $t = t_{n+2}$ the sample is classified as D or G, it will be classified as forest on all three images.

The classification of secondary vegetation (land cover structure classes 4, 5, 6A, 6B) is hardly affected by the application of the rules based on land cover change. The classification result for pastures and for wet (semi-) natural grasslands increases by adding the rules based on land cover change. The classification result for dry (semi-) natural grasslands was hardly improved by adding these rules.

To summarize: application of the change matrix in Figure 7.5 increased the classification accuracy for pastures and (semi-) natural grasslands, at the expense of decreasing the classification accuracy for forest. This effect was mitigated by adding the rule that a sample can be classified as forest again if it has not been classified as non-forest for more than one consecutive time. Addition of this rule improves the classification accuracy for forest as well as the overall classification accuracy.

Classification accuracy first increases with the number of images and then stabilizes, with slight variations. Images that showed lower classification accuracy for the rules based on image characteristics (e.g. images 8 and 9) can cause a small temporary drop in accuracy. It is probable that the moisture content of the topsoil was high when these images were recorded. No weather data were available for the days before July 10, 1994, when image 8 was recorded. On September 3, 1994, 2 mm of rain was recorded at the El Trueno station (just north of El Retorno). It did not rain at this station on September 4 or September 5, 1994, when image 9 was recorded. An increase in the humidity of the topsoil causes an increase in the backscatter level of the land cover structure classes with low biomass, because of a larger contribution by the topsoil to the total backscatter. For the land cover structure classes with high biomass, the backscatter remains fairly stable because of the relatively small contribution by the topsoil to the total backscatter level. The total effect is a decrease in contrast between the land cover structure classes.

7.7. Application of the decision rules to the images

The decision rules based on image characteristics (Section 7.2) and those based on land cover change (Section 7.4) have been applied to the field data set comprising the two subsets of training and control samples, in Sections 7.3 and 7.5. For these samples, plots were delineated with polygons on the images. The same set of polygons was used for all images to extract the image characteristics for the samples.

The procedure was: images are segmented. Segments are filled with average σ^0 per segment. Maximum difference of σ^0 over time is calculated per pixel over three subsequent segmented images. Individual segmented images are classified per pixel with the rules based on the average σ^0 per segment and the maximum difference in σ^0 over three subsequent images: the image to be classified and the two previous images, as shown in Figure 7.1. For the classification of images 1, 2 and 3, the same maximum differences have been used, namely those over these three images.

For the application of the rules based on the average σ^0 per segment over three subsequent images and the maximum difference in σ^0 over the same three images, as shown in Figure 7.3, the three subsequent segmented images are averaged on a per pixel basis. Maximum difference of σ^0 with time is calculated per pixel over the same three segmented images. After classification per image (according to Figure 7.1) or per average of three images (according to Figure 7.3), the decision rules based on land cover change, as shown in the matrix of Figure 7.5, are applied, with the adaptation that at least two consecutive "non-forest" classifications are needed before a pixel cannot be classified as forest again (see Section 7.5).

The procedure is illustrated for two areas of 7.5 x 7.5 km in Figures 7.6—7.13. The first area is on the edge of primary forest, where land cover is changing rapidly. The second area is along the main road where land cover is practically stable. For each area, first the 1992 color composite is shown (detail of Figure 5.1), followed by the results of segmentation and application of the decision rules based on image characteristics (per image and per average of three images) and based on land cover change. For comparison, the AIRSAR images of 31 May 1993 are shown (Figures 7.9 and 7.13). Different land cover types can be distinguished well in these images (Quiñones 1995).

For both examples, the area classified as secondary vegetation by the combination of the rules based on the averages of three images (Figure 7.3) with the rules based on land cover change (Figure 7.5) is far too large, mainly at the expense of the area under pasture. When using the AIRSAR images as a reference, the combination of the rules for individual, segmented images (Figure 7.1) followed by application of the rules based on land cover change (Figure 7.5) gives better classification results. Although the increase in accuracy between using only rules based on image characteristics or a combination of rules based on image characteristics and on land cover change was only small for the training and control sets, the increase in accuracy in the classification of the images is very evident.

A horizontal line can be seen in the segmented images; this is an artefact. The image was too large for the segmentation algorithm to be segmented as a whole. It was therefore divided into smaller parts that were segmented separately and re-joined before classification. The artefact disappears almost completely in the classification, as can be seen in Figures 7.7 and 7.8.

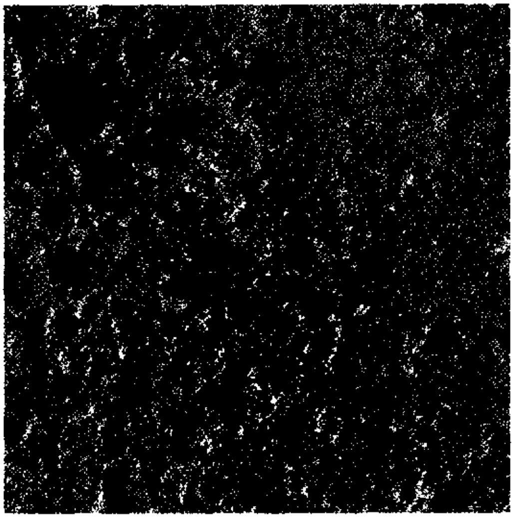


Figure 7.6: Forest edge.
Detail of color composite of three ERS-1 images of 1992. Red: image 22-12-1992; green: image 04-08-1992; blue: image 26-05-1992. The size of the area is 7.5 x 7.5 km.

Figure 7.7.a, b, c (pages 142, 143 and 144): Forest edge. Application of the rules based on image characteristics for individual images (Figure 7.1) and the rules based on land cover change (Figure 7.5 with adaptation for reclassification as forest). The first row shows the same subsection for the nine segmented images. The gray tones indicate the average backscatter level per segment, with lighter shades for higher backscatter levels. The second row shows the classification result with the rules based on image characteristics (Figure 7.1). The third row shows the result after also applying the rules based on land cover change (Figure 7.5, adapted). The size of the area is 7.5 x 7.5 km.

Figure 7.8.a, b (pages 145 and 146): Forest edge. Application of the rules based on image characteristics for averages of three images (Figure 7.3) and the rules based on land cover change (Figure 7.5 with adaptation for reclassification as forest). The first row shows the same subsection for the seven averages of three subsequent segmented images. The gray tones indicate the average backscatter level per segment, with lighter shades for higher backscatter levels. The second row shows the classification result with the rules based on image characteristics (Figure 7.3). The third row shows the result after also applying the rules based on land cover change (Figure 7.5, adapted). The size of the area is 7.5 x 7.5 km.

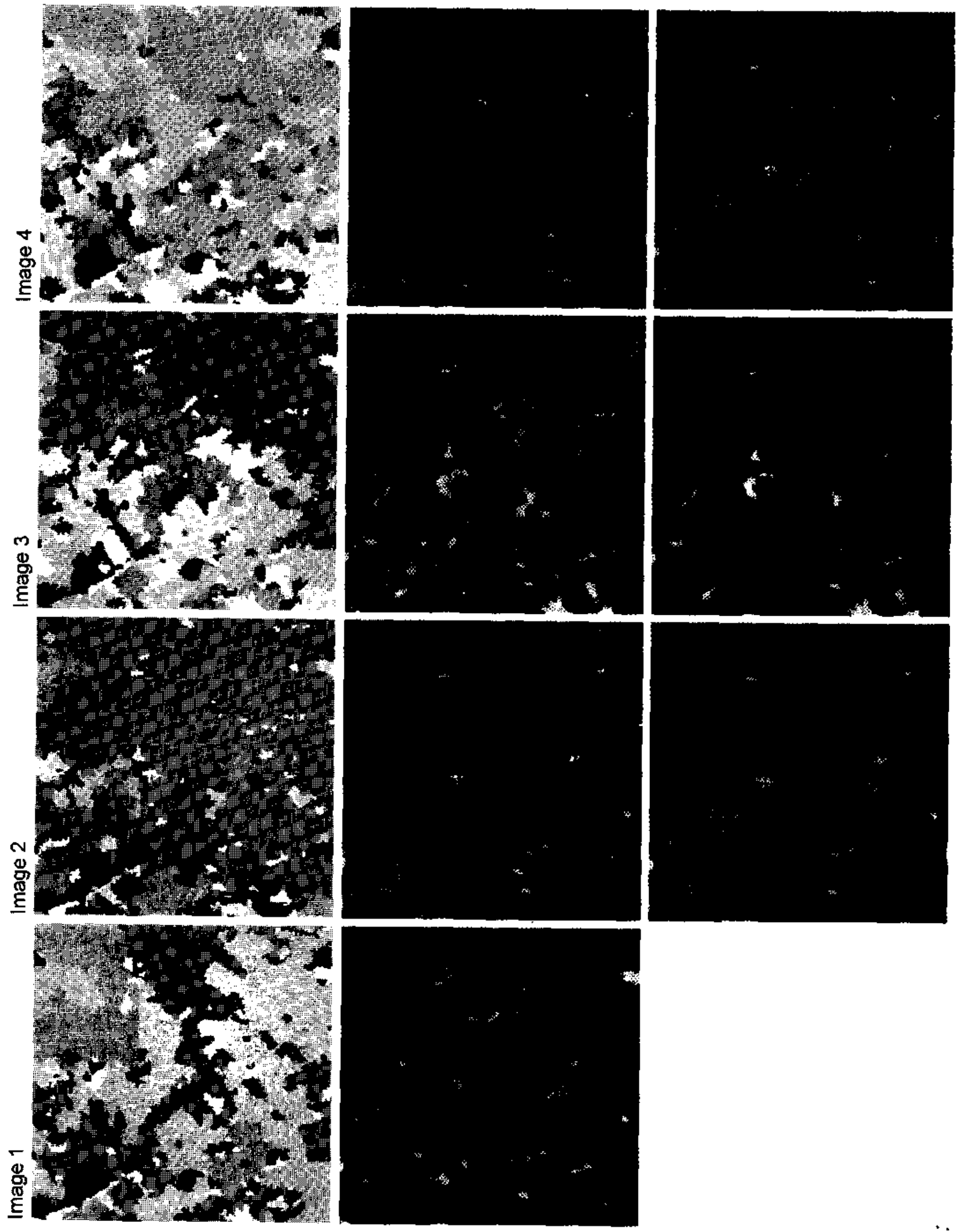


Figure 7.7.a:

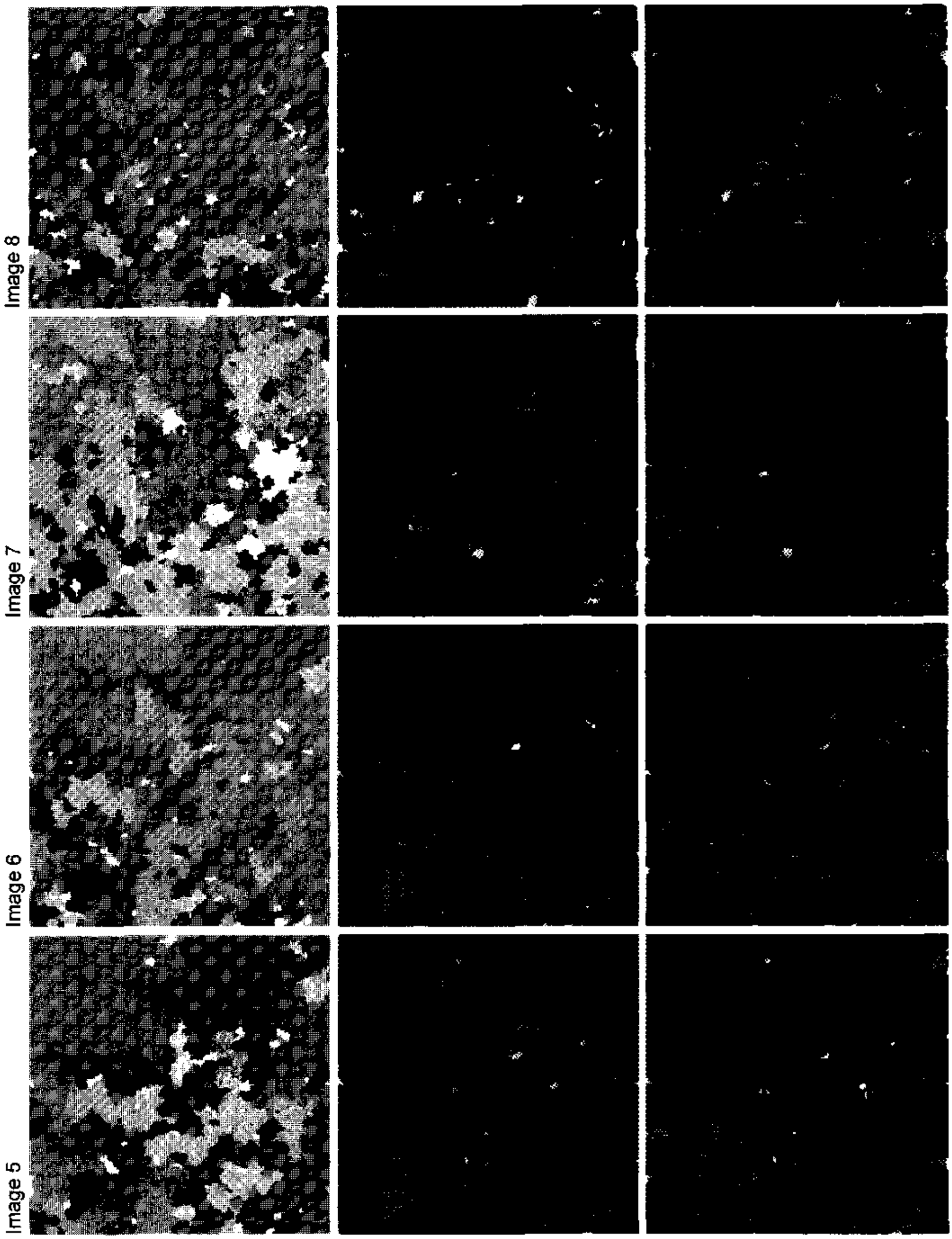


Figure 7.7.b:

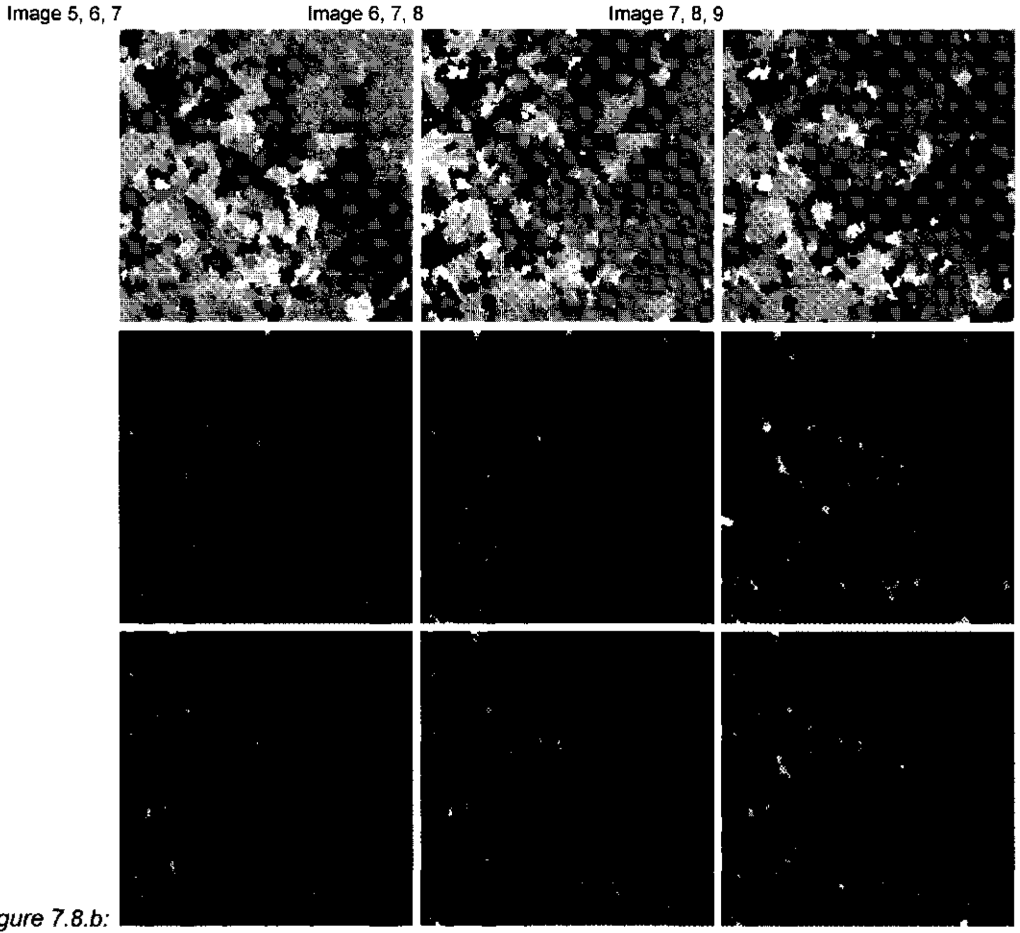


Figure 7.8.b:

Legend figure 7.8.a, b

Top row: segmented images
Middle row: classification with the decision tree of Figure 7.3

Bottom row: classification with the decision tree of Figure 7.3 and the change matrix of Figure 7.5 with adaptation for reclassification as forest

LAND COVER CLASSES

- ■ Primary forest
- ■ Secondary vegetation
- ▨ Secondary vegetation with *Cecropia spp.*
- ■ Pasture
- ■ Pasture and secondary vegetation
- ■ Miscellaneous

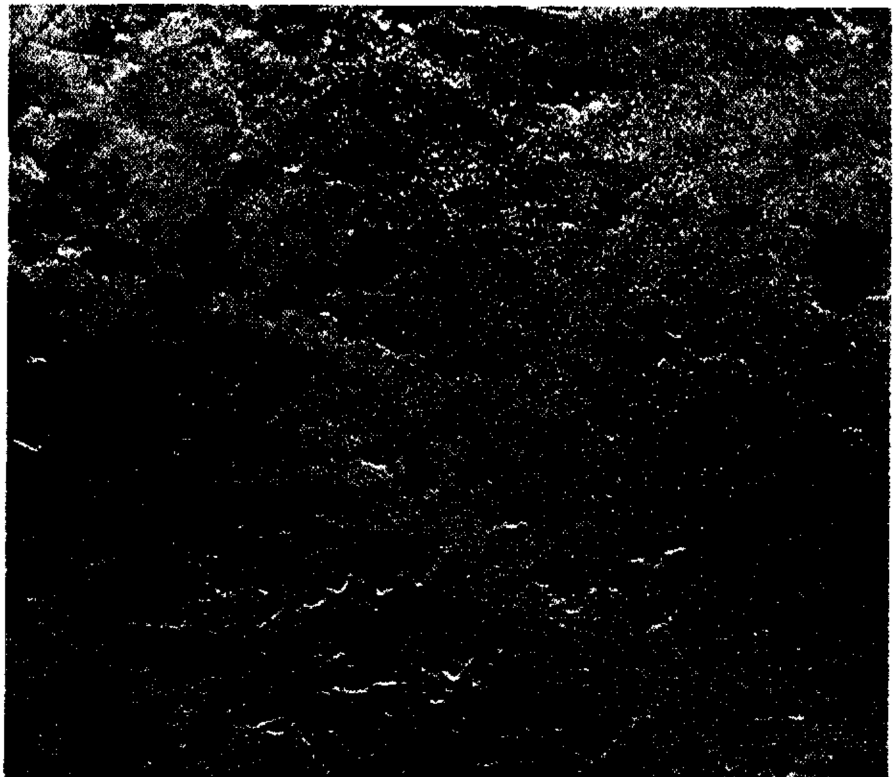


Figure 7.9: Forest edge (area slightly larger than in Figures 7.6, 7.7 and 7.8). Full power AIRSAR image of the 31 May 1993. Red: P-band; green: L-band, blue: C-band. The primary forest appears in light red, pastures in dark and medium blue, secondary vegetation in turquoise tones. The forest has been removed recently in the small, intense red areas.

Figure 7.10: Main road. Detail of color composite of three ERS-1 images of 1992. Red: image 22-12-1992; green: image 04-08-1992; blue: image 26-05-1992. The size of the area is 7.5 x 7.5 km.

Figure 7.11.a, b, c (pages 149, 150, 151): Main road. Application of the rules based on image characteristics for individual images (Figure 7.1) and the rules based on land cover change (Figure 7.5 with adaptation for reclassification as forest). The first row shows the same subsection for the nine segmented images. The gray tones indicate the average backscatter level per segment, with lighter shades for higher backscatter levels. The second row shows the classification result with the rules based on image characteristics (Figure 7.1). The third row shows the result after also applying the rules based on land cover change (Figure 7.5, adapted). The size of the area is 7.5 x 7.5 km.

Figure 7.12.a, b (pages 152, 153): Main road. Application of the rules based on image characteristics for averages of three images (Figure 7.3) and the rules based on land cover change (Figure 7.5 with adaptation for reclassification as forest). The first row shows the same subsection for the seven averages of three subsequent segmented images. The gray tones indicate the average backscatter level per segment, with lighter shades for higher backscatter levels. The second row shows the classification result with the rules based on image characteristics (Figure 7.3). The third row shows the result after also applying the rules based on land cover change (Figure 7.5, adapted). The size of the area is 7.5 x 7.5 km.

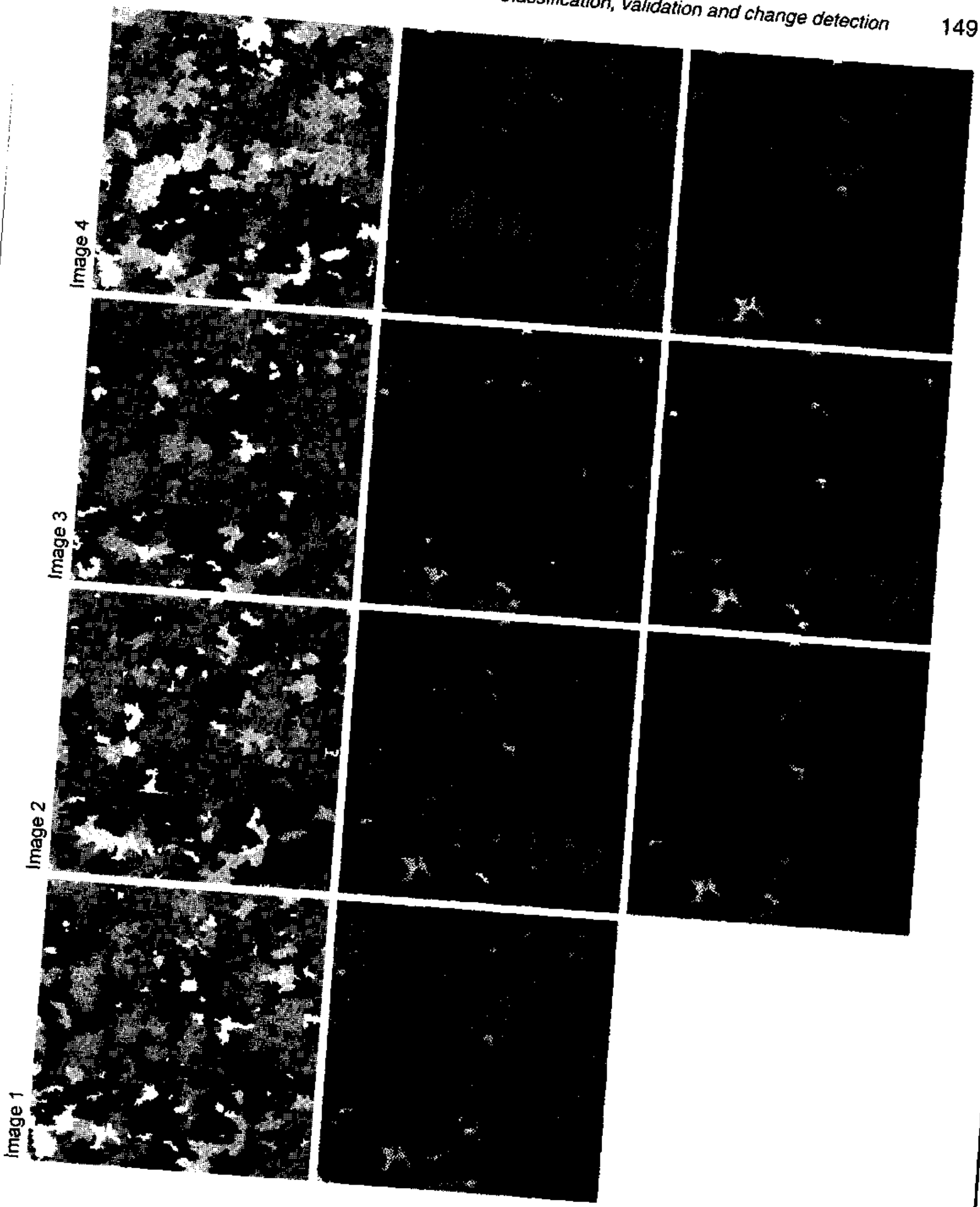


Figure 7.11.a:

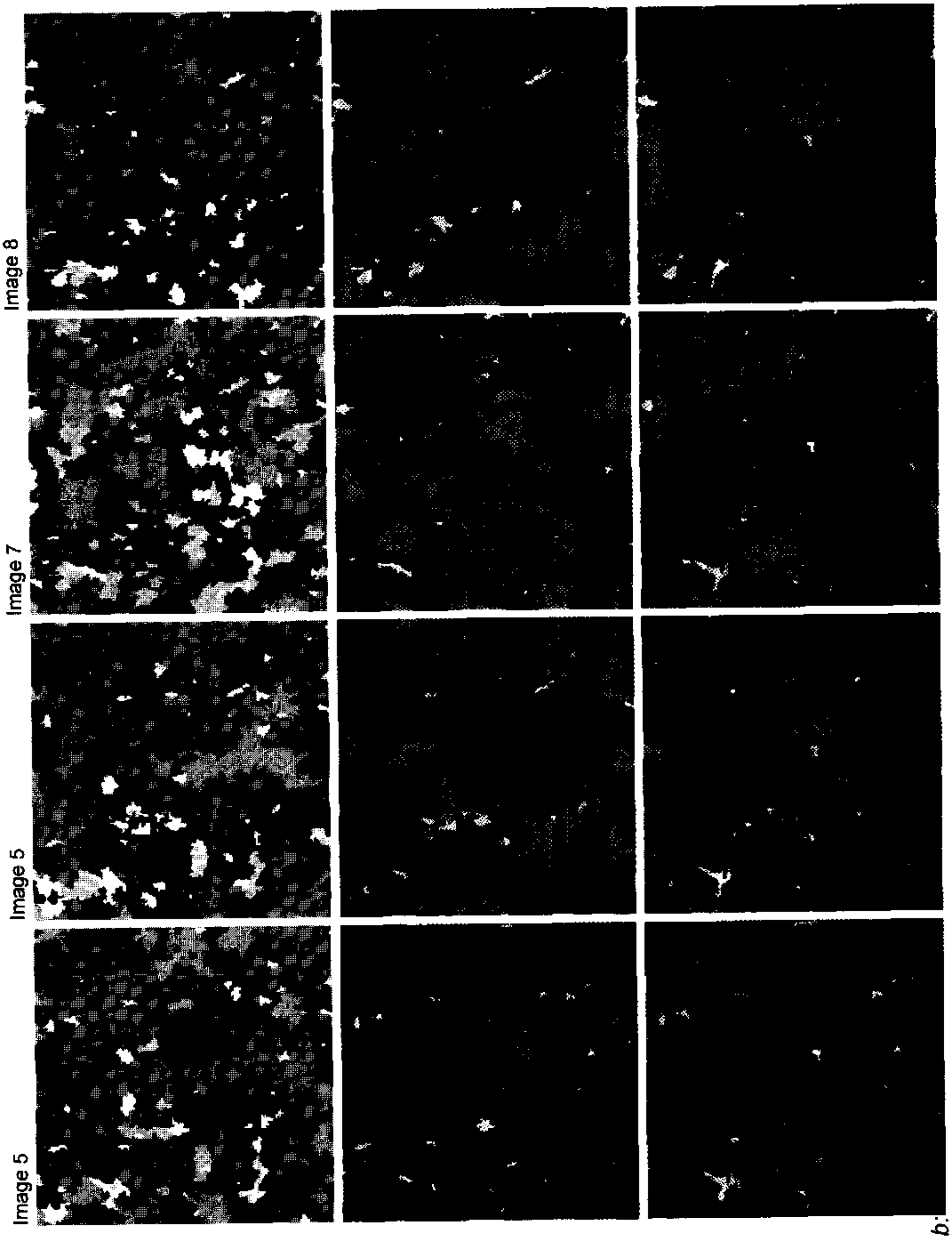


Figure 7.11.b:

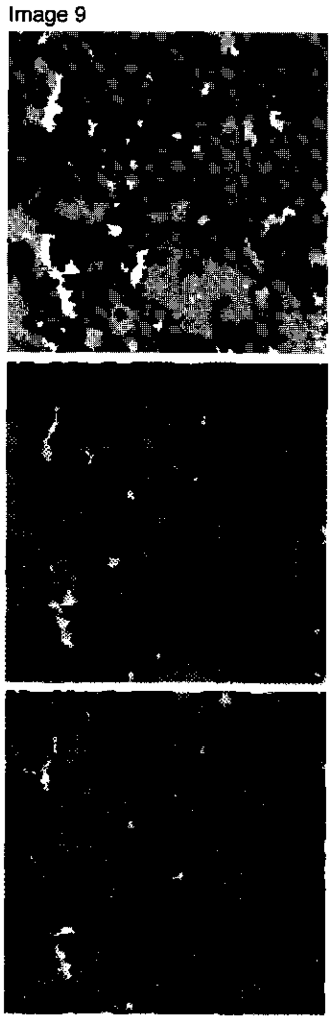


Figure 7.11.c:

Legend figure 7.11.a, b, c

Top row: segmented images
Middle row: classification with the decision tree of Figure 7.1

Bottom row: classification with the decision tree of Figure 7.1 and the change matrix of Figure 7.5 with adaptation for reclassification as forest

LAND COVER CLASSES

- ■ Primary forest
- ■ Secondary vegetation
- ░ Secondary vegetation with *Cecropia spp.*
- ■ Pasture
- ▓ Pasture and secondary vegetation
- ■ Miscellaneous

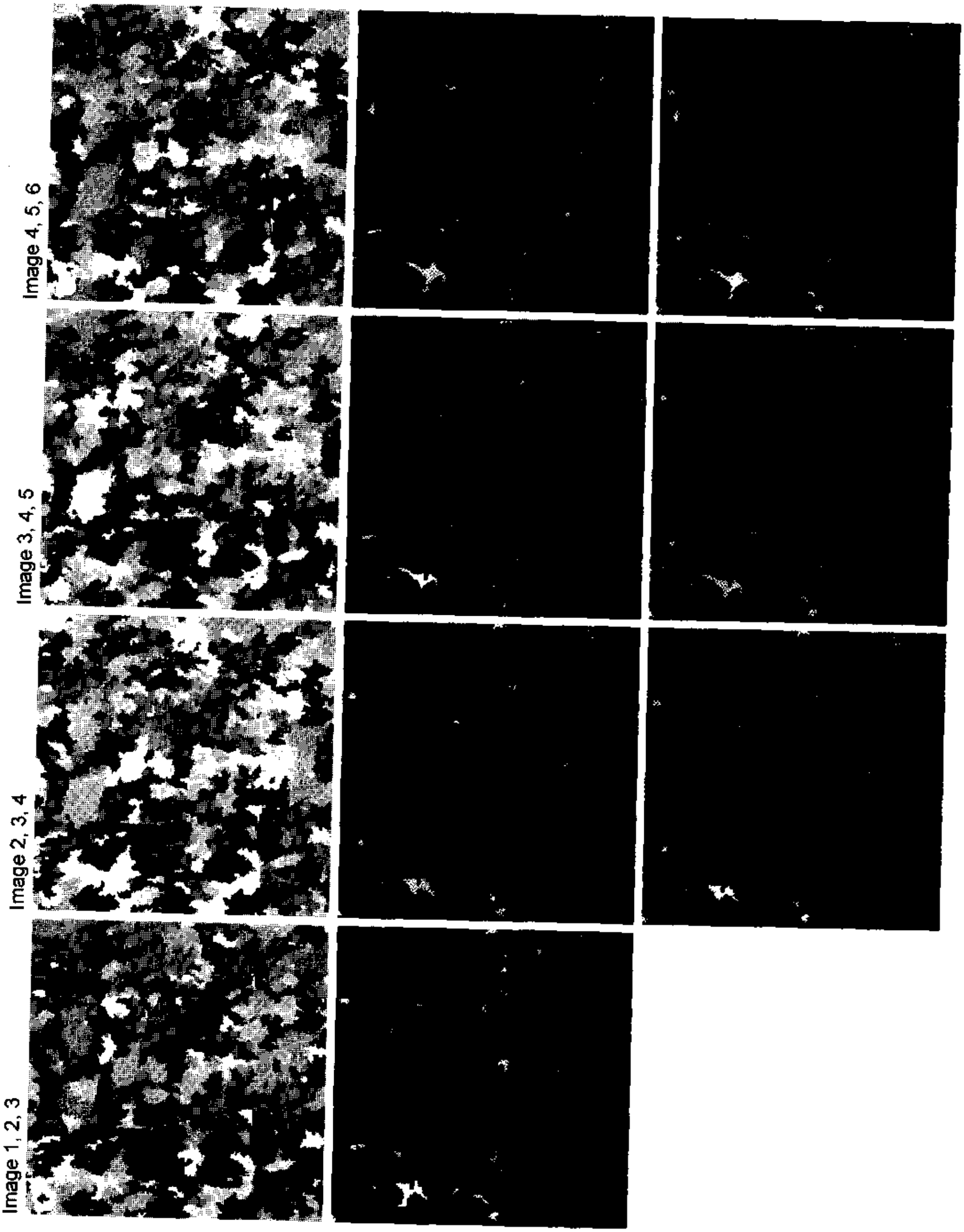


Figure 7.12.a:

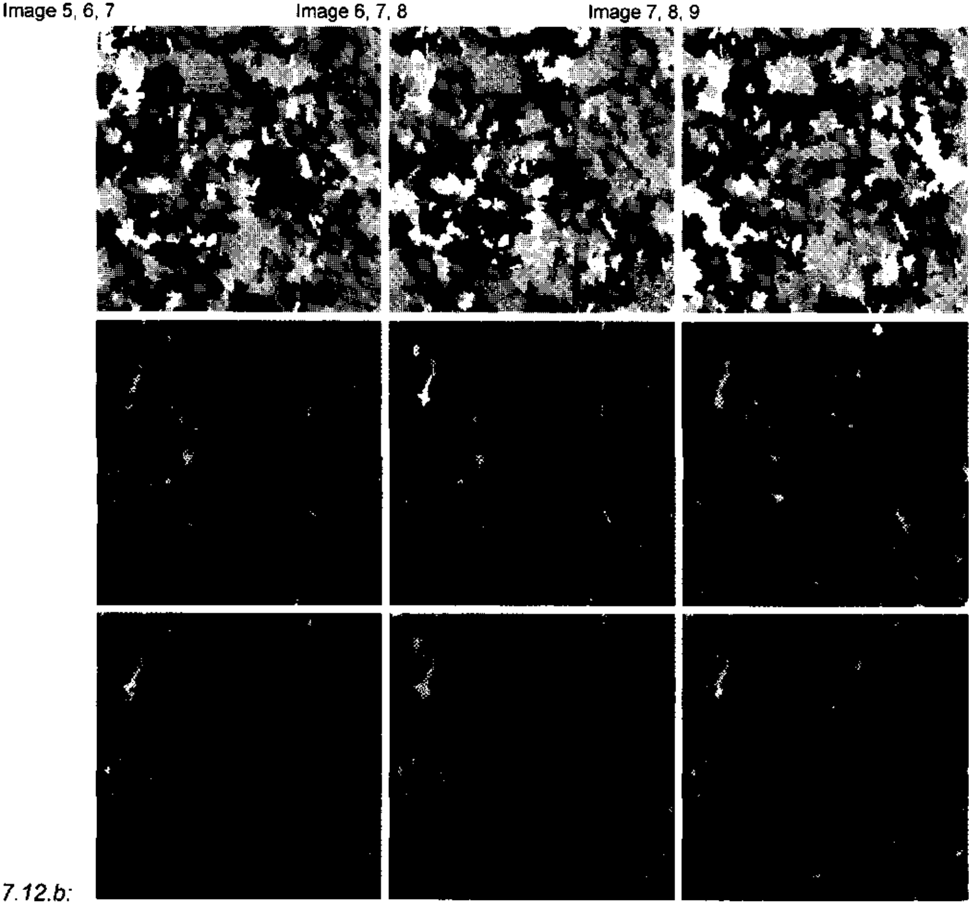


Figure 7.12.b:

Legend figure 7.12.a, b

Top row: segmented images
Middle row: classification with
the decision tree of Figure 7.3

Bottom row: classification with
the decision tree of Figure 7.3
and the change matrix of Figure 7.5
with adaptation for reclassification
as forest

LAND COVER CLASSES

- ■ Primary forest
- ■ Secondary vegetation
- ▨ Secondary vegetation with *Cecropia spp.*
- ■ Pasture
- ■ Pasture and secondary vegetation
- ■ Miscellaneous

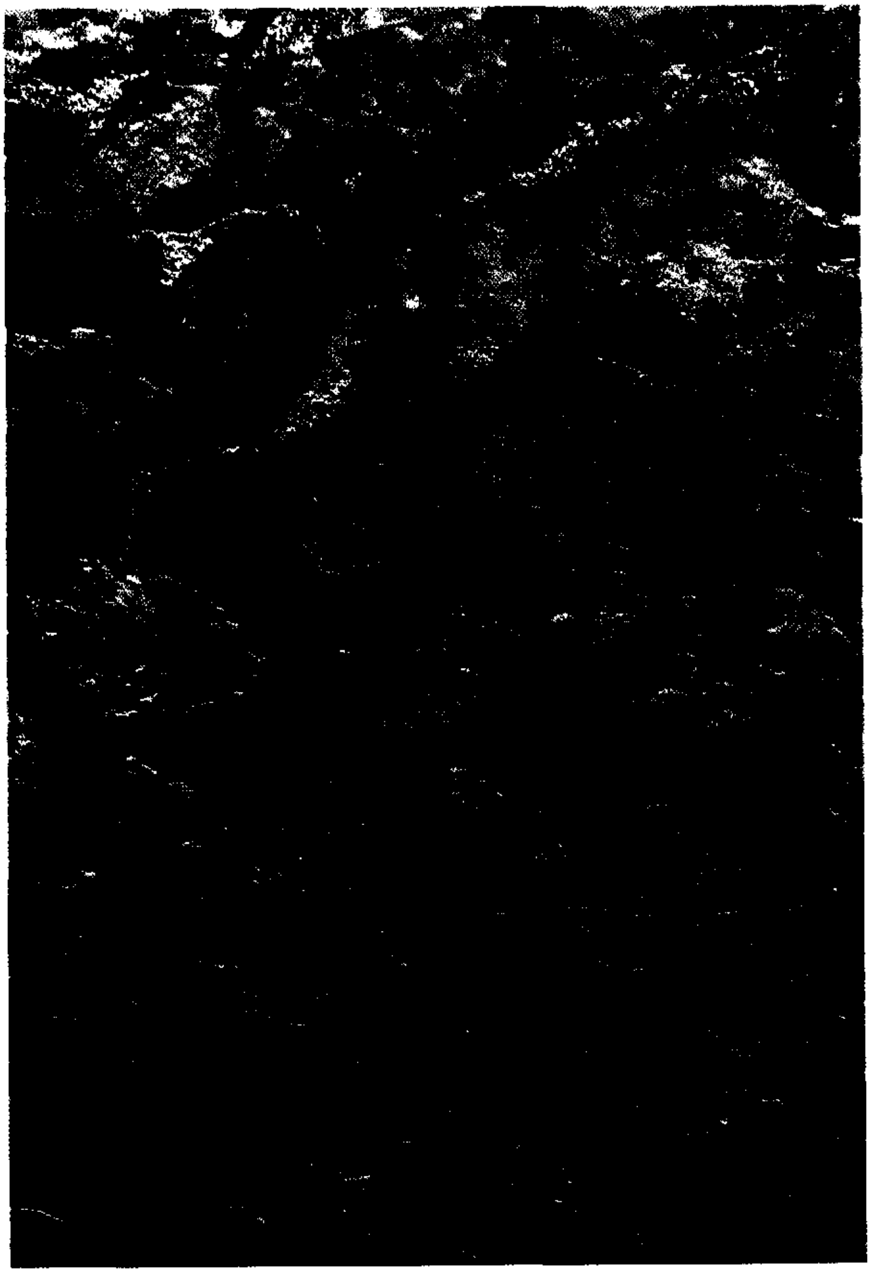


Figure 7.13: Main road (same area as in Figures 7.9, 7.10 and 7.11). Full power AIRSAR image of the 31 May 1993. Red: P-band; green: L-band, blue: C-band. The size of the area is 7.5 x 7.5 km. The primary forest appears in light red, pastures in dark and medium blue, secondary vegetation in turquoise tones. The forest has been removed recently in the small, intense red areas.

7.8. Discussion and conclusions

An overview of the results of the classifications of the samples of the training and control sets, carried out in the previous sections, is given in Tables 7.13 and 7.14. As can be seen from these tables, the overall classification accuracies vary roughly between 60% and 70%. For both training and control sets, classification of individual segmented images gives a more accurate result than classification of averages of three segmented images, for classification with one set as well as with a combination of both sets of decision rules. Classification of individual segmented images with rules based on image characteristics shows better results than classification with a Maximum Likelihood classifier, although for classification of averages of three images, the results with a Maximum Likelihood classifier are better. Classification with both sets of decision rules, i.e. those based on image characteristics and those based on land cover change, shows the highest overall classification accuracy.

When applied to the training and control sets, the addition of rules based on land cover change to the classification shows an increase in accuracy of just a few percent, which might not be considered very impressive because of the small sample set. However, visual comparison of the classification of the segmented images with the AIRSAR images, as presented in the previous section, easily reveals that the increment in accuracy after application of the second set of rules, based on land cover change, is quite large.

The accuracy of the classification with rules based on image characteristics varies. Apparently this is due to the field conditions at the moment the image was recorded. If an image is recorded under wet conditions, the moisture content of the topsoil causes an increase in backscatter of vegetation with low biomass, like pastures. The (higher) backscatter of vegetation with high biomass, like forests, does not show such an increase, resulting in a decrease of contrast between land cover types in the image. If subsequent images are recorded under similar conditions, differences in backscatter level for the same pixel over these images will be small, irrespective of the land cover type, thus making the criteria based on differences in backscatter level over subsequent images less useful for classification. So both wet conditions during recording of the image as well as recording of subsequent images under similar conditions can have a negative effect on the accuracy of classification with rules based on image characteristics. After application of the rules based on land cover change, classification accuracy varies less over the images and varies around a higher level (i.e. there is a higher overall accuracy).

Classification and especially change detection can be improved by a better knowledge of the initial situation, as classifications of images are partly based upon knowledge of the previous situation. Better knowledge of the initial situation can be acquired from additional imagery (SPOT, JERS-1 aerial photographs, high resolution airborne radar) or field surveys. At regular time intervals, the classification and change detection as performed by the monitoring system, based on ERS images, has to be checked thoroughly for a sample of the plots in the area, in order to calibrate the system, adapt the decision rules if necessary and prevent errors from propagating. This regular checking, calibrating and updating is very important as new classifications are partly based upon previous classifications.

This study has not attempted integration with other sources of remote sensing data because techniques for image fusion were scarce at the start of the study and development of these techniques was outside the scope of this thesis. Recent studies on image fusion have shown that a combination of ERS-1 with optical data (Landsat-TM or SPOT) gives better results than each of the images on its own. As fusion techniques have been developed in the past few years, additional use of other images in the system is not expected to cause major difficulties, although the classification algorithms will have to be extended.

Classification accuracy not only varies with the images, it also varies with the landscape, land cover class and the size and shape of the plots. Steeply dissected areas are classified less accurately than flat terrain; classification of pastures is more accurate than of secondary vegetation, and small, elongate or irregularly shaped plots are classified less accurately than large, square ones.

Relative accuracies can be shifted to suit the objective of the system's user. If the error of misclassifying a forest as a pasture is less important for the user than the error of misclassifying a pasture as a forest, rules can be adapted in such a way that the risk of misclassifying a pasture as a forest is minimized at the expense of increasing the chance of misclassifying forest as pasture.

One of the changes in land cover that is important for land use planning in Guaviare is the degradation of pastures, characterized by soil compaction, loss of nutrients, increase of the percentage of bare soil, and increase in the cover of toxic or unpalatable plants (Martinez, 1992). With the current system, it is not possible to monitor this type of degradation, although if the pasture is planted within the time covered by monitoring, it is possible to assess the age of the pasture and this can give an indication of the amount of degradation to be expected.

Table 7.13: ***Overview of the classification results.*** *Percentage of samples of the* ***training set*** *classified correctly with the decision rules based on image characteristics for* ***individual images*** *(Figure 7.1), decision rules based on image characteristics for* ***averages of three images*** *(Figure 7.3), decision rules based on image characteristics for* ***averages of nine images*** *(Figure 7.2) and combinations of these rules with the rules based on land cover change (Figure 7.5 with adaptation for reclassification as forest as described in Section 7.5).*

Land cover structure class	Total number of samples	Percentage of samples classified correctly per land cover structure class				
		Rules based on image characteristics Average classification result per image or averaged images.			Rules based on image characteristics and land cover change. Result after 9 images	
		Individual images Fig. 7.1	Averages of 3 images, Fig 7.3	Averages of 9 images, Fig. 7.2	Individual images Fig. 7.1 + 7.5	Averages of 3 images Fig. 7.3 + 7.5
1	4	64	57	50	25	25
2	10	91	89	90	80	80
3	4	81	64	50	75	50
4	4	42	64	75	50	75
5	5	49	57	80	40	40
6B	3	30	38	33	0	0
6A	2	50	64	100	50	50
7	9	65	43	67	78	78
8	14	83	71	86	100	93
9	2	56	64	100	100	100
10	3	93	95	100	100	100
11	2	83	50	100	50	50
12	3	100	100	100	100	100
13	3	56	52	67	100	100
Total	68	71	66	78	74	72

SAMENVATTING

Inleiding

Inventarisaties van de toestand van het bos in de wereld laten een snelle achteruitgang zien van zowel het totale met bos bedekte areaal als een degradatie van het overgebleven bos. Dit feit, in combinatie met een groeiende bewustwording van de belangrijke en onvervangbare functies van deze bossen voor de lokale bevolking en de wereldgemeenschap, heeft het lot van de bossen op de internationale agenda geplaatst. De meeste aandacht is gericht op het snelle verdwijnen van tropische regenwouden, maar ontbossing is ook een probleem op hogere breedtegraden. Inspanningen om de kaalkap van tropisch regenwoud in te perken en te reguleren hadden vaak niet het gewenste effect, niet alleen door de complexiteit van de sociale, economische en politieke factoren die de drijvende krachten vormen achter ontbossing, maar ook door het gebrek aan actuele informatie over de plaats, omvang en snelheid van het proces. Voor een verstandig en duurzaam gebruik van het bos hebben de verantwoordelijke autoriteiten behoefte aan tijdige informatie over de actuele toestand van het bos en de veranderingen die plaatsvinden, voor het plannen van hun regelgeving en voor het monitoren van de effecten. Tot nog toe leverden wereldwijde monitoring inspanningen, zoals die van FRA/TFAP en TREES, geen informatie met voldoende ruimtelijk en thematisch detail voor het lokale bosbeheer. Daarom is er *behoefte aan een systeem voor het monitoren van tropisch regenwoud op een lokale of* regionale schaal. Omdat uitgebreid verzamelen van veldgegevens in de meeste bosgebieden niet mogelijk is vanwege de slechte toegankelijkheid, kan het gebruik van remote sensing, met name radar met zijn toepasbaarheid onder alle weersomstandigheden, een bruikbare oplossing bieden voor kartering en monitoring.

Het gebied van San José del Guaviare, in de Colombiaanse Amazone, werd uitgezocht als geschikt testgebied voor het ontwikkelen van een dergelijk monitoringsysteem. De geologie, bodem en vegetatie van het studiegebied zijn in het laatste decennium bestudeerd. De sociale en economische geschiedenis en de geschiedenis van het landgebruik zijn ook bekend uit eerdere studies. De landbedekking in het gebied is erg dynamisch door de migratie naar het gebied. Daardoor kon verwacht worden dat er genoeg veranderingen zouden zijn in de paar jaar tijd dat het project duurt om de mogelijkheden van het systeem om veranderingen in landbedekking te ontdekken uit te kunnen testen. Eveneens was er vanuit IGAC, COA en Tropenbos een grote interesse om een testproject te hebben in dit gebied.

Beschrijving van het gebied

Het studiegebied ligt aan de noordelijke rand van het Departement Guaviare, tussen 2°35' en 2°20' N en72°47' en 72°35' W. San José, de hoofdstad van het departement, ligt aan de Guaviare rivier. Het gebied heeft een tropisch seizoensklimaat. Het gebied kan worden verdeeld in twee geologische landschapseenheden: het hoogland of *tierra firme* en de alluviale vlakte of *vega*. De *tierra firme* bestaat uit een golvende erosievlakte, de "Plio-

Pleistocene versneden vlakte van de Amazone", gevormd in uitgebreide en heterogene afzettingen uit het Boven-Tertiair, en uit Paleozoïsche kwartsiet zandsteen mesas of cuestas, en Paleozoïsche nephelien-syeniet rotsen. De *vega* bestaat uit kwartaire rivier terrassen en riviervlaktes. Karakteristiek voor de bodems in de "Plio-Pleistocene versneden vlakte van de Amazone" zijn een lage bodemvruchtbaarheid en een hoge aluminiumverzadiging. Een laag laterietgrind nabij het oppervlak komt vaak voor op de toppen en het bovenste deel van de hellingen. De bodemtextuur is variabel. De zandsteen cuestas zijn grotendeels bedekt met bodems met een grove textuur en een lage bodemvruchtbaarheid. In het moedermateriaal van de nephelien syeniet rotsen hebben zich bodems ontwikkeld met een fijnere textuur en een hogere bodemvruchtbaarheid. De bodems in de alluviale vlakte hebben een wisselende textuur, terwijl de bodemvruchtbaarheid afhangt van de oorsprong van de sedimenten.

De trek van mensen uit andere regio's van Colombia naar het Guaviare gebied werd voornamelijk veroorzaakt door geweld en door het systeem van landeigendomsrecht in de Andes regio, dat de concentratie van landeigendom bevordert. Eerst was de migratie naar de regio Guaviare spontaan, later werd deze ondersteund door de regering. Oorspronkelijk was het gebied grotendeels bedekt met niet-bladverliezend tropisch bos. Een groot deel van het bos is gekapt en vervangen door graslanden, landbouwgewassen, of secundaire vegetatie. Het overgebleven bos is gedeeltelijk verstoord door de selectieve kap van grote, waardevolle bomen. De zandsteen cuestas zijn bedekt met een grassavanne met lage bomen.

Veeteelt is nu het meest voorkomende landgebruik in het hele *tierra firme* gebied. In de gebieden met natuurlijke savannes is de veeteelt extensiever dan in andere delen van de *tierra firme*. Na het kappen en branden van het primaire bos in de Plio-Pleistocene versneden vlakte van de Amazone worden eenjarige of meerjarige landbouwgewassen geplant. Meer permanente gewassen, zoals rubber, fruitbomen, suikerriet en coca, zijn te vinden in een veel kleiner gebied. Het aantal jaren dat een veld wordt gebruikt voor landbouwgewassen varieert, maar na enige tijd zal het of braak komen te liggen, zodat zich secundair bos ontwikkelt, of met gras worden beplant. Eenmaal beplant met gras blijft een veld gewoonlijk weiland, hoewel dit kan degraderen wanneer het boerenbedrijf verlaten wordt. De verbouw van gewassen is het belangrijkste landgebruik in de alluviale vlakte, hoewel er ook begrazing voorkomt.

Algemene beschrijving van het monitoringsysteem

Het monitoringsysteem dat hier gepresenteerd wordt, is gebaseerd op radarbeelden van de ERS-1 en -2 satellieten. Het systeem heeft een generische structuur, hetgeen het geschikt maakt voor toepassing in een groot scala aan gebieden door slechts een paar parameters bij te stellen of hoogstens door een paar specifieke componenten te vervangen. Binnen het systeem worden beelden verwerkt met behulp van formele regels en classificaties van eerdere beelden. Deze regels zijn gebaseerd op de relatie tussen beeldkenmerken en structuur van de landbedekking en op kennis van het veranderingsproces van de landbedekking, geformaliseerd in modellen. De resultaten van de classificatie worden geëxporteerd naar een Geografisch Informatie Systeem (GIS) voor uitvoer op het gebied van landbedekking en veranderingen in de landbedekking. Het systeem als geheel, de modellen en de classificatie van de beelden, worden gevalideerd met veldwaarnemingen, andere remote sensing data of nieuwe modellen. Na validatie kan het systeem worden verbeterd en kan het systeem een iteratieproces ondergaan waarin ook eerdere classificaties betrokken zijn.

Algemene aanpak van de ontwikkeling van beslisregels

In het veld worden data verzameld van de structuur van de vegetatie. Deze structuur wordt beschreven als het bedekkingspercentage van groene biomassa binnen een aantal horizontale strata, de aanwezigheid van bepaalde structuurgroepen van planten, zoals palmen, epifyten, stam *Musaceae* en klimplanten en lianen, en de bedekkingspercentages van kale bodem en dood hout. Deze gegevens worden geclusterd om typerende structuurklassen te vinden. Uit de satellietbeelden worden beeldkenmerken geëxtraheerd voor iedere veldwaarneming en de relatie tussen de landbedekkingsstructuurklassen en de beeldkenmerken wordt vastgesteld. Deze relatie kan geformaliseerd worden in regels die gebruikt worden in beeldclassificatie.

Multi-temporele gegevens van de landbedekking worden geanalyseerd om het proces van de verandering van de landbedekking te begrijpen. Deze gegevens en informatie uit de literatuur worden gebruikt om een model te ontwikkelen van het veranderingsproces van de landbedekking, dat in staat is om mogelijke veranderingen in de landbedekking te berekenen. Uit de resultaten van het model kan een tweede set formele regels geformuleerd worden, gebaseerd op mogelijke veranderingen in de landbedekking en deze set kan ook gebruikt worden in de beeldclassificatie.

Met een segmentatie-algoritme worden de satellietbeelden gesegmenteerd. Deze gesegmenteerde beelden worden geclassificeerd met gebruikmaking van beide sets regels: degene die zijn gebaseerd op beeldkenmerken en degene die zijn gebaseerd op de mogelijke veranderingen in de landbedekking.

Analyse van de gegevens van Guaviare

Voor de Guaviare regio resulteerde het clusteren van de in het veld verzamelde gegevens van vegetatiestructuur in elf vegetatiestructuurclusters. Deze werden gebruikt om zeven brede, a priori landbedekkingsklassen (ook wel gebruikersklassen genoemd) onder te verdelen in dertien landbedekkingsstructuurklassen. Clustering was gebaseerd op de bedekkingspercentages van groene vegetatie in de strata: hoge bomen, middelhoge bomen, lage bomen, struiken, hoge grassen, lage grassen en kruiden. De aanwezigheid van palmen, epifyten, stam *Musaceae* en klimplanten en lianen, of de bedekkingspercentages van dood hout en kale grond hadden weinig of geen invloed op de clustering van deze set gegevens. Een beslisboom werd gemaakt om nieuwe vegetatiegegevens uit het veld, evenals de uitkomst van het model van de verandering van de landbedekking te classificeren in landbedekkingsstructuurklassen op basis van de bedekkingspercentages in van te voren gedefinieerde strata.

Er waren negen ERS-1 beelden tussen 1992 en 1994 beschikbaar van het studiegebied. Op de beelden werden de veldwaarnemingen omlijnd met polygonen en twee beeldkenmerken werden geëxtraheerd: de gemiddelde backscatter per polygoon en het maximale verschil in deze gemiddelde backscatter over drie opeenvolgende beelden. Deze twee beeldkenmerken werden gerelateerd aan landbedekkingsstructuurklassen. Simulatie van het niveau en de variatie van de backscatter van de verschillende landbedekkingsstructuurklassen met het theoretische model UTACAN bevestigde de experimentele bevindingen.

De multi-kanaal versie van het RCSEG algoritme, gebaseerd op de detectie van grenzen- en segmentgroei, werd gebruikt voor het segmenteren van beelden voorafgaand aan de classificatie. Beelden uit hetzelfde jaar werden als verschillende kanalen samen gesegmenteerd. Segmentatieresultaten lieten veel variatie zien, maar het classificatieresultaat was stabieler, omdat verschillende segmenten in dezelfde landbedekkingsstructuurklasse geclassificeerd werden.

Veranderingsmodellen

De analyse van de veldwaarnemingen van verschillende jaren en de informatie uit andere studies zijn gebruikt om het proces van verandering van de landbedekking te modelleren in het BOSTOS model. BOSTOS berekent mogelijke veranderingen in de vegetatiestructuur, uitgedrukt in bedekkingspercentages van groene vegetatie in van te voren gedefinieerde strata, alsmede de hoeveelheid dood hout. Verschillende scenario's met variërende managementingrepen kunnen doorgerekend worden om de mogelijke veranderingen tussen landbedekkingsstructuurklassen te berekenen. Niet alle mogelijke veranderingen tussen landbedekkingsstructuurklassen kunnen al helemaal beschreven worden. Verdere ontwikkeling en verbetering van het BOSTOS model zou zich kunnen toespitsen op twee aspecten: verbetering van de nauwkeurigheid van de schattingen van de parameters en constanten met behulp van veldwaarnemingen; en de introductie van ruimtelijke aspecten, met inbegrip van ruimtelijke variatie, in het model.

Classificatie, validatie en detectie van veranderingen

Een eerste set regels werd ontwikkeld uit de relatie tussen beeldkenmerken en landbedekkingsstructuur. Een tweede set regels werd ontwikkeld op basis van de mogelijke veranderingen tussen landbedekkingsstructuurklassen, zoals berekend met het BOSTOS model. Alle negen beelden werden gesegmenteerd met het RCSEG algoritme en vervolgens geclassificeerd met deze twee sets regels. Niet alle dertien landbedekkingsstructuurklassen konden onderscheiden worden op de beelden. De resultaten laten zien dat, terwijl het moeilijk is om landbedekking te karteren met een enkel ERS-1 beeld, drie beelden binnen een tijdsduur van een jaar gebruikt kunnen worden om bossen te onderscheiden van graslanden, onder voorwaarde dat de beelden genomen zijn in verschillende seizoenen. Secundaire vegetatie is een erg heterogene vorm van landbedekking, die verward kan worden met zowel bos als grasland. Tijdseries van ERS-1 beelden over meerdere jaren kunnen uiteindelijk gebruikt worden om ook secundaire vegetatie te onderscheiden van bossen en graslanden. Classificatienauwkeurigheden, wanneer tijdseries geclassificeerd worden met beide sets formele regels, bedragen meer dan 60% voor bossen, ongeveer 40% voor secundaire vegetatie, en 80 tot 90% voor weilanden en natuurlijke graslanden. De classificatie met behulp van formele regels gaf betere resultaten dan de classificatie met Maximum Likelihood. De nauwkeurigheid neemt eerst toe met de tijd dat het monitoringsysteem functioneert, dat wil zeggen met het aantal beelden, en wordt daarna stabiel.

Conclusies en toekomstperspectief

Deze studie heeft laten zien dat het mogelijk is om landbedekking te monitoren in een gebied met tropisch regenwoud met behulp van ERS-1 beelden. Bossen kunnen worden onderscheiden van andere vormen van landbedekking en veranderingen in de landbedekking kunnen gedetecteerd worden. Het vaststellen van de precieze aard van de verandering in landbedekking is echter moeilijker en minder nauwkeurig vast te stellen dan het feit dat er een verandering heeft plaatsgevonden. Het betrekken van kennis van de relatie tussen de structuur van de landbedekking en de beeldkenmerken en van het proces van verandering van de landbedekking heeft een positief effect op de nauwkeurigheid van de beeldclassificatie in het monitoringsysteem.

De nauwkeurigheid van het systeem kan verder worden verbeterd door initialisatie met een nauwkeurige kaart van de landbedekking. Andere mogelijke verbeteringen kunnen gevonden worden in de verdere ontwikkeling van de modellen die ten grondslag liggen aan de sets regels, met inbegrip van de validatie van de aannamen en de parameters. Wanneer waarschijnlijkheden gebruikt worden in plaats van de meest waarschijnlijke keuzes, zoals gebruikt in dit onderzoek, kan het systeem zelflerende eigenschappen ontwikkelen.

Het systeem kan uitgebreid worden om ook andere sensoren te omvatten, waardoor de nauwkeurigheid vergroot wordt door data synergie, maar het is ook mogelijk om delen van het gebied te monitoren met een andere temporele, ruimtelijke of radiometrische resolutie, in overeenstemming met de behoefte van de gebruiker en de verwachte veranderingen. Niet in de laatste plaats zal de ingebruikname van nieuwe radarsensoren op satelliet platformen, gepland voor het begin van de volgende eeuw, de mate van detaillering waarmee de landbedekking kan worden gemonitord met satelliet remote sensing belangrijk verbeteren. Dit is reeds aangetoond door de ontwikkeling van geavanceerde vliegtuig-SAR-systemen en door de SIR-C missie.

a una extensa superficie ondulada de denudación la "planicie Amazonica disectada del Plio-Pleistoceno" formada por grandes depósitos heterogéneos del Terciario Superior, así como cuestas de arenisca Cuarcíticas del Paleozóico, y rocas sienita nefelínica del Paleozóico. La unidad de vega comprende terrazas ribereñas y planicies de inundación del Cuaternario. Los suelos de la planicie disectada Amazónica del Plio-Pleistoceno están caracterizados por su baja fertilidad y alta saturación de aluminio. Es común encontrar en las cimas, una capa de gravas petroférricas cerca de la superficie. La textura de los suelos es variable. Las cuestas de areniscas están principalmente cubiertas por suelos de textura gruesa y baja fertilidad. En aquellas áreas donde el material parental está compuesto por syenita nefelinica, se desarrollan suelos de texturas mas finas y fértiles. Los suelos de las planicies de inundación tienen texturas variadas, mientras que la fertilidad depende del orígen de los sedimentos.

El desplazamiento de la población proveniente de otras regiones de Colombia hacia el Guaviare fue mayormente determinado por la violencia y el sistema de tenencia de la tierra en la región de los Andes, el cual favorecía la concentración de la propiedad de la tierra. Al principio, el movimiento migratorio a la región del Guaviare fue espontáneo, y después fue apoyado por el gobiemo. Originalmente el área estaba cubierta en su mayoría por bosques siempre verdes. Gran parte de estos bosques ha sido cortada y reemplazada por pastos, cultivos agrícolas y vegetación secundaria. Una parte del bosque restante ha sido perturbado por la tala selectiva de árboles de gran valor económico. Las cuestas de areniscas están cubiertas por vegetación de sabanas de gramíneas con árboles achaparrados.

En áreas de tierra firme, la ganadería es la actividad preponderante. Esta actividad es mas extensiva en las áreas de sabanas naturales que en otros sectores de la tierra firme. Después de cortar y quemar el bosque primario que cubre la planicie Amazónica disectada del Plio-Plieistoceno, se establecen cultivos anuales y permanentes. Un área mas pequeña es cultivada con cultivos permanentes como caucho, frutales, caña de azúcar y coca. El número de años en que la tierra es usada para cultivos varía, pero después de cierto tiempo estos son dejados en rastrojo (barbecho) para así permitir el desarrollo de un bosque secundario, o convertidos en pastos. Usualmente el bosque secundario es seguido por otro período de cultivos y finalmente por pastos. Normalmente un área cubierta de pastos se mantiene así, a pesar de que esta puediera regenerarse o degradarse si la finca es abandonada. El uso de la tierra dominante en la planicie aluvial es la agricultura pero tambien se observa algún pastoreo.

Bosquejo del sistema de monitoreo

El sistema de monitoreo aquí presentado está basado en el uso de imágenes de radar de los satélites ERS-1 y -2. El sistema tiene una estructura genérica, lo cual lo hace apto para su uso en un amplio rango de áreas a través del ajuste de algunos parámetros, o a lo sumo, reemplazando algunos componentes específicos. Dentro del sistema, las imágenes son procesadas usando clasificaciones y reglas formales de imágenes previas. Estas reglas están basadas en la relación que existe entre las características de la imagen y la estructura de la cobertura de la tierra y en el conocimiento sobre el proceso de cambio de cobertura de la tierra los cuales están formalizados en modelos. El resultado de la clasificación es exportado a un Sistema de Información Geográfica (SIG) para generar las salidas sobre la cubertura y cambios en la cobertura de la tierra. El sistema, sus modelos y la clasificación de las imágenes son validados con datos de campo, otros datos de percepción remota o modelos nuevos, lo cual puede conducir al mejoramiento del sistema. Depués de validado, el sistema puede pasar a un proceso de iteracción dentro del cual son incluidas también clasificaciones previas.

Enfoque general para el desarrollo de las reglas de decisión

Los datos relacionados con la estructura de la vegetación son recolectados en campo. Esta estructura es descrita como el porcentaje de cobertura de biomasa verde dentro del número de estratos horizontales, la presencia de ciertos grupos estructurales de plantas, como palmas, epífitas, *Musaceae* de tallo y enrredaderas, lianas y bejucos, y el porcentaje de cobertura de suelo desnudo y material leñoso muerto. Estos datos son agrupados para así encontrar clases estructurales típicas. Las imágenes de satélite son analizadas para extraer las características de la imagen por cada área muestra y así evaluar la relación entre la estructura de la cobertura de la tierra y las características de la imagen. Esta relación puede ser formalizada en reglas para ser usadas en la clasificación de la imagen.

Datos multi-temporales de cobertura de la tierra son analizados para así entender el proceso de cambio de cobertura de la tierra en el área. Estos datos, así como la información obtenida de estudios previos son usados para desarrollar un modelo de cambios de cobertura de la tierra capaz de calcular (o predecir) los posibles cambios. De los resultados obtenidos del modelo, se puede formular otro conjunto de reglas de decisión basadas en posibles cambios de cobertura de la tierra, los cuales también pueden ser usados en la clasificación de la imagen.

Análisis del conjunto de datos del Guaviare

Para la región del Guaviare, el agrupamiento de los datos de estructura de vegetación colectados en campo resultó en 11 grupos de estructura de vegetación. Estos grupos fueron usados para subdividir las 7 clases de cobertura de la tierra (llamadas también clases del usuario) en 13 clases de estructura de cobertura de la tierra. El agrupamiento se basó en el porcentaje de cobertura de la vegetación verde en el estrato, árboles altos, árboles medios, árboles bajos, arbustos, gramíneas altas, gramíneas bajas, y otras hierbas. La presencia de palmas, *Musaceae* de tallo y enrredaderas, lianas y bejucos, o el porcentaje de cobertura de material leñoso muerto y suelos desnudos tuvo poca o ninguna influencia en el agrupamiento del conjunto de datos. Se construyó un anagrama de desiciones para clasificar muestras nuevas de vegetación así como para generar la salida del modelo de cambios de cobertura en clases de estructura de cobertura de la tierra basado en el porcentaje de cobertura en estratos pre-definidos.

Entre 1992 y 1994, existían 9 imágenes disponibles del ERS-1 para el área de estudio. Las muestras de campo fueron delimitadas con polígonos sobre las imágenes y dos características de las imágenes fueron extraídas: promedio de señal de retorno (backscatter) por polígono y la diferencia máxima de este promedio sobre tres imágenes consecutivas.

Estas dos características de las imágenes fueron relacionadas a las clases de estructura de cobertura de la tierra. La implementación de modelos de simulación de los niveles y variación de la señal de retorno (backscatter) de las diferentes clases de estructura de cobertura de la tierra usando el modelo teórico UTACAN, confirmó los hallazgos experimentales.

La versión multi-canal del algoritmo RCSEG, basado en la detección de bordes y el crecimiento de segmentos, fue usada para la segmentación de la imagen antes de la clasificación. De esta forma, imagénes del mismo año fueron segmentadas conjuntamente como canales diferentes. Los resultados de la segmentación mostraron una gran variación pero los resultados de la clasificación fueron mas estables, debido a que los diferentes segmentos fueron clasificados como la misma clase de cobertura de la tierra.

Modelos de cambio

Análisis de los datos de campo correspondientes a varios años, e información proveniente de otros estudios fueron usados para modelar el proceso de cambio de cobertura de la tierra usando el modelo BOSTOS. Este modelo calcula los cambios posibles en la estructura de la vegetación, expresado en porcentaje de cobertura de la vegetación verde en un estrato pre-definido, así como la cantidad de material leñoso muerto. Se construyeron diferentes escenarios con intervenciones de manejo variadas para calcular los posibles cambios entre las clases de estructura de cobertura de la tierra. Hasta ahora, no ha sido posible describir completamente todas las transiciones posibles entre las clases de estructura de cobertura de la tierra. El mejoramiento y futuro desarrollo del modelo BOSTOS podria concentrarse en dos aspectos principales: mejoramiento en la precisión de la estimación de parámetros a través de observaciones de campo, y la introducción de los aspectos espaciales, incluyendo la variación espacial, dentro del modelo.

Clasificación , validación y detección de cambios

Inicialmente se establecieron un conjunto de reglas basadas en la relación entre las características de la imagen y la estructura de la cobertura de la tierra. Un segundo grupo de reglas fue desarrollado con base en los posibles cambios entre las clases de estructura de cobertura de la tierra, calculadas con el modelo BOSTOS. Las nueves imágenes fueron segmentadas usando el algoritmo RCSEG y posteriormente clasificadas usando los grupos de reglas antes mencionados. No todas la clases de estructura de cobertura de la tierra (13) pudieron ser identificadas en las imágenes. Los resultados muestran que mientras es difícil mapear la cobertura de la tierra usando una imagen ERS-1, el uso de tres imágenes para un período de un año puede separar bosques de pastos, tomando en cuenta que las imágenes fueron tomadas en estaciones diferentes. La vegetación secundaria es un tipo de cobertura muy heterogénea y puede ser confundida tanto con bosques como con pastos. Series temporales sobre varios años de las imágenes ERS-1, pueden ser usadas eventualmente para separar vegetación secundaria de boques y pastos. Las precisiones de la clasifiacción usando series temporales y los dos conjuntos de reglas son: mayor de 60% para bosques, aproximadamente 40% para vegetación secundaria, y entre 80 y 90% para pastos y sabanas naturales. La clasificación usando reglas formales dio mejores resultados que la clasificación usando el clasificador de máxima similitud. La precisión aumenta principalmente con el tiempo en que el sistema de monitoreo ha estado funcionando, ej. con el número de imagenes, después se estabiliza.

Conclusiones y perspectivas

Este estudio ha demostrado que es posible monitorear la cobertura de la tierra para áreas de bosque húmedo tropical usando imágenes ERS-1. La cobertura de bosques puede ser diferenciada de otros tipos de cobertura y los cambios en la cobertura de la tierra pueden ser detectados. Sin embrago la evaluación de la índole de los cambios en la cobertura de la tierra, es mas difícil y menos precisa que la evaluación del cambio en si. La incorporación del conocimiento acerca de la relación entre la estructura de la cubertura de la tierra y las características de la imagen, y del proceso del cambio de cobertura de la tierra incrementa la precisión de la clasificación de las imágenes en el sistema de monitoreo.

La precisión del sistema puede ser mejorada aún usando un mapa de cobertura de la tierra de alta confiabilidad. Otras posibles mejoras pueden estar dadas a través de desarrollos adicionales de los modelos básicos de los conjuntos de reglas, incluyendo la verificación de las premisas y los parámetros. Cuando se usan probabilidades en la clasificación, en lugar de las selecciones mas probables, como fue usado en esta investigación, el sistema puede adquirir capacidades de auto-aprendizaje.

El sistema puede ser ampliado para incluir otros tipos de sensores y así incrementar su precisión a través del intercambio de datos, pero también es posible monitorear partes de un área usando diferentes resoluciones temporales, espaciales y radiométricas, de acuerdo a las necesidades del usuario y de los cambios esperados. Por último, pero no menos importante, la disponibilidad de sensores nuevos de radar en plataformas de satélites, programadas para principios del siglo 20, mejorarán enormemente el nivel de detalle con el cual la cobertura de la tierra puede ser monitoreada usando percepción remota satelitaria. Esto ha sido ya demostrado a través del desarrollo de los sistemas avanzados sobre plataformas aéreas SAR y la misión SIR-C.

REFERENCES

Acosta, L.E., 1993. *Guaviare Puente a la Amazonia.* Corporación Colombiana para la Amazonia - Araracuara (COA), Santafé de Bogotá, Colombia.

Andrade, A., 1985. *Landscape Ecological Planning, a case in the Colombia Llanos.* Msc. Thesis. ITC, Enschede, The Netherlands.

Andrade, A. and A. Etter, 1987. *Levantamiento ecologico del area de colonización de San José del Guaviare (informe y memoria explicativa a los mapas).* Convenio realizado con el CIAF-IGAC, Corporación de Araracuara, Proyecto DAINCO-CASAM. Corporación de Araracuara, Bogotá, Colombia.

Andrade, G.I., A. Hurtado G., R. Torres, 1992. *Amazonia Colombiana, diversidad y conflicto.* Centro de estudios ganaderos y agricolas (CEGA), Santafé de Bogotá, Colombia.

Anonymus, 1988. A global strategy for tropical forestry - report of an international task force on forestry research. Sponsored by the Rockefeller Foundation, United Nations Development Programme, World Bank, FAO.

Attema, E.P.W. and F.T. Ulaby, 1978. Vegetation modelled as a water cloud. *Radio Science,* Vol. 13, pp. 357—364.

Baquero, H.I., 1983. *Estudio preliminar del impacto de los sistemas agroforestales, silvopastoriles, silviculturales, investigados por CONIF/HOLANDA.* CONIF, Bogotá, Colombia.

Barkman, J.J., 1979. The investigation of vegetation texture and structure. In: M.J.A. Werger. *The study of vegetation,* pp. 123—160. Dr W. Junk Publishers, The Hague, the Netherlands.

Bijker, W. and D.H. Hoekman, 1994. A remote sensing monitoring system for a colonization area in tropical rain forest. *VI Simposio Latino Americano de Percepcion Remota (SELPER), 3—8 October 1993, Cartagena, Colombia.*
[also:1994, ESA proceedings, SAREX final workshop]

Bijker, W and W. van Wijngaarden, 1994. Land use modelling for image interpretation and change detection. Guaviare pilot area. *VI Simposio Latino Americano de Percepcion Remota (SELPER), 3—8 October 1993, Cartagena de las Indias, Colombia.*

Bourcheron, P.S., 1983. Spatial aspects of vegetation structure. In: F.B. Golley (ed.), *Tropical rain forest ecosystems, structure and function.* Ecosystems of the world, Vol. 14A. Elsevier, Amsterdam, the Netherlands.

Bruenig, E.F., 1996. *Conservation and management of tropical rainforests. An integrated approach to sustainalbility.* CAB International, Wallingford, U.K.

Van der Burg, G., J.C. Venema, J. Spaa, D.H. Hoekman, J.J. van der Sanden, P.G. Reichert, 1992. *Feasibility study on global operational forest cover monitoring network for FAO using satellite remote sensing.* BCRS Report 92-05, Delft, the Netherlands

Burley, T.M., 1961. Land use or land ustilization? *Profesisonal Geographer,* 13, 6, pp 18—20.

Caves, R.G. and S. Quegan, 1995. The role of segmentation in multi-channel SAR image analysis. *RSS '95 Remote Sensing in Action; Proceedings of the 21st Annual Conference of the Remote Sensing Society, 11—14 September 1995, University of Southampton, U.K.*

Chavez C., M., 1987. *Informe Diagnóstico Preliminar sobre la situación actual de las comunidades indígenas Guayabero y Tukano de las reservas Barrancón, La Fuga y Panuré.* Corporación de Araracuara, DAINCO-CASAM, Bogotá, Colombia.

COA, 1992. *Corporacion, Colombiana para la Amamazonia - Araracuara-.* (Leaflet). COA, Bogotá, Colombia.

Diepen, C. A. van, J. Wolf, H. van Keulen and C. Rappolt, 1988. WOFOST: a simulation model for crop production. *Soil Use and Management,* Vol. 5, pp. 16—24. Blackwell, Oxford, U.K.

Dominguez, C., *without date* Análisis crítico de la colonización Amazónica en Guaviare, Caquetá y Putumayo. Vol. I. Corporación Colombiana para la Amazonia - Araracuara, Bogotá, Colombia.

Duran, 1979, quoted by Acosta, 1993 (see above), but not in his literature list.

El Espectador newspaper. Bogotá, Colombia. August 6, 1996.
Available trough World Wide Web http://www.elespectador.com/

FAO, 1990. *Tropical Forestry Action Plan.* FAO medal 1990 leaflet. FAO, Rome, Italy.

Forrester, J.W., 1968. *Principles of systems.* Text and workbook, chapters 1—10. Wright-Allen Press Inc., Cambridge, U.K.

Gils, H.A.M.J. van, H.G.J. Huizing, A. Kannegieter and D. van der Zee, 1991. The evolution of the ITC system of rural land use and land cover classification (LUCC). *ITC Journal* 1991-3, pp. 163—167. ITC, Enschede, the Netherlands.

Givnish, T.J., 1984. Leaf and canopy adaptations in tropical forests. In: E. Medina, H.A. Mooney and C. Vázquez-Yánes, Physical ecology of plants of the wet tropics. *Proceedings of an international symposium held in Oxatepec and los Tuxtlas, Mexico, 29 June—6 July 1983.* Dr. W. Junk Publishers, The Hague, 1984.

Gonzalez, 1989: Acosta, 1993 (see above) quotes this author, but this reference is not in his literature list. It might be that he means the following reference that is included in the list:

Gonzalez, J.J. 1990. El Guaviare: *Una historia de fronteras.* Proyecto Colonización. U. de Utrecht/COA, The Netherlands/Colombia

Hallé, F. and R.A.A. Oldeman, 1970. *Essai sur l'architecture et la dynamique de croissance des arbres tropicaux.* Monographie. Collection de monographies de botanique et de biologie vegetale, no. 6. Paris, France.

Hill, M.O., 1979. *TWINSPAN - a FORTRAN Program for arranging Multivariate Data in an Ordered Two Way Table by Classification of the Individuals and the Attributes.* Cornell University, Department of Ecology and Systematics, Ithaca, New York.

Hoekman, D.H., 1990. *Radar remote sensing data for applications in forestry.* Ph.D. thesis, University of Wageningen, the Netherlands.

Hoekman, D.H., J.J. van der Sanden and W. Bijker, 1994a. Results of the SAREX-92 Campaign in Guyana and Colombia..*Workshop Proceedings SAREX-92 South American Radar Experiment, ESA Headquarters, Paris, 6—8 December 1993.* ESA wpp-76, Paris.

Hoekman, D.H., J.J. van der Sanden and W. Bijker, 1994b. *Radar remote sensing of tropical rain forests: The SAREX-92 campaign in Guyana and Colombia; First interim report.* BCRS Report 94-01, Delft, the Netherlands.

Hoekman, D.H., J.J. van der Sanden and W. Bijker, 1994c. The AIRSAR-93 and SAREX-92 campaigns in Guyana and Colombia; *Proceedings of IGARSS '94, 8—12 August 1994, Pasadena, California.*

Hoekman, D.H., F. Amar and M.J. Quiñones, 1995. Biomass and structure estimation of primary and secundary tropical rain forests using AirSAR data. *Proceedings of IGARSS '95, 10—14 July 1995, Firenze, Italy, pp. 706—707.*

Hoekman, D.H., J.J. van der Sanden and W. Bijker, 1996. *Radar remote sensing of tropical rain forests: The AIRSAR-93 campaign in Guyana and Colombia.* BCRS report 96-02. BCRS, Delft, the Netherlands.

IBM, 1975. *Continuous system modelling program III (CSMP III). Program reference manual SH 19-7001-3.* Data Processing Division IBM, Houston, USA.

IEEE, 1992. *Proceedings of the IEEE International Conference on Fuzzy Systems, San Diego, California, March 1992.*

Janssen, D.M., R.T. Dierkx, H.H. van Laar and M.J. Alagos, 1988. *PCSMP on IBM PC-AT's or PC-XT's and compatibles.* Simulation Report CABO-TT 15, CABO, Wageningen, the Netherlands.

Jongman, R.H.G., C.J.F ter Braak and O.F.R. van Tongeren (eds.), 1995. *Data analysis in community and landscape ecology.* Cambridge University Press, Cambridge, U.K.

Karam, M.A., A.K. Fung, R.H. Lang and N.S. Chauhan, 1992. A microwave scattering model for layered vegetation, *IEEE Transactions on Geoscience and Remote Sensing,* Vol. GE-30, pp. 767—784.

Karremans, J.A.J., 1990a. *El proceso de colonización en el Guaviare. Un análisis cuantitativo.* Corporación Colombiana para la Amazonia - Araracuara, Bogotá, Colombia and University of Utrecht, Utrecht, the Netherlands.

Karremans, J.A.J., 1990b. Altemative models for land use and land occupation in Amazonia. *Proceedings of FOREST '90, Manaus, Brazil, 7—13 October 1990.*

Kent, M. and P. Coker, 1992. *Vegetation description and analysis - a practical approach.* Belhaven press, London, United Kingdom and CRC Press Inc. Boca Raton, Florida, USA.

Küchler, A.W., 1967. *Vegetation mapping.* Ronald Press, New York.

Leffelaar, P.A., 1993. *On System Analysis and Simulation of Ecological Processes.* Kluwer Academic Publishers, Dordrecht/Boston/London.

Lopes, A., E. Nezry, R. Touzi, H. Lauwer, 1993. Structure detection and statistical adaptive speckle filtering in SAR images. *Int. J. of Remote Sensing,* Vol. 14, no. 9, pp. 1735—1758. Taylor & Francis Ltd. London.

Martínez, L.J., 1992. *Effect of livestock on soil degradation processes in the Colombian Amazon region. Case study of the Guaviare colonization area.* M.Sc. thesis. ITC, Enschede, the Netherlands.

Martínez M., J.L. and D.E. Vanegas R., 1994a. *GIS applications for spatial planning in the Colombian Amazin region: a case study of the Guaviare colonization area. Part 1 - Diagnosis.* ITC Journal 1994-3, pp. 215—223. ITC, Enschede, The Netherlands.

Martínez M., J.L. and D.E. Vanegas R., 1994b. *GIS applications for spatial planning in the Colombian Amazon region: a case study of the Guaviare colonization area. Part 2 - Evaluating altematives.* ITC Joumal 1994-3, pp. 224—232. ITC, Enschede, The Netherlands.

Malingreau, J.P. and R. Dacunha, 1992. *Satellite based global forest monitoring and information system, a blueprint for the design of an operational project.* INPE, World Forest Watch, JRC.

McIntyre, G.A., 1952. A method for unbiased selective sampling , using ranked sets. *Aust. J. Agric. Res.* 3, 385-90.

Molano, A., 1987. *Selva adentro. Una historia oral de la colonización del Guaviare.* El Ancora editores, Bogotá Colombia.

Ovden, 1986. Acosta, 1993 (see above) quotes this author, but this reference is not in his literature list. It might be that he means the following reference that is included in the list:

Ovden, A. den, 1987. *Grupos de hecho: Simón Bolivar - el Hobo - San Antonio. Historia; Motivación;* Evaluación desde julio 1983 hasta agosto 1986, COA-DAINCO-CASAM, San José del Guaviare, Colombia.

PRORADAM, 1979. *La Amazonia Colombiana y sus recursos*, Bogota, Colombia.

Quiñones, M.J., 1995. *Assesment of AIRSAR airborne, polarimetric data for forested land recognition and tropical forest structure and physiognomic composition analysis.* M.Sc. thesis, ITC, Enschede, the Netherlands.

Rangel Suarez, A. 1996. Coca y Guerra. El Tiempo, 25 August 1996, Bogotá, Colombia

Saldarriaga, J.G., D.C. West, M.L. Tharp and C. Uhl, 1988. Long-term chronosequence of forest succession in the upper Rio Negro of Colombia and Venezuela. *Journal of Ecology* 76, pp.938—958.

El Tiempo newspaper. Bogotá, Colombia, June 10, 1996 and August 25, 1996.
Available trough World Wide Web http://www.eltiempo.com/

Tomlinson, P.B., 1983. Structural elements of the rain forest. In: F.B. Golley (ed.), *Tropical rain forest ecosystems, structure and function.* Ecosystems of the world, Vol. 14A. Elsevier, Amsterdam, the Netherlands.

Torro, A.P. and J.G. Saldariaga, 1990. Algunas caracteristicas de la sucesion secundaria en campos de cultivo abandonados en el medio Caqueta, Amazonas, Colombia. *Colombia Amazonica* 4; numero 2:23:30.

UNESCO, 1973. *International classification and mapping of vegetation = Classification international et cartographie de la vegetation = Classification internacional y cartografia de la vegetacion.* UNESCO, Paris, France

Vaessen, 1991. Quoted by Acosta, 1993 (see above), but not in his literature list.

Verweij, P.A., 1995. *Spatial and temporal modelling of vegetation patterns; burning and grazing in the paramo of Los Nevados National Park, Colombia.* ITC publication no. 30. ITC, Enschede, the Netherlands.

Wismann, V., A. Cavanie, D.H. Hoekman, I.H. Woodhouse, K. Boehnke and C. Schmullius, 1996. *Land surface observations using the ERS-1 windscatterometer.* Final Report ESTEC Study Contract 11103/94/NL/CN, ESA/ESTEC, Noordwijk, the Netherlands.

Wijngaarden, W. van, 1985. *Elephants-Trees-Grass-Grazers; relationships between climate, soils, vegetation and large herbivores in a semi-arid savanna ecosystem (Tsavo, Kenya).* ITC publication no. 4, ITC, Enschede, the Netherlands.

BIOGRAPHY

Wietske Bijker was born on 10 June 1965 in Den Helder, the Netherlands. She obtained her high school (VWO) diploma in 1983 and continued her studies at Wageningen Agricultural University, specializing in 'Soil Science of the Tropics and Subtropics'. She did practical training between 1986 and 1987 on Curaçao and Aruba, in the Netherlands' Antilles, on translating land evaluation and land use planning procedures to be executed with a Geographical Information System. This work resulted in a "physical potential map" for part of Aruba, which could be used as a basis for spatial planning.

Her MSc research, carried out between 1987 and 1988 in Bogor, Indonesia, was on land evaluation for urban development in a rural area. She did additional MSc research in 1989 on river dynamics and the formation of travertine in Limagne, France, graduating in January 1990. In the same year she worked for three months as a researcher at the Department of Soil Science and Geology, Wageningen Agricultural University, on improving a model for the simulation of growth and water use of tropical rain forests.

Since October 1990 she has worked in the Department of Land Resources and Urban Sciences, ITC, on several projects involving the monitoring of tropical rain forest, mainly in Colombia. The projects were funded by the Tropenbos Foundation, the Dutch Remote Sensing Board (BCRS) and ITC. The research for this PhD thesis was carried out in the framework of these projects.