

Fall 1996

Assessing land use/cover change in Costa Rica

Gerardo-Arturo Sanchez-Azofeifa
University of New Hampshire, Durham

Follow this and additional works at: <https://scholars.unh.edu/dissertation>

Recommended Citation

Sanchez-Azofeifa, Gerardo-Arturo, "Assessing land use/cover change in Costa Rica" (1996). *Doctoral Dissertations*. 1923.
<https://scholars.unh.edu/dissertation/1923>

This Dissertation is brought to you for free and open access by the Student Scholarship at University of New Hampshire Scholars' Repository. It has been accepted for inclusion in Doctoral Dissertations by an authorized administrator of University of New Hampshire Scholars' Repository. For more information, please contact nicole.hentz@unh.edu.

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

**ASSESSING LAND USE/COVER CHANGE IN
COSTA RICA**

BY

GERARDO-ARTURO SANCHEZ-AZOFEIFA

**B.S. Universidad Autonoma de Centro America, 1987
Licensee Civil Engineering, Universidad de Costa Rica, 1991
M.Sc. University of New Hampshire, 1993**

DISSERTATION

**Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of**

Doctor of Philosophy

in

Earth Sciences

September, 1996

UMI Number: 9703370

Copyright 1996 by
Sanchez-Azofeifa, Gerardo-Arturo

All rights reserved.

UMI Microform 9703370
Copyright 1996, by UMI Company. All rights reserved.

This microform edition is protected against unauthorized
copying under Title 17, United States Code.


UMI
300 North Zeeb Road
Ann Arbor, MI 48103


ALL RIGHTS RESERVED

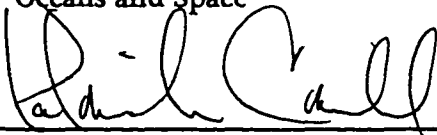
© 1996

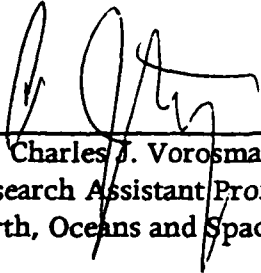
Gerardo-Arturo Sanchez-Azofeifa

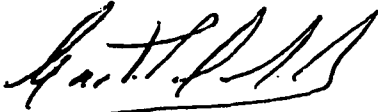
This dissertation has been examined and approved.


Dissertation Director, Dr. Robert C. Harriss
Professor of Earth Sciences and Earth,
Oceans and Space


Dr. David L. Skole
Research Assistant Professor of Earth,
Oceans and Space


Dr. Patrick M. Crill
Research Associate Professor of Earth Sciences and
Earth, Oceans and Space


Dr. Charles J. Vorosmarty
Research Assistant Professor of Earth Sciences and
Earth, Oceans and Space


Dr. Carlos A. Quesada-Mateo
Director, Center for Research on Sustainable Development
University of Costa Rica

8/20/96

Date

ACKNOWLEDGMENTS

I would like to acknowledge the help and guidance of my committee. I extend special appreciation to Dr. Robert C. Harriss his mentorship during my years at the University of New Hampshire. I would also like to extend my appreciation to Dr. David L. Skole for his teaching and support during my studies at the University of New Hampshire. Special thanks are given to Dr. Carlos Quesada, who since my undergraduate studies at the University of Costa Rica, has provided unconditional support and mentorship which make it possible for me to reach my academic goals. I would like to recognize the help provided by my colleagues William Salas, Walter Chomentowsky, Karen Velkamp, Mike Routhier and Ari Wertheimer of the NASA Pathfinder Project at UNH for their support along the years. I would like to thank my wife Christine wife for her support along these years, as well as my parents, Gerardo Sanchez and Libia de Sánchez, and my parents-in-law, Lawrence and Filomena Orosz for their support.

Special thanks are given to the Center for Research of the University of Costa Rica (CIEDES), the Vice-Presidency for Research of the University of Costa Rica for their support to my work. In addition, I would like to thank the Central American Project for Climate Change / Central American Committee on Water Resources (CAPCC/CRRH) and the CAPCC director, Max Campos, for his support.

Financial support came from NASA Mission to Planet Earth and the University of Costa Rica.

PREFACE

The need for an accurate and precise forest cover inventory to quantify the rate of primary forest loss in Costa Rica is becoming a matter of urgency. As forest resources vanish from the national landscape, important impacts on water resources, biodiversity, the carbon cycle and other trace gases are important to quantify. Moreover, the goals of sustainable forestry and biodiversity conservation strategies defined by Costa Rica can only be achieved if state-of-the-art remote sensing data and GIS techniques are integrated to fully understand Costa Rica's forest landscape.

This dissertation focuses on answering three fundamental questions:

1. What is the extent of primary forest cover in Costa?
2. What is the degree of habitat fragmentation and which are the most affected areas?
3. How can current state-of-the-art technology in remote sensing and geographic information systems help to take an accurate and precise inventory of the extension of primary forest in Costa Rica?

The answer to these questions will provide important knowledge which can be applied to the following:

National Forest Cover Assessment: The definition of future conservation policies in Costa Rica will depend on accurate and precise knowledge of the spatial distribution of forest cover. Sound forest cover assessments will be important for determining the rate of forest loss and the rate of regeneration of abandoned lands. Moreover, the success of deforestation

monitoring program in Costa Rica, will require the use of statistical tools for sampling those satellite scenes or subsets of them which are representative of the land use/cover dynamics in the country. In addition, this program must be flexible enough to take advantage of new technologies from the emerging Landsat 7 data and < 1 m resolution satellites.

Biodiversity: Spatial distribution of forest islands is a key component in sampling genetic/biodiversity resources in fragmented ecosystems, as well as in the definition of conservation areas (small reserves). A continued deforestation monitoring program will also be important in order to evaluate biodiversity loss in terms of ethical and aesthetic reasons, the direct loss of economic benefits from biodiversity in the form of the essential services provided by natural ecosystems, and the identification of area for the development of “in-situ” and “off-situ” biodiversity conservation and restoration programs.

Water Resources: Watershed protection is a key component in achieving sustainable management of water resources. An accurate forest assessment will assist in the implementation of soil and water resources conservation programs. Additionally, an accurate forest resources assessment will assist in the implementation of a more comprehensive national water balance.

Climate Change: Information provided by a nationwide forest cover assessment has important implications for climate change research at the national and regional level. The information provided by means of remote sensing interpretation can help to fill a critical gap in terms of carbon estimates (stocks and fluxes) in Costa Rica, as well as to define policy for the definition of a national baseline for the country's inventory of greenhouse gases. Additionally, an accurate estimation of land cover change and its spatial distribution is critical

on the quantification of trace gas emissions such as Nitroxide (N₂O).

This document consists of four chapters, each one written in the style of a published paper. Because of the nature of this dissertation, some tables and figures will overlap. The following is a summary of the contents of this dissertation.

Chapter 1: *Tropical deforestation and habitat fragmentation in Costa Rica.* This manuscript explores previous studies dealing with the study of deforestation and land use change in Costa Rica. The chapter outlines the steps followed to quantify Costa Rica's state of forest cover and forest fragmentation during 1991. This paper also quantifies the degree of forest loss between 1986 and 1991. The degree of habitat fragmentation at the life zone level in Costa Rica is also presented in this paper. This chapter presents a framework for integrating state-of-the-art methodologies for thematic accuracy assessment, and the development of a new methodology to study the sensitivity of Landsat TM in terms of the percentage of canopy closure extracted from the sensor.

Chapter 2: *Can stratified sampling be used to estimate tropical deforestation?* Sound sampling of remote sensing data bases is critical in order to achieve a high degree of precision and accuracy in monitoring tropical deforestation. The correct selection of satellite scenes (or subscenes) is important in order to achieve estimates of tropical deforestation which are close to the true mean. This paper explores the use of sampling from a data base from the Brazilian Amazon. The concept of persistence coupled with stratified sampling is implemented to study the impact of different criteria for scene selection and their impacts on

estimation of tropical deforestation.

Chapter 3: *A review of the factors that have contributed to land use/cover change Costa Rica.* This chapter reviews the history of land use/cover change in Costa Rica using the country's agricultural census as the main source of information. This paper explores the different mechanisms contributing to the expansion of permanent and annual crops, and pasture land. It also discusses the limitations of Costa Rica's agricultural census in estimating forest cover. The manuscript concludes with the need for a more comprehensive understanding of LUCC problems in Costa Rica by using remote sensing and geographic information systems. This paper is will be in press in Hall, C.H.; Leon-Perez, C.; Leclerc, G. (Eds.), *Geographical Modeling: Agriculture, Economy, and Environment in Costa Rica*, Academic Press, New York.

Chapter 4: *Implications of LUCC to water resources management in Costa Rica.* This chapter focusses on an analysis of the status of forest cover and forest fragmentation of 13 of the most important drainage basins in Costa Rica. It also explores in detail, the role that the current sediment monitoring program in Costa Rica is playing in terms of detection of LUCC impacts on sediment production. Findings of this paper indicate that the current sediment monitoring program is not capable of detecting LUCC in Costa Rica, and suggests the need for designing a more comprehensive sediment monitoring program in order to complement current measurement efforts.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iv
PREFACE	v
LIST OF TABLES	xi
LIST OF FIGURES	xiii
ABSTRACT	xviii
CHAPTER	PAGE
1. TROPICAL DEFORESTATION AND HABITAT FRAGMENTATION IN COSTA RICA	1
Introduction	2
Tropical Deforestation in Costa Rica	4
Methods	11
Results	31
Discussion	40
Conclusions	47
2. CAN STRATIFIED SAMPLING BE USED TO ESTIMATE TROPICAL DEFORESTATION?	73
Introduction	73
Background	75

Methods	79
Results	82
Conclusions	85
3. A REVIEW OF FACTORS WHICH HAVE CONTRIBUTED TO LAND USE/COVER CHANGE IN COSTA RICA	102
Introduction	102
Methods	104
Results	104
Discussion	114
Conclusions	117
4. IMPLICATIONS OF LAND USE/COVER CHANGE TO HYDROPOWER PRODUCTION IN COSTA RICA	136
Introduction	136
Methods	140
Results	142
Discussion	151
Conclusion	155
REFERENCES	170
APPENDIX A	179
APPENDIX B.....	181

LIST OF TABLES

TABLE	PAGE
Table 1.1. Forest / Non-Forest threshold as a function of forest cover (%)	49
Table 1.2. Costa Rica 1991 forest cover assessment, forest distribution by province	50
Table 1.3. Costa Rica 1991 forest cover assessment, forest distribution by life zone	51
Table 1.4. Costa Rica 1991 forest cover assessment, forest distribution by life zone transition	52
Table 1.5. Costa Rica 1991 forest cover assessment, forest island size distribution	53
Table 1.6. Costa Rica 1991 forest cover assessment, fragmentation statistics by life zone	54
Table 1.7. 1986-1991 Deforestation analysis comparison between path 15 / row 53 Landsat TM scene, island size distribution change	55
Table 1.8. Remaining forest and deforestation rates in Costa Rica by life zone	56
Table 1.9. Costa Rica 1991 forest cover assessment, thematic accuracy assessment	57
Table 1.10. Costa Rica 1991 forest cover assessment, Landsat TM sensitivity analysis	58
Table 2.1. Amazon Basin, number of scenes selected from different stratification criteria	88
Table 3.1. Costa Rica's cattle annual growth rates (%)	120
Table 3.2. Costa Rica's pasture land annual growth rates (%)	120

Table 3.3. Costa Rica's sugar cane annual growth rates (%)	120
Table 3.4. Costa Rica's coffee annual growth rates (%)	120
Table 3.5. Costa Rica: Source of land use to expand pasture land	121
Table 3.6. Correlation between pasture area (1950, 1963, 1973 and 1984) and other socio-economic variables	122
Table 3.7. Comparison of forest cover estimates from different sources and methods	123
Table 4.1. Hydropower potential, forest cover and suspended sediment production for selected drainage basins in Costa Rica	158
Table 4.2. Rank of drainage basins in Costa Rica as function of forest fragmentation	159
Table 4.3. Impact of "El Niño" at the Abangares and Grande de Terraba drainage basins	160

LIST OF FIGURES

FIGURE	PAGE
Figure 1.1. Costa Rica, location of Landsat TM scenes (WRS-2) tile systems used for the 1991 forest cover assessment	59
Figure 1.2. Costa Rica 1991 forest cover assessment, methodologic steps follow during the definition of primary forest cover	60
Figure 1.3. Puerto Viejo de Sarapiquí, location of sites for positional accuracy assessment	61
Figure 1.4. Puerto Viejo de Sarapiquí, location of transects for positional accuracy assessment	62
Figure 1.5. Correlation between transect extracted from the Landsat TM scene and the classification of the aerial photography	63
Figure 1.6. Correlation between percentage forest cover on a 5 x 5 kernel window from the aerial photography and its correspondent TM digital number for (a) band 2, (b) band 3, © band 4, and (d) band 5. Points represent the average of three transects	64
Figure 1.7. Costa Rica 1991 forest cover assessment, primary forest	65
Figure 1.8. Costa Rica 1991 forest cover assessment, primary forest and national roads	66
Figure 1.9. Costa Rica 1991 forest cover assessment, primary forest distribution by province. The Cartago and Limon province are the areas with less infrastructure (roads) development	67
Figure 1.10. Costa Rica 1991 forest cover assessment, forest distribution by Holdridge life zones	68
Figure 1.11. Costa Rica 1991 forest cover assessment, forest distribution by Holdridge life zone transition	69

Figure 1.12. Costa Rica 1991 forest cover assessment, rate of forest loss at the Holdridge life zone level. Rates of forest loss is for Landsat TM scene path 15 / row 53 between 1986 and 1991	70
Figure 1.13. Location of ground control points for thematic accuracy assessment	71
Figure 1.14. Correlation between Landsat TM band 2 digital number and % forest cover from aerial photography. A forest gap with a forest canopy closure of ~60% is observed in this transect	72
Figure 2.1. Distribution of satellites scenes for the Amazon Basin	89
Figure 2.2. Stratification scheme follow to generate a stratified population Level-3 for random sampling	90
Figure 2.3. Comparison of normalized variances for level-2 stratified populations (1978, 1988 data sets) and level-3 stratified population. The level-3 population was generated by using persistence	91
Figure 2.4. Random sampling procedure on a stratified population level-3	92
Figure 2.5. Frequency distribution for the original satellite scene sampling population (a) 1978, and (b) 1988	93
Figure 2.6. Frequency distribution for level-2 satellite scene population (a) 1978, and (b) 1988	94
Figure 2.7. Persistence analysis for three time periods, (a) 1975-1978 ($r^2 = 0.81$) and (b) 1978-1988 ($r^2 = 0.63$). Persistence decreases over time as deforestation patchiness increases	95
Figure 2.8. Selected satellite scenes by using persistence.....	96
Figure 2.9. Frequency distribution of selected satellite scenes using persistence. The level-3 population has the same frequency distribution than the level-1 population.....	97
Figure 2.10. Rate of forest change between 1978 and 1988 for 202 satellites scenes at the Amazon basin. A total of 33 and 14 scenes were selected for a 5% and 10% change, respectively.....	98
Figure 2.11. Location of selected scenes using a 10% forest change threshold.....	99

Figure 2.12. Location of selected scenes using a 5% forest change threshold.....	101
Figure 2.13. Frequency distribution for scenes selected using (a) 10% change and (b) 5% change. None of the selected samples follow the original frequency distribution.....	102
Figure 3.1. Aggregated agricultural census data by province. (a) Cattle, (b) pasture area, (c) sugar cane area and (d) coffee area.....	124
Figure 3.2. Primary forest cover (from Sader & Joyce, 1988) and pasture area (from agricultural census) in Costa Rica between 1940 and 1984.....	125
Figure 3.3. Relative contribution of the agriculture sector to Costa Rica's gross national product (GNP). Agriculture's contribution to the GNP drops from 41% (1950) to 20% (1984) as a result of a transformation of the country production system.....	126
Figure 3.4. Percentage of Costa Rica's national territory occupied by annual and permanent crops, pasture, forest, abandoned land and other uses. Information generated from 1950, 1963, 1973 and 1984 agricultural census (Source: Direccion General de Estadisticas y Censos, 1950; 1963; 1973 and 1984).....	127
Figure 3.5. (a) Growth of pasture land, number of heads of cattle, total meat production and other population in Costa Rica, (b) change in normalized (constant 1966 colones) standing meat prices in the international and internal market.....	128
Figure 3.6. (a) Percentage of the total meat production used for internal consumption and exports, (b) change in normalized (constant 1966 colones) standing meat prices for the international and internal market.....	129
Figure 3.7. Sugar cane area and coffee plantations area growth in Costa Rica between 1950 and 1984. (Source: Direccion General de Estadisticas y Censos, 1950; 1963; 1973 and 1984).....	130
Figure 3.8.a. Spatial distribution of coffee plantation in Costa Rica, reference year is 1950. Source: Direccion General de Estadisticas y Censos, Costa Rica (1950).....	131
Figure 3.8.b. Spatial distribution of coffee plantation in Costa Rica, reference year is 1984. An expansion of coffee plantation outside the Central Valley (San Jose City) is observed. Source: Direccion General de Estadisticas y Censos, Costa Rica (1950).....	132

Figure 3.9. Comparison between forest cover information from the 1984 agricultural census and the 1984 National Geographic Institute land use map. Forest cover from the agricultural census is been systematically under-estimated by the current sampling scheme.....	133
Figure 3.10. Comparison between 1984 forest cover from Costa Rica’s National Geographic Institute (IGN, 1984) and forest cover derived from a 1986 Landsat TM scene (path 15 / row 53) acquired on February 6th, 1986. The high correlation ($r^2 = 0.87$) between the IGN information and the Landsat TM classification indicates that agricultural census are under-estimating current forest cover in Costa Rica.....	134
Figure 3.11. Comparison between forest cover information from several agricultural census and work performed by Sader and Joyce (1988). Forest cover is systematically under-estimated by the agricultural census.....	135
Figure 4.1. Costa Rica 1991 forest cover and national watershed system. Forest cover represents all units with 80% of higher canopy closure.....	161
Figure 4.2. Monthly sediment double-mass curves for stations Palomo (monitoring primary forest) and La Troya (zone of shifting agriculture) compared with station pattern Montecristo (primary forest). La Troya presents more complex behavior as a result of LUCC process in this basin (After Sanchez & Harriss, 1994).....	162
Figure 4.3. Relative differences to the long term mean of suspended sediment samples at the Pacuare River basin, Costa Rica. An departure from the mean it is observed at the end of the record as a result of the April 22, 1991 earthquake (7.5 Richter scale).....	163
Figure 4.4. Annual suspended sediment production for selected drainage basins on the Caribbean coast of Costa Rica: (a) Barbilla watershed, (b) La Estrella watershed, and (c) Sixaola watershed. A significant increase on sediment production it is observed during 1991 as a result of the April 22, 1991 earthquake.....	164
Figure 4.5. Total sediment production for the Pacific and Caribbean watersheds in Costa Rica. The number of hurricanes is also presented during the 1971-1984 period.....	165

Figure 4.6. Grande de Terraba watershed annual suspended sediment production and mean annual precipitation. A reduction on sediment production is observed during “El Niño” years (1972-1973, 1976-1977, 1979-1980, and 1982-1983). Even though these reductions seems to be important, they are not significant different from the long-term mean.....166

Figure 4.7. The Abangares watershed annual suspended sediment production and mean annual precipitation. A reduction on sediment production is observed during “El Niño” years (1972-1973, 1976-1977, 1979-1980, and 1982-1983). Even though these reductions seems to be important, they are not significant different from the long-term mean..... 167

Figure 4.8. Total sediment production for selected watersheds in Costa Rica as function of their 1984 forest cover. Forest cover represents information extracted from the Costa Rica’s National Geographic Institute land use map (IGN, 1984)..... 168

Figure 4.9. Total sediment production for selected watersheds in Costa Rica as function of their 1991 forest cover. Forest cover represents ~80% of higher forest canopy closure, forest cover was extracted using a December 31, 1990 Landsat TM (path 15 / row 53)..... 169

ABSTRACT

ASSESSING LAND USE/COVER CHANGE IN COSTA RICA

By

Gerardo-Arturo Sánchez-Azofeifa
University of New Hampshire, September 1996

The need for accurate estimates of forest cover and forest fragmentation is a critical issue for developing countries such as Costa Rica. Accurate estimates of forest cover can help in several sectors related to the environment and economic development. This dissertation focuses on providing an accurate and precise estimate of forest cover in Costa Rica. The year 1991 was used as a baseline. Landsat Thematic Mapper was the remote sensing sensor used in this analysis. This dissertation concludes that: (1) Twenty-nine percent (~1,400,000 ha) of the country was under primary forest (80% canopy closure) in 1991. Of the total forest cover, 71% is outside national parks and 29% is protected by the national parks. (2) Forest loss (for scene path 15 / row 53) during five years period (1986-1991) was 224,970 ha, and it was estimated that the rate was ~44,994 ha/yr. (3) Deforestation produced an increase in island fragments during the study period. Between 1986 and 1991, the total number of islands between three and 50 ha, and 50 and 100 ha increased by 524 and 45, respectively. Fifteen new islands with areas greater than 500 ha were created. (4) Results suggest that the extent of tropical deforestation goes beyond estimations of total forest loss at the national level. The impacts at the national level have greater roots deeper roots when the

CHAPTER 1

TROPICAL DEFORESTATION AND HABITAT FRAGMENTATION IN COSTA RICA

Introduction

Environmental degradation of tropical environments is a major concern for developing countries (Allen & Barnes, 1985). Deforestation and its impact on soil erosion, water pollution, biodiversity losses, and degradation of scenic values are factors influencing economic productivity, quality of life, and well-being. Despite growing public concern and increasing political rhetoric, actions have been relatively ineffective in managing this great problem. Tropical forests are being degraded in critical ecosystems, and old growth forest lands suitable for timber production are being lost at rates far exceeding reforestation efforts.

The goals of sustainable development in developing countries are not being met partly because of a lack of access to advanced technology for environmental monitoring. Remote sensing techniques and geographic information systems are unique and important state-of-the-art tools for monitoring degradation of tropical ecosystems. These tools can define priority areas for conservation and development, and also be used to accurately and efficiently verify the effectiveness of land use planning.

As these technologies are becoming more accessible to developing countries, old and new problems are being reassessed, and the impact of the interactions between the natural

environment and economic development are easier to detect. Additionally, existing and newly identified problems, as well as their solutions, are becoming more clear through a more systemic and holistic assessment of them.

Costa Rica's situation is a good example of the needs that many developing countries in the humid tropics have for improved methods for natural resource assessment and management. Costa Rica's variety of ecosystems is determined by a complex combination of microclimates, aspect, topography and the spatial distribution of precipitation. These variables compounded with high variability in soil types, and the bridge effect between the North and South American subcontinents are responsible for its great ecological richness. It has been estimated that between 4% and 5% of all plant and bird species in the world are present in its forests. Therefore, there is no wonder that the country contains around 12,000 plant species (1,500 of them are different kinds of orchids), 850 bird species, 218 reptile species, 205 mammal species and 130 fresh water fish species. (Quesada, 1990; Janzen, 1983).

Costa Rica is a clear example of the complex interactions between the environment, population and development. A key study by Sader and Joyce (1988) estimated that between 1940 and 1984, Costa Rica had lost about 50% of its original forest cover. The study reported that by 1984, only 17% of the country's primary forest cover remained. The impacts of environmental degradation on Costa Rica's GNP have been studied by Solorzano et al. (1991). The authors stated that "in the twenty years between 1970 and 1989, the country lost natural resources worth more than one year's gross domestic product." The same report indicated that the deforestation process has been so rapid, that it accounted for 85 percent of

the estimated total resource depreciation for 1989.

Furthermore, Costa Rica's Strategy for Sustainable Development (Quesada, 1990) clearly indicates that among the most critical issues affecting the country's sustainable development are those of unproductive land use changes, environmental quality degradation, the accelerated nature of energy demand, and watershed degradation. All of these issues are in turn related to land pressures and growing environmental demands by a still high rate of population growth, exacerbated by a continuous flow of migrants from neighboring Central American countries.

Integrated resources planning and a management, and long term effective policies associated with land use zoning and environmental quality control, require objective data about the location and magnitude of natural resource degradation. This information can help to document the importance and urgency of these problems. This documentation if properly channeled to the decision makers, will be of great value to define consistent policies for making sustainable economic progress.

The purpose of this paper is to address the problem of monitoring current forest cover and forest loss in Costa Rica, using remote sensing and Geographic Information Systems (GIS) as the main basis for the work. The analysis recognizes that forest cover information from Costa Rica's agricultural census is not good enough to estimate country-level deforestation and deforestation rates. I also suggest that forest cover studies to-date have not provided enough information to adequately quantify the forest loss and its fragmentation. A GIS was used to integrate different types of spatial data (e.g. political divisions, and ecologic life zones) with data from Landsat Thematic Mapper (TM) satellite scenes from 1986 and

1991. The generated information makes it possible to: (1) make a comprehensive assessment of Costa Rica's forest cover in 1991, and (2) measure the rate of tropical deforestation in central Costa Rica between 1986 and 1991. Moreover, the integration of remote sensing derived information with spatial information such as ecologic life zones, made it possible to estimate the remaining forest cover for each ecologic class, and quantify forest fragmentation by the life zone.

Tropical Deforestation in Costa Rica

In 1992, Costa Rica's Strategy for Sustainable Development (ECODES) indicated that trends of unsustainable management of the country's forest resources in the last 50 years will deplete of all primary forest of commercial timber by 1995 (Quesada-Mateo, 1990). In addition, ECODES stated that deforestation impacts also result in habitat loss and general environmental deterioration of drainage basins. The latter point is an important one for a country where more than 90% of its energy generation comes from hydropower (Costa Rica, 1995).

Costa Rica's deforestation rate between 1976 and 1980 had been estimated at 3.19 percent per year (FAO, 1990). This high deforestation rate ranked the country as fifth in the world (in terms of percentage). Reforestation efforts were estimated as being negligible before 1979, and had increased at a slow rate since them (Lutz et al., 1990; Butterfield, 1994).

The dynamics of land-use / land-cover change (LUCC) in Costa Rica during the last

30 years have generally been driven by the expansion of the agricultural and cattle frontier (Centro-Cientifico-Tropical, 1982; Harrison, 1991; Quesada-Mateo, 1990; Ramirez & Maldonado, 1988). This LUCC process was encouraged by legislation which placed low value on forest and high value on agricultural development (Gaupp, 1992). Tropical deforestation was also considered to be important to expansion of meat production, and was strongly supported through national and international loans (Aguilar et al. 1982). Deforestation was used as a tool to expand grazing land without regard for potential environmental degradation. By 1980, the Tropical Science Center of Costa Rica indicated that up to 76% of all the land with potential for crop production was occupied by pastures (Centro-Cientifico-Tropical, 1982). Additionally, Harrison (1991) have also concluded that during the early stages of Costa Rica's deforestation, the demand for agricultural land (usually for pasture), rather than the demand for timber, was another force driving deforestation.

Costa Rica's deforestation had important economic consequences. Solorzano et al. (1991) estimated that the annual depreciation of the Gross National Product (GNP), between 1970 and 1989, due to deforestation ranged from \$42 million to \$422 million U.S. dollars. These authors estimated that in 1984 the total net value related to forest loss was \$167.3 million U.S. dollars, which was equivalent to \$69 U.S. per capita. In addition, their study indicated that in 1988 and 1989, depreciation of the forest assets increased public external debt by approximately 36 percent. Sanchez-Azofeifa and Quesada-Mateo (1995) indicated that the deforestation rates in Costa Rica have decreased significantly in the last decade. Deforestation rates may have been reduced as a result of several elements factors: (1) *an increase in the cost of wood*; this reduced per capita demand, (2) *the increase in the*

efficiency of harvest, by reducing wood volumes burned or wasted, and by an increase in the number of exploitable species; (3) *increased efficiency at the industrial level*, including improvements in the exploitable yields at the saw mill; (4) *a greater desire to protect forests by the organized rural population*; (5) *the increase of private reserve areas* for the purpose of exploiting eco-tourism, or as protection estates located in buffer zones around national parks with a view of maintaining open options for a future sustainable exploitation; (6) *the development of financial incentives* by the central government for the preservation of forest; and (7) *the presence of several joint implementation initiatives* as part of projects dealing with carbon sequestration and the Framework Convention for Climate Change (FCCC).

However, the positive forces described above should not be used to obscure continuing impacts of deforestation. Several socioeconomic factors continue pressures for deforestation. A relatively high population growth rate (2.6% per year) and an increasing distortion in income distribution. Such forces are promoting a dangerous bias in land tenancy, seriously affecting lower income groups, both in the rural and the urban milieus. Marginal rural and urban populations are and will continue to be important forces driving land invasions of forest areas (Mora, 1993). Additionally, high rates of migration from neighboring countries, due to deterioration of living standards, is also an issue of concern. These are some elements that must be properly evaluated within the framework of conservation policies and deforestation control.

Overview of Remote Sensing and GIS Studies in Costa Rica

Most of the current research in the area of remote sensing and GIS in Central America has focussed on Costa Rica. The country's political stability has permitted the development of several research projects in the area of tropical deforestation, habitat fragmentation and land use dynamics (Sader & Joyce, 1988; Luvall et al., 1990; Sader et al., 1991; Veldkamp et al, 1992).

The first attempts to implement a nationwide natural resources inventory in Costa Rica dates back to the late 1970's early 1980's (Campbell, Rodriguez, & Sader, 1979; Sader, 1980). This first attempt was coordinated by the Costa Rican government and the U.S. Agency for International Development (US AID). The former study was prompted by concerns of Costa Rica's government regarding accelerated rates of land use change and their associated impacts on the national environment. Campbell et al. (1979) implemented a three phase project to design an operational natural resource inventory and information system for Costa Rica. This system used aerial photography and Landsat Multi spectral Scanner (MSS) satellite scenes.

Sader's (1980) project was also part of the national natural resource inventory sponsored by U.S. AID. The main goal of this project was to evaluate the applicability of Landsat MSS information for resource management in Costa Rica. Landsat MSS information was used as the primary data source to estimate the area of coffee lands in the Naranjo region. This study used a GIS and a stratified data base to improve coffee detection. Sader concluded that remote sensing derived information was able to estimate coffee areas within 8% error. In addition, this study reported that Landsat MSS was able to identify mangrove and

grassland classes reasonably well, but was considerably less accurate in the identification of forest and brush. Remote sensing results were compared with aerial photography derived information. Even though Sader's study provided important insights regarding the application of remote sensing technologies in Costa Rica, it was suggested that aerial photography was better suited for Costa Rica's interests at that time.

Sader (1988) conducted a second study related to application of remote sensing and GIS technology in Costa Rica. This study focussed on the use of multi temporal Landsat MSS to monitor and map forest change dynamics. Satellite analysis was compared to aerial photography interpretation. A normalized difference vegetation index (NDVI) was computed for a subset of a satellite scene in Northeastern Costa Rica (La Selva Research Station). MSS scenes were acquired for January 1976, 1984, and February 1986. Sader's conclusions indicated that the use of multi-temporal NDVI, without cross reference to aerial photography, was not recommended for operational forest inventory programs where the objective is to update forest maps or forest area statistics. The study also suggested that a combination of two dates of imagery was adequate to detect forest change using NDVI.

The only comprehensive country-wide forest cover and deforestation study for Costa Rica has been presented by Sader and Joyce (1988). Their study attempted to measure relatively undisturbed natural forest with an upper canopy cover of 80% or more. The study period was between 1940 and 1983. This country study involved aerial photography interpretation and digitizing of available forest cover maps. Maps provided by several Costa Rican institutions and aerial photography interpretation were integrated into a GIS with other spatial data bases (i.e. roads, slope ranges, etc.). The minimum mapping unit was 55 ha (750

m grid). The study reported that total primary forest remaining in 1940, 1950, 1961, 1977, and 1983 was 67, 56, 45, 32, and 17 percent of Costa Rica's territory, respectively. This paper concluded that: (1) deforestation had initially occurred in tropical dry and moist life zones; during intermediate periods, tropical and premontane moist and wet zones were more affected; (2) by 1983, only the less accessible high rainfall zones in rugged terrain retained relatively undisturbed forest; and (3) the reported forest areas estimates pertained only to primary forest as portrayed by the source maps, indicating that total forest area in Costa Rica could be higher than what they figured. The authors concluded that there was a need for future development of quantitative estimates of deforestation and afforestation for Costa Rica using remote sensing techniques.

Remote sensing and GIS technology has also been implemented in Costa Rica to monitor migratory bird habitats (Sader, Powell & Rappole, 1991). This project was implemented in north-eastern Costa Rica, in the vicinity of La Selva Research Station and the Braulio Carrillo National Park. An unsupervised Gaussian maximum likelihood classification was performed on a February 6, 1986 Landsat Thematic Mapper (TM). Results indicated an overall accuracy of the forest and non-forest map was 70% (Kappa correction). Forest class accuracy was reported to be 93%. The study concluded that satellite remote sensing was able to provide information about habitat availability and habitat conversion that could not be obtained by other means at that time. The study reported problems in classifying successional and secondary growth habitats when the unsupervised classification technique was used. Unsupervised classifications were unable to distinguish between major vegetation groups that are important for migratory birds. The authors concluded that the use of a supervised

classification, where plots are selected using aerial photography in successional and secondary growth would improve the classification of habitat types.

Several regional studies integrating remote sensing and other socio-economic information using GIS were conducted in Costa Rica during the 1990's (Mulders, De Bruin, & Schuiling, 1992; Velkamp, 1992; Alfaro et al., 1994; Velkamp & Fresco, 1994; Velkamp & Fresco, 1995; Stoorvogel, Schipper, & Jansen, 1995; Schipper, Jansen, & Stoorvogel, 1995). Velkamp (1992) presented a clear example of the potential of Geographic information systems for studying and monitoring deforestation at the regional level in Costa Rica. This study links a quantitative inventory of deforestation to possible factors driving forest clearing, like accessibility and soil quality. Aerial photography taken in 1952, 1960, 1971 and 1973 for a 395 km² area in the Atlantic region of Costa Rica was used. This study integrated several data layers of information such as soil fertility, river networks and road distribution. The integration of the former layers of information made it possible to understand some of the dynamics of deforestation in the Atlantic region. The study concluded that aerial photography offers a good means for deforestation analysis in Costa Rica.

More comprehensive mapping of deforestation on a regional scale was performed by the Timber and Forest Sector Cooperation Project. This project is part of a Costa Rican and German Government conservation project (COSEFORMA, 1994). This project was funded by the German Agency for International Development (GTZ). The project focussed on the northern region of Costa Rica (5,600 km²). The study's objective was to create a geographic data base to support a regional plan for forest development in San Carlos (Costa Rica's northern region). The result of this project was a 1:50,000 map which indicates six different

kinds of forest disturbance. This project did not provide information regarding the state of forest fragmentation in the study area, nor the rate of tropical deforestation in the region.

Deforestation and its consequences have been studied for at least two decades. The brief review of results presented above documents the progress that has been made in applying remote sensing and GIS tools to address questions related to conservation biology, deforestation, and land use. This study builds on previous work, providing the first comprehensive country-wide assessment of deforestation and forest fragmentation with high resolution (30 m) Landsat Thematic Mapper (TM) data.

Methods

In order to explore the extent of Costa Rica's forest cover in 1991 and 1986 remote sensing and geographic information systems were used to meet the needs for high spatial resolution. Costa Rica's tropical forest was mapped from four Landsat TM scenes in 1991, and from one Landsat TM scene for central Costa Rica in 1986 (Figure 1.1). LANDSAT Thematic Mapper (TM) satellite information with a spatial resolution of 28.5 x 28.5 m and 7 spectral bands were used in the analysis. The following sections outline and describe in detailed the methodology used in this study (Figure 1.2).

Data Acquisition Procedures

Forest cover area can be extracted using several remote sensing platforms. These platforms have a wide range of spatial and spectral resolutions. Currently, the French Systeme

Probatoire d'Observation de la Terre (SPOT), the U.S. Landsat and the AVHRR on board the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites, are common sensors used to map deforestation.

Townshend and Justice (1988) had concluded that the ability to detect changes through time using remotely-sensed systems is a complex function of the spatio-temporal characteristics of the landscape and the image properties; most important is the spatial resolution, radiometric fidelity and, frequency of acquisition. Therefore, taking for former issues into consideration, a three step data acquisition model was implemented for this study. The main considerations were (1) spatial resolution, (2) temporal resolution, and (3) spectral resolution. The objective of this model was to select the best possible satellite scenes to implement a study of forest cover/fragmentation in Costa Rica.

There has been considerable success using fine and medium scale resolution techniques to monitor land-cover conversion and deforestation processes in Costa Rica (Sader & Joyce, 1988; Sader, 1988). At the same time, there is important evidence that coarse-resolution imagery tends to overestimate the deforested area in the tropics (Skole, 1992). Additionally, Townshend and Justice (1988) have concluded that spatial resolutions finer than 1 km are highly desirable for change detection.

U.S. Landsat Multispectral Scanner (MSS) (80 x 80 m) and the U.S. Landsat Thematic Mapper (TM) (30 x 30 m) were considered in this study. MSS and TM data can be acquired in the United States at relatively low cost through a U.S. Global Change Research Program initiative. Additionally, Landsat TM data can also be obtained by Latin American research institutes at the CLIRSEN-Ecuador receiving station. Skole and Tucker (1993)

studying the Brazilian Amazon showed that Landsat TM provides enough spatial resolution to map forest cover, forest fragmentation and tropical deforestation. Landsat TM provides larger geographic coverage at less cost than SPOT satellite scenes, and at a finer spatial resolution than the MSS platform (28.5 x 28.5 m versus 57.0 x 57.0 m). In addition, Skole (1994) comparing resolutions and accuracy of Landsat TM, SPOT and AVHRR has suggested that a research program to measure and map deforestation in tropical forest would be best implemented using high resolution data such as TM. This recommendation agrees with Townshend and Justice (1988) which suggested that LUCC process can be better monitored and mapped using spatial resolutions of 250 m or less.

The most important sampling issue for this study was cloud cover. Costa Rica has two different precipitation regimes. The Caribbean region has the most rain during December and January, which is the dry season for the Pacific region. Research experience regarding data acquisition for Costa Rica indicates that almost all scenes collected during the last 20 years by the U.S. Landsat program have a high percentage of cloud cover. The main temporal criterion for scene selection was to acquire dry season Landsat TM scenes collected between January and March in the Pacific region, and during late September to early November in the Atlantic region. A cloud cover of 20 percent or less was required.

The selection of the sensor was also a function of the spectral resolution. Proper spectral resolution makes it possible to clearly identify forest and non-forest classes. The SPOT XS, or Multi spectral contains 3 bands: green (band 1, 0.50-0.59 μm), red (band 2, 0.61-0.68 μm) and reflective infrared (band 3, 0.79-0.89 μm). The reflective infrared band on the SPOT XS sensor, is responsive to the amount of vegetation biomass present in a scene.

The MSS sensor records electromagnetic radiation (EMR) in four bands: green (band 1, 0.50-0.60 μm), red (band 2, 0.60-0.70 μm), reflective infrared (band 3, 0.70-0.80 μm) and reflective infrared (band 4, 0.80-1.10 μm). Bands 1 and 2 are in the visible portion of the spectrum and are useful in detecting cultural features such as roads. Bands 3 and 4 are in the near-infrared portion of the spectrum and can be used in land/water and vegetation discrimination. Band 2 is the red chlorophyll absorption band of healthy green vegetation and represents the one of the most important MSS bands for vegetation discrimination. Band 3 is especially responsive to the amount of vegetation biomass present in a scene. Finally, Landsat TM detectors record EMR in seven bands: blue (band 1, 0.45-0.52 μm), green (band 2, 0.52-0.60 μm), red (band 3, 0.63-0.69 μm), reflective-infrared (band 4, 0.76-0.90 μm), mid-infrared (band 5, 1.55-1.74 μm), thermal-infrared (band 6, 10.40-12.50 μm), and mid-infrared (Band 7, 2.08-2.35 μm). Landsat TM bands 1, 2 and 3 are in the visible portion of the spectrum and are useful in detecting cultural features such as roads. Bands 4, 5, and 7 are in the reflective-infrared portion of the spectrum and can be used in land/water discrimination. Band 6 is in the thermal portion of the spectrum and is used for thermal mapping. The advantage of Landsat TM over the MSS and SPOT sensors is the number of bands in the near and mid-infrared. Band 5 is specially important because is sensitive to the amount of water in plants, which is useful in crop drought studies and in plant health analyses. A full description of the Landsat TM sensor can be found in Short (1992).

Taking the former three criteria into consideration, and the recommendations by Townshed & Justice (1988) and Skole (1992), the data acquisition model focussed on acquiring available TM scenes for Costa Rica. The WRS-2 tile system for Landsat was used

as a reference framework. Figure 1.1 presents the location on Path and Row and other characteristics of the selected scenes for this study.

Classification Algorithms

Geographic Registration. Satellite images first bulk corrected and later georeferenced into an Universal Transverse Mercator projection (UTM-Zone 16 North). Georeferencing refers to the process of assigning map coordinates to image data. Ground control points (GCP) were selected from 1:50,000 topographic maps (Instituto Geografico Nacional, 1994). Scenes were georeferenced to map coordinates. Latitude and longitude coordinates on decimal degrees were extracted from the topographic maps using a Trimble Geographic Positional System (GPS). Reference points in decimal degrees were transformed into UTM coordinates for Zone 16 North using ARC/INFO. Selected points were projected into the bulk corrected satellite scenes using a first order linear transformation (ERDAS, 1991).

A root mean square error (RMS) of 0.50 was defined as standard for all images. The RMS error is the distance between the input (source) location of a GCP, and the retransformed location of the same GCP. RMS error is expressed as a distance in the source coordinate system, in this case, pixel widths. For the selected scenes rectification was accurate within 30 meters. Scenes were resampled using the nearest neighbor algorithm.

Extraction of Forest Classes. Due to its geographic and climatic condition, Costa Rica posses a rich combination of vegetation and wildlife. Twelve life zones and twelve transition zones, containing 44 vegetation macro types and nine subdivisions are present (Janzen,

1983). Due to this complexity, and the limits of remote sensing for discriminating subtle differences in vegetation, it is difficult to try to map each individual forest type with a wall-to-wall approach. In this case, a forest/non-forest class system that is mutually exclusive was selected. That means that all of the area classified as forest should fall into one category class (Congalton, 1991).

A classification using primary forest, non-forest, water, clouds, urban area and cloud shadows was implemented. The class defined as "*primary forest*" referred to relatively undisturbed forest. Classes were extracted using a supervised classification: the maximum likelihood procedure. In this procedure, the identity and location of feature classes (e.g. primary forest) are known *a priori* by identifying points on the image in which there were ancillary data available from aerial photography and field calibration. Aerial photography obtained from Costa Rica's National Geographic Institute were used for site selection and verification of the satellite classification. Field work for selected classes were implemented in Costa Rica during 1994-95 on points around San Jose City, La Selva research station and the Upper Reventazon basin (Figure 1.13). Field work consisted on a cross reference of land cover features between the aerial photography and satellite scenes. This points were later used during the accuracy assessment analysis.

Criteria for Elimination of Clusters. Criteria for the elimination of small clusters of pixels in a given feature class is related to the minimum mapping unit. The minimum possible scale is driven by the spatial resolution of the input data (e.g. Landsat MSS and TM). The size of the *minimum mapping unit* (MMU) will depend on the spatial resolution of the input data,

in this case 28.5 x 28.5 m. The minimum mapping unit is defined as the minimum thematic units represented on a map. Under the MMU criterion, groups of clusters that do not present a significant contribution to the final product are eliminated. In addition, elimination of pixels is based on national standards for a specific cartographic product. Baker et al. (1979) stated that the scale of the final map, not the photo or imagery scale, may dictate the minimum size of areal units.

Final map scale was selected to be 1:250,000. The scale was selected because of the use of satellite false color composite photos for comparison and definition of classes. For the 1:250,000 scale, minimum mapping unit is ~30,000 m² or ~3 ha (United States Geological Survey, 1986). The selected MMU represents those polygons with ~ 6 pixels on the side.

GIS for Data Integration. Resulting masses of primary forest from the supervised classification were converted from raster to a vector. Once coverages were transformed into a vector format, those polygons with areas less than the MMU were eliminated. The vector output was plotted on transparent paper at 1:250,000 scale and overlaid on top of a color composite photo-product (bands 4,3,2) of the same image. Errors related to misclassified, and omitted or mislabeled polygons were checked and corrected. This process was repeated more than two times to assure high quality control.

Once each individual scene was checked for classification errors, the 1986 and 1991 scenes were overlaid. The reason for the overlay was to check for spurious polygons. This process is also known as “in-pair” processing (Chomentowsky, 1994). Spurious polygons are

those that were classified as primary forest in 1991, but did not exist in 1986. These inconsistencies were identified, cross checked with the photographic product, and eliminated from the 1991 forest map.

When all satellite scenes passed quality control, vector coverages were transformed to raster format and integrated into a mosaic. A raster transformation from each final vector coverage was performed to avoid edge matching problems, as well as the presence of small polygons along the matching area. The final grid coverage, containing the final mosaic, was transformed to vector format for analysis of total forest cover, total deforestation and habitat fragmentation.

Methods for Thematic Accuracy Assessment

The selection of the sample size. Important considerations regarding sample size are (1) the sample size must be large enough to provide precision at a specified significance level, (2) sample point selection must be unbiased, (3) the sampling procedure should have a low probability of accepting a map of low accuracy, (4) the sampling procedure should have a high probability of accepting a map of high accuracy, and (5) the procedure should require a minimum number of ground control points (Fitzpatrick-Lins, 1981; Congalton, 1988).

The number of sites will depend on the expected percent accuracy (p). The binomial distribution has been recognized as the best mathematical model to use for accuracy assessment (Congalton, 1988). Fitzpatrick-Lins (1981) and later Jensen (1986) have recommended that the number of points to be sampled can be derived from the formulas for the binomial probability theory. The recommended equation for the appropriate sample size,

N is

$$N = \frac{Z^2 pq}{E^2} \quad (2.1)$$

where p is the expected percent accuracy, q the difference between 100 and p , E the allowable error, and N the number of points to be sampled. In general, Z is equal to 2, and it is generalized from the standard normal deviate of 1.96 for the 95% two sided confidence level.

Once the sample size has been defined, Global Positioning Systems (GPS) can be used for in-the-field collection of sampling points. The GPS system consists of an array of 18 NAVSTAR (Navigation System with Time And Ranging) satellites. NAVSTAR satellites circle the earth in 20,000 km circular orbits within a 12-hour period. Signals from three NAVSTAR satellites give a two-dimensional (latitude and longitude) position, and four satellites provide complete three-dimensional position (latitude, longitude and elevation) (Wilkie, 1991).

August et al. (1994) have recommended to collect an average 300 fixes per site. This technique, with differential correction, will provide data within 6 m of a true location. When differential correction is not used, each fix will be between 75 m of the true location (which is below the MMU). The authors also concluded that averaging fixes significantly improves the accuracy.

In addition, three important conditions must be set when data is collected. First, plot size must agree with the minimum mapping unit of the final cartographic product. Second, selected sites must be consistent with the land use/land cover that the satellite image is

representing. Third, the total number of points per class must be proportional to the area cover for each class in the map.

The first condition will avoid the selection of mixed plots. Sites will be selected in a fashion that deforestation or primary forest must be at least 3 ha in surface area. This will ensure compatibility with the MMU of the final cartographic product. Secondly, the temporal variability and growth rate of vegetation in the tropics must be considered during site selection. There is a strong possibility that errors can be included in the data base if sites are misclassified in the field. In order to avoid misclassification errors, the best option is to have synchronized satellite scene acquisition and GPS site selection/collection during at the same time or season that the image is acquired.

Finally, it is important to sample a proportional number of points. This means that the number of points to be selected and collected in the field must represent a percentage of each class (e.g. forest, non-forest, etc.) in the final map. This process is defined as weighted sampling. This procedure will assure a fair representation of the final sample, as well as will prevent bias toward one class or another.

In addition, site selection for field data collection must consider the issue of scene selection by stratified sampling. Stratification is defined as those sets of criteria used to select the lowest and most representative elements from a population, minimizing the error, and producing less bias in estimation of a predictive variable. In those cases in which there are several scenes for site selection, stratification is recommended to identify and select scenes for accuracy assessment. Stratified sampling considering criteria such as percentages of forest, non-forest, secondary growth and other important classes must be used as reference variables.

Selection of scenes to perform accuracy assessments will depend on the possibility of accessing the sampling site. Random selection of sampling sites for accuracy assessment is recommended in order to provide bias-free sites (Berry and Baker, 1968). However, in several cases, access to randomly selected points is restricted by the accessibility in the field (terrain, roads, etc). A GIS consisting of national and rural road networks is recommended as a tool for site selection. An overlay of the WRS-2 reference system, with information regarding scene land cover dynamics and road networks will permit researchers to select scenes which allow for the accessibility problem. Criteria such as distance from population centers, quality of roads, travel time and road conditions can be used to select those scenes where a potential accuracy assessment can be performed.

Calculations. Field data must be entered in an error matrix for accuracy assessment (Table A.1). An error matrix is a square array of numbers organized in rows and columns to express the relative number of sample units assigned to each studied class. By convention, columns represent reference data and rows represent the generated information (Congalton, 1991).

The 95% confidence limit for each category in the final map product, is estimated following the two-tailed test from the binomial distribution (Jensen, 1986):

$$p = p^* \pm [1.96 \sqrt{\frac{p^* q^*}{n} + \frac{50}{n}}] \quad (2.2)$$

where p^* is the value of the true percent corrected, q^* is equal to $100 - p^*$ and n is the number of points sampled for each category.

The overall accuracy of a map is represented by the ratio of the total correctly classified pixels versus the total number of pixels. Fitzpatrick-Lins (1981) and Jensen (1986) presented a lower limit for the overall accuracy. This lower limit is obtained from the 95% one-tailed binomial distribution:

$$p = p' - [1.645 \sqrt{\frac{p'q'}{n} + \frac{50}{n}}] \quad (2.3)$$

where p is the accuracy for the map expressed as percentage, p' is the ratio between the number of points classified correctly to the number of points (overall accuracy), q' is calculated as $100 - p'$ and n is the sample size.

The concept of weighted overall accuracy has been presented by several authors (Berry, 1962; Fitzpatrick-Lins, 1986; Rosenfield, 1982). Most sample points are selected in those categories that cover most of the map area, and the fewest points are from categories that cover the least area. Weighted overall accuracy accounts for the distribution of points as a function of class area. The formulation for p_w is as follows:

$$p_w = \frac{1}{n} \times \sum (c_{ii} \times a_i) \quad (2.4)$$

where n is the sample size, c_{ii} is the diagonal value of the error matrix, and a_i is the weight for each class.

The KAPPA is another measure of summarizing the accuracy of the error matrix (Cohen, 1960). The KAPPA statistic is used as a powerful technique for the comparison of matrices (Conglaton, 1991). The result of performing a KAPPA analysis is a KHAT statistic

(an estimate of KAPPA). The KHAT statistics is computed as:

$$KHAT = \frac{N \sum c_{ii} - \sum R_{i.} R_{.i}}{N^2 - \sum R_{i.} R_{.i}} \quad (2.5)$$

where + represents summation over the index.

Another measure of accuracy for the error matrix is the Tau coefficient. Ma and Redmond (1995) indicated that Tau adjusts the percentage agreement better than KAPPA. It is also easy to calculate and interpret. The Tau coefficient is superficially similar to Kappa, and is calculated as:

$$T = \frac{P_o - P_r}{1 - P_r} \quad (2.6)$$

where P_o is the percentage agreement, and P_r is the random agreement. P_o and P_r can be calculated for a sample of size N as:

$$P_o = \frac{1}{N} \sum c_{ii} \quad (2.7)$$

$$P_r = \frac{1}{N^2} \sum (R_{i.} c_{ii}) \quad (2.8)$$

For land use / land cover classifications based on equal probability of group membership, the Tau coefficient becomes T_e . In this case T_e is adjustment of the percentage of agreement (P_o) by the number of groups:

$$T = T_e = \frac{P_o - \frac{1}{M}}{1 - \frac{1}{M}} \quad (2.9)$$

where M is the number of classes. For a classifications similar to the NASA pathfinder, where M= 4 classes, the Te becomes:

$$f_e = \frac{p - 0.25}{0.75} \quad (2.10)$$

where p is the overall accuracy of the map (sum of the diagonals divided by the total number of samples).

For classifications based on unequal probabilities the Tau coefficient becomes T_p . T_p will be an adjustment of percentage of agreement (P_o) by the number of groups and the "a priori" probabilities:

$$P_r = \frac{1}{M} \quad (2.11)$$

The Tau coefficient also accounts for the following cases in which error matrices are generated from:

- (1) unsupervised classifications with equal probabilities: The random agreement coefficient (Pr) will be determined by the number of groups (1/M)
- (2) supervised classifications with equal probabilities of group membership: random agreement (Pr) is determined by the number of groups (1/M)
- (3) supervised classification with unequal probability of group membership: random agreement (Pr) will be determined by:

$$P_r = \frac{1}{N^2} \sum R_i \cdot c_{ii} \quad (2.12)$$

Methods for Positional Accuracy Assessment

Most of the current standard error techniques in remote sensing interpretation deal with identifying error in individual pixel assignments, a process that is known as thematic accuracy assessment (Fitzpatrick-Lins, 1981; Congalton, 1988). These techniques overlook the fundamental fact that satellite image interpretation is a process of generalization of boundaries between feature classes (Wang & Howarth, 1993). Variance in the delineation of feature boundaries translate into variance, and error, in the estimation of feature geometry and, hence, calculation of areas. There are only a few approaches in the literature to estimate shape variance. Most of these studies focussed on developing methodologies to evaluate hand digitizing errors. For example, error definition from hand digitizing has been studied by Dunn, Harrison and White (1990). Dunn et al. (1990) presented an empirical approach to estimate positional accuracy and measure error in digital data bases. Their premise was to introduce the concept of epsilon band. The epsilon band concept stated that cartographic lines are surrounded on each side by an area constant width *epsilon*. This approach suggested that error distribution along digitized lines follows some probability density function (pdf). In addition, it was assumed that the error is global along the whole map without any spatial variability (Edwards & Lowell, 1996). The epsilon band concept has been used by Skole and Tucker (1993) to test positional accuracy on digitized deforestation data sets for the Brazilian Amazon. The authors indicated that variance associated with interpretation and delineation

of forest/non-forest polygons for the Amazon basin was less than 10% overall.

Shape or area error estimation from remote sensing satellites has been studied by Wang & Howard (1993). This paper indicated the boundary definition process is driven by a process of stochastic boundary interpretation based on a probability vector rather than a deterministic approach. The probability vector provide important information regarding uncertainties in boundary pixel allocation. Several realizations (or interpretations) can be obtained from a polygon. The authors stated that the result of a remote sensing classification is a unique version of a population. The elements of the population are defined as realizations. Each realization represents a sample from a population of possible classifications.

Wang and Howard (1993) stated that realizations of forest-non-forest classes are affected by the relative position of boundary pixels between classes. The term boundary pixel refers to a pixel that has properties which are confused with some of the adjacent pixels in geographic space. The authors concluded that in the context of thematic mapping, errors in boundary position are related to the way in which boundaries are generalized.

The methods presented in this chapter differ from the original approaches of Dunn et al. (1990) and Wang and Howard (1993). Aerial photography and remote sensing information were integrated into a three phase procedure to study the issue of boundary accuracy assessment in the Costa Rica final cartographic product. These steps were (1) rectification and selection of test sites, (2) definition of relationships between aerial photography and Landsat TM, and (3) definition of forest islands and comparison of results.

Aerial photography taken in 1992 by the Defense Mapping Agency (scale 1:40,000) and Landsat TM information acquired on January 1st 1991, was used in this study. A study

plot in northeastern Costa Rica was selected as study site.

During Phase 1, aerial photography was scanned and geo-referenced to the 1991 Landsat TM scene. A RMS of 0.5 and a first order transformation were used for georeferencing. A nearest neighbor algorithm was used as a resample technique (ERDAS, 1991). The final spatial resolution of the scanned aerial photography was 5 x 5 m. Aerial photography was interpreted for forest non-forest classes. Three test sites consisting of isolated forest islands were selected from the aerial photography (Figure 1.3). Study sites were identified and clipped from the aerial photography, the Landsat TM scenes and the final GIS cartographic product. Study sites were located on the central part of the aerial photography to avoid edge distortions. Island No. 1 was selected as a sampling source.

During Phase 2, three cross sections from island No.1 were extracted from the aerial photography and the satellite scene (Figure 1.4). A kernel window of 5x5 pixels from the aerial photography was used. The geographic location of the central pixel on each kernel window in the georeferenced aerial photography represented the approximately the same geographic location on the Landsat TM pixel. The location of the central Landsat TM pixel is not the exact location of the central point of the 5x5 pixel aerial photography kernel window, this because of the distortions of the aerial photography and the variance associated with the georeference of the aerial photography to "real world" coordinates. For each kernel window, the total percentage of forest cover was estimated from the aerial photography. Percentage of forest was correlated to its correspondent digital number on each band of the Landsat TM cross section (Figure 1.5). Figure 1.6 presents the correlation between the digital number from each Landsat TM band and the percentage of forest cover from the aerial

photography.

Finally, phase three involved the selection of a digital number that represents a threshold between different canopy density classes (Table 1.1). Selected pixels representing 70, 80 and 90 percent canopy density were extracted from the selected Landsat TM forest island No. 1. Selected pixels for each canopy density class were used as training sites in a supervised classification with equal probabilities. Raster results were transformed into vector format and compared with results from the final map product. Total area, perimeter, shape index and fractal dimension were used as a comparison criteria for each simulated forest island against the final GIS reference islands. This comparison was used as a criterion to define the final canopy closure represented in the final map.

Shape index and fractal dimension were used to evaluate the sensitivity of the sensor in terms of total area and island shape to the reference islands. These two factors were estimated by using the following expressions:

$$SHAPE = \frac{0.25P_{ij}}{\sqrt{a_{ij}}} \quad (2.13)$$

$$FRACT = \frac{2\ln(0.25P_{ij})}{\ln a_{ij}} \quad (2.14)$$

where P_{ij} and a_{ij} represent the perimeter and area of the i^{th} and j^{th} island. The former two expressions can only be used when P_{ij} and a_{ij} are extracted from vector format data bases

(McGarigal & Marks, 1994).

Quantification of Forest Fragmentation

Quantification of tropical forest fragmentation between classes was normalized by using the concept of patch density, mean patch size, patch size standard deviation and patch size coefficient of variation (McGarigal & Marks, 1994). Patch density and mean patch size are considered first-order-statistics and provide basic standardized information about the selected landscape unit. The patch size standard deviation and patch size coefficient of variation are defined as second-order-statistics, which provide key information in terms of landscape heterogeneity that is not captured by the first-order statistics.

Patch density (PD) is considered a fundamental variable of landscape structure. Patch density expresses the number of patches per unit-area basis. McGarigal & Marks (1994) indicated that the PD concept facilitates comparisons between landscapes of variable size. PD for vector representations of the landscape is calculated as:

$$PD = \frac{n_i}{A} (10,000)(100) \quad (2.15)$$

where, n_i represents the total number of patches of a land use case I and A represents the landscape area (m^2). PD is expressed by the number of patches per 100 hectares. If the number of patches, and not their area or distribution, is important, McGarigal & Marks (1994) have indicated that patch density for a particular patch size could serve as a good fragmentation index.

Mean patch size (MPS) can serve also as a habitat fragmentation index. The progressive reduction in the size of habitat fragments is a key component of habitat fragmentation (Askins, 1995; Bierregaard, 1992). MPS (in hectares) is defined as:

$$MPS = \sum_{j=1}^n \frac{a_{ij}}{n_i} \left[\frac{1}{10,000} \right] \quad (2.16)$$

Patch size standard deviation (PSSD) is a measure of absolute variation. PSSD is a function of the mean patch size and the difference in patch size among patches. PSSD is a useful parameter to use in conjunction with mean patch size. Patch size coefficient of variation (PSCV) is a better indicator of patch variability among landscapes. PSCV measures relative variability about the mean, not absolute variability. PSSD and PSCV are calculated as:

$$PSSD = \sqrt{\frac{\sum_{j=1}^n \left[a_{ij} - \left[\frac{\sum_{j=1}^n a_{ij}}{n_i} \right]^2 \right]}{n_i} \times \frac{1}{10,000}} \quad (2.17)$$

$$PSCI = \frac{PSSD}{MPS} \times 100 \quad (2.18)$$

Fragmentation statistics were compared at the Holdridge life zone level. The life zone concept is an *association though as a natural unit in which the vegetation, the animal*

activities, the climate, the land physiography, geological formation and the soil are interrelated in a unique combination which has a distinct aspect or physiognomy (Holdridge, 1995). Life zones comprise equivalently weighted divisions of the three major climatic factors: heat, precipitation and moisture.

Results

Analysis of Spatial Distribution of Forest Cover in 1991

Total forest cover. Four Landsat TM scenes with less than 20% cloud cover were used to map 1991 forest cover. These four scenes represent 93% of Costa Rica's territory. The analysis for 1991 showed that 29% (1,361,491 ha) of the country was covered with primary forest with a canopy density of ~80%, 54% (2,546,423 ha) was identified as non-forest, and 17% (800,687 ha) was covered with clouds (Figure 1.7). Highest cloud cover was in the northern zone and the Peninsula de Osa.

Our results are significantly different from those of Sader and Joyce (1988). Sader and Joyce reported that only 17% forest cover was present in 1983, in contrast with the 29% reported in this study. There are some possible explanations for the differences. First, the Sader and Joyce (1988) study was based on digitized maps from different sources (which can contain important classification errors). Second, the minimum mapping unit selected for the 1983 study was 55 ha, in contrast with 3 ha in this study. Sader and Joyce were aware of this potential difference and suggested that their reported forest area could be underestimated.

By overlaying the new 1991 forest cover image on maps of national parks, I calculate that of the total primary forest mapped, 29% percent of the mapped primary forest is

protected by national parks, and 71% is outside of these protected areas. Existing forest cover is spatially concentrated along the central cordillera, where high slopes and accesses is difficult.

Four main forest islands, with areas higher than 10^3 ha, were delineated along the central cordillera. The presence of these forest islands is related to the existence of national parks, and road construction along "pasos". "Pasos" is a Costa Rican term used to identify geographic depressions between the main mountain systems in the country. There is a strong correlation between location of roads and gaps in existing forest. This pattern has been documented by several authors (Sader & Joyce, 1988; Veldkamp et al., 1992). Figure 1.8 presents the location of the remaining forest islands in Costa Rica relative to the national road network.

Forest distribution by province. Table 1.2 and Figure 1.9 present the total distribution of primary forest at the province level. Provinces with the least primary forest cover were Guanacaste (3%), Alajuela (16%), Puntarenas (19%) and San Jose (30%). The highest forest cover was estimated for Cartago (68%) and Limon (60%). The highest forest cover in Cartago is likely due to the presence of several conservation areas for water resource protection in the Reventazon and Pacuare River Basins (Sanchez-Azofeifa & Harriss, 1994). Even though the Limon province has one of the highest percentages of remaining forest cover, pasture area growth rates have been estimated to be 7% per year (DGEC, 1973; DGEC, 1984). This trend suggests a potential conflict between conservation and land use change (deforestation) in the region.

Ecological characteristics of forest clearing. When associated by life zone (Table 1.3 and Figure 1.10), the analysis indicates that only 0.1% of the total tropical dry forest (bs-T) life zone is currently covered with primary forest with an upper canopy density of 80%. Approximately 1.8% of the moist-premontane (bh-P) remains covered with primary forest. Life zones such as moist tropical (bh-T), moist Lower-Montane (bh-MB) and pluvial sub-alpine also showed low forest cover: 5.1%, 15.8% and 7.8%, respectively. Life zones with the most forest cover are the Pluvial Lower-Montane (bp-MB) forest (84%) and pluvial Montane (bp-M) forest (90%).

Extension of forest cover was also analyzed for life zone transitions (Table 1.4 and Figure 1.11). Life zone transitions are defined as subdivisions into the Holdridge life zones and represent transitional vegetation stages between classes. Our results indicate that deforestation has affected those life zone transitions between the moist tropical forest and its drier neighbor classes. Low forest cover is observed for transitions between humid-tropical to dry forest (0.7%), humid-tropical to Premontane (1.9%) and humid-premontane to Basal (0.8%).

Analysis of Forest Cover Fragmentation in 1991

Forest fragmentation at the national level. At the national level, forest fragments between 3 ha and 500 ha were analyzed in order to understand Costa Rica's forest fragmentation process. Table 1.5 presents the distribution of fragments for the whole country. Our results indicate that 5.5% (74,530 ha) of the remaining forest in Costa Rica is fragmented between 3 to 50 ha (7134 islands), and 6.5% is fragmented in ranges that varies from 50 to 500 ha.

An 88% of the total forest cover presents areas higher than 500 ha.

Forest fragmentation at the life zone level. First order and second order statistics were used to study fragmentation. Table 1.6 presents fragmentation statistics individual life zones. Life zones were ranked using patch density as a criterion. Results show a higher degree of fragmentation for the very-humid montane forest, humid lower-montane forest and very-humid lower-montane forest. Mean patch size (MPS) was estimated to be 53 ha (636 islands), 28.3 ha (129 islands) and 102.2 ha (495 islands), respectively. These three life zones ranked first, second, and third when patch density was used as a normalized index to compare fragmentation between life zones. Less fragmentation was observed for pluvial-lower-montane forest (MPS = 1071.4 ha, 271 islands), and pluvial-montane forest (MPS = 3016.2, 38 islands). These two forest classes present the highest forest cover, 84% and 90%, respectively.

The impact of landscape fragmentation is also observed when the Patch Size Coefficient of Variation (PSCV) is used as a fragmentation index. Low relative variability is observed for the very-humid montane (236%), the humid lower-montane (180%) and the very-humid lower-montane (426%) forest. This variability is interpreted as a high degree of fragmentation within these classes. A lower patch size coefficient of variance (PSCV) is consistent with high patch density (PD) values.

It is important to indicate that even though the humid premontane forest life zone shows a low fragmentation index (PD), its total forest cover is only 1.75% of the total life zone area. Therefore, first and second-order fragmentation statistics are not significant for this

life zone.

Rate of Forest Loss in Central Costa Rica (1986-1991)

Forest loss for the study area. In order to estimate the rate of change in forest cover in Costa Rica between 1986 and 1991, two satellite scenes for path 15, row 53 were selected to perform a comparative analysis. These scenes cover 47% (2,405,550 ha) of Costa Rica's territory. Total forest cover (areas ≥ 3 ha) was estimated to be 1,044,191 ha and 819,291 ha in 1986 and 1991, respectively. Deforestation during the 5-year period was 224,970 ha. The estimated total forest loss for the study area, over a 5 year period, was 21% of the 1986 forest cover (~44,994 ha/yr).

Our analysis showed that deforestation produced an increase in island fragments during the study period. Table 1.7 presents a comparison of frequency distributions of forest islands between 1986 and 1991. Between 1986 and 1991, the total number of forest islands between 3 and 50 ha and 50 and 100 ha increased by 524 and 45, respectively. In addition, 15 new islands with areas greater than 500 ha were created. Deforestation produced a net increase in the total area of fragmented forest islands for all categories with the exception of forest islands between 100-150 ha and 450-500 ha. Thus, forest lost in islands with areas greater than 450 ha contributed to the increase in the number of forest islands in the smaller class ranges.

Forest loss by life zone. The analysis of forest loss by life zone (Table 1.8, Figure 1.12) indicated that deforestation occurred in all life zones, lower loss rates were observed for the

pluvial lower-montane (bp-MB, 0.46%/yr) and pluvial montane (bp-M, 0.74%/yr). These two life zones maintained the highest forest cover during the study period: 89% and 88% for 1986, and 87% and 85% for 1991, respectively. The highest deforestation rate was estimated to be 9.93%/yr for the humid tropical forest. This life zone has almost vanished from Costa Rica's landscape. Forest cover for the whole humid tropical life zone was estimated to be only 3.5% for 1986 and only 1.8% for 1991.

When deforestation rates are compared against changes in the number of islands (Table 1.8), it is possible to observe that the humid tropical forest (bh-T) was reduced by 195 islands, as a result of its high deforestation rate. In addition, forests such as humid premontane (bh-P), humid lower-montane (bh-MB) and pluvial montane (bp-M) showed reductions in their number of islands (66, 13, and 15 respectively). Most life zones responded to deforestation with an increase in the number of islands. Life zones such as very-humid tropical (bmh-T), very-humid premontane (bmh-P), pluvial premontane (bp-P), very-humid lower-montane (bmh-MB) and pluvial lower-montane (bp-LM) showed an increase in the number of islands (355, 362, 182, 111, and 49, respectively). This fragmentation trend is consistent with the overall 1991 fragmentation level discussed in the previous sections.

Thematic Accuracy Assessment

An allowable error of 10% and an expected accuracy of 85% were selected for the final classification. The total number of points to satisfy the former conditions, using the binomial probability theory, is 51. A total of 89 GPS points were collected in Costa Rica during the 1995 dry season (Figure 1.13). For each GPS point a total of 300 fixes was

collected at a given location. Points were collected on the scene path 15 / row 53. This scene was selected because it provides a good transportation network at the national and rural road level. The number of collected points for each class (forest/non-forest) was proportional to each class in the satellite scene. Of the selected points, 33% (29 points) were collected in forest areas, and 67% (60) were collected in non-forest areas. Sample sites represented forest and non-forest areas of 3 ha or higher, and with no change between 1991 and 1995. A contingency table or error matrix (Table 1.9) was used to estimate user's and producer's accuracy, as well as overall accuracy. KHAT (Congalton, 1991) and Tau coefficients (Ma & Redmond, 1995) were also estimated.

Results indicated an overall accuracy of 94% for the forest / non-forest classification. This overall accuracy is superior to the expected 85% accuracy selected at the beginning the study. Forest user's and producer's accuracy, assessment was 88% [73,100] and 97% [88,100], respectively. Numbers in brackets represent the 95% confidence interval calculated from the binomial distribution. Non-forest user's and producer's accuracy assessment was 98% [94,100] and 93% [86,100], respectively.

The KHAT coefficient analysis showed 88% agreement between classes. The KHAT coefficient indicates that every time that a pixel is randomly selected and assigned a forest / non-forest class, the selection will be correct 88% of the time. The Tau coefficient analysis showed 89% agreement. The Tau coefficient indicates that 89% more pixels were classified correctly than would be expected by random assignment. This means that based on the data collected in the field, the agreement between the map product and the real land use was correct 89% of the time. Ma & Redmond (1995) showed that overall, the KHAT coefficient

underestimates the variance of the agreement between the field and the map product. The authors have recommended using the Tau coefficient over the KHAT coefficient. In addition, the Tau coefficient is an adjustment of the percentage of agreement by the number of classes or groups being mapped, and as a measure of classification accuracy, it is independent of the class or group size. The Tau coefficient of agreement was selected over the KHAT coefficient to represent the overall accuracy of the classification. Appendix B presents a summary of the thematic accuracy assessment analysis.

Positional Accuracy Assessment

A detailed analysis of the correlation between the Landsat digital number and its corresponding percentage of forest from the aerial photography indicates that forest with upper canopy closure of 80% and higher is been extracted from the Landsat TM sensor (Figure 1.5a-1.5d). In addition, the 5x5 pixel kernel window from the aerial photography (pixel size 5x5 m) was able to detect gaps in the forest area. These are elements that are not observed on the Landsat TM pixel due to its spatial resolution (28.5 x 28.5 m). For example, Figure 1.14 correlates an increase in the digital number of band 2 with an decrease in the percentage of forest. This gap in the canopy is identified in the aerial photography but not in the satellite scene due to the effect of mixed pixels. A relative high correlation ($r^2 = 0.76$) is observed between the percentage of forest in the aerial photography and the band 2 averaged digital numbers from the three cross sections (Figure 1.6a). This high correlation is a result of band 2 being in the visible portion of the electromagnetic spectrum. Band 2 is in the region between the blue and red chlorophyll absorption bands (0.52-0.60 microns).

Other significant correlations were also observed with band 3 ($r^2 = 0.63$) and band 5 ($r^2 = 0.59$) (Figure 1.6b and 1.6c) as a result of these bands being in the near and mid-infrared, where the signal of healthy vegetation is reflected in the electromagnetic spectrum. On the basis of these correlations we used bands 2, 3 and 5 in conjunction with aerial photography to identify, simulate, and compare the percentage of canopy density extracted from a supervised remote sensing classification.

Table 1.10 presents a comparison between the observed and simulated forest classes for different canopy closure percentages. In general, the 70% canopy density simulation had the tendency to overestimate each island's area and perimeter when compared with the reference island. The 90% canopy density showed a tendency to underestimate these two variables. Shape index and fractal dimensions also presented significant differences at the 70% and 90% canopy density. Minimum differences for the shape index and the fractal dimension were present at the 80% canopy density simulation. These results indicate how sensitive the classification is to subtle changes in digital numbers caused by atmospheric conditions, time of year, etc.

The integration of the three phase methodology also suggests that scan aerial photography can be used (1) to simulate forest/non-forest classes generated from high resolution satellite sensors (e.g., SPOT, or the new forthcoming high resolution satellites part of the EOS platform), (2) to correlate extracted forest classes from high resolution satellites with more coarse resolution satellites such as Landsat TM, and (3) as an important source of information to detect the percentage canopy closure being mapped by conventional supervised or un-supervised classification algorithms. There are only two restrictions. The first is the

need for aerial photography to be acquired at the same time or season as the satellite scene, so comparisons and simulations such as the one presented here can be performed. The second is the need for aerial photography with high quality resolution and processing.

Discussion

The integration of remote sensing and GIS information has also provided important insights regarding Costa Rica's forest status during late 1980's and early 1990's. Four important issues were quantified: (1) the extent of the forest at the national level, (2) the remaining primary forest as a function life zones, (3) the level of forest fragmentation at the national and life zone levels and (4) the rate of forest loss for Central Costa Rica between 1986 and 1991. These issues are critical to researchers in the area of biodiversity, and sustainable management and conservation of Costa Rica's forests.

Results at the national level indicated that 29% (~1,400,000 ha) of the country was under primary forest cover in 1991. Of the total forest cover, 71% is outside of national parks and 29% is protected by them. This figures have important implications for biodiversity conservation and restoration, water resources management, and climate change.

Biodiversity and conservation. From the biodiversity point of view, spatial distributions of forest islands are key components in sampling genetic/biodiversity resources in fragmented ecosystems, as well in the definition of conservation areas and their linkage to current national parks. Ehrlich and Wilson (199?) have suggested three important reasons for concern

regarding biodiversity loss: (1) ethical and aesthetic reasons, (2) the direct loss of economic benefits from biodiversity in the form of foods, medicines, industrial products, and the potential for gaining many more, and (3) the loss the essential services provided by natural ecosystems, of which diverse species are the key working parts. The three reasons become important when we realize that the tropical dry forest (bs-T), the humid tropical forest (bh-T) and the humid lower montane (bh-MB) forest have almost vanished from the Costa Rican landscape. The remaining fragments of these forests are critical for research and conservation, as well as for the national heritage of all Costa Ricans. Sound conservation policies on the former life zones will make it possible to identify and preserve the main biological characteristics of these areas, as well as to understand the linkages and ecological cycles and interactions presented there. It is a national responsibility for present and future policy makers to preserve what it is left for the future generations.

Currently, 29% of the primary forest nationwide is protected by national parks. This is the most important aspect of Costa Rica's national conservation policy. Unfortunately, these policies did not prevent the destruction of critical biologic corridors between old growth forest islands. Although these forested islands seem large enough to support the current biological population, it is expected that a good deal of biologic value has been lost as a result of big gaps between them (Kruess & Tschamtker, 1994; Askins, 1995). Due to current land use patterns in these areas, land tenure policies, and the relative distance between islands, is difficult to expect consolidation of an ecologic link between them.

A new evaluation of forest clearing policies is necessary in Costa Rica to prevent the increase of forest fragmentation in the 71% of the forest that is outside of conservation areas.

Results of this study can provide important insights to decision makers regarding forest management. These results can also help the government to make well-informed and environmentally sound decisions regarding the planning of human settlements and land use/cover change in areas where little primary forest remains.

Establishing small reserves in forest fragments close to continuous protected areas is one possible application of the results of this study. These small reserves can provide a valuable service in conservation strategies for preserving biological diversity in addition to providing long-term educational and scientific contributions to society (Shafer, 1995). Integration of remote sensing results can help scientists to identify those small areas that can provide continuity along biologic corridors in a same life zone or along transition zones. Additionally, first and second-order fragmentation statistics in conjunction with knowledge about population biology in buffer areas around conservation areas, can help to define the minimum size of ecosystems for conservation. This approach can help efforts to recuperate critical transitions between life zones, such as tropical dry forest to humid forest, and humid forest to basal.

Water Resources. Watershed protection is a key component to achieve sustainable management of water resources. Results from this forest assessment can assist in the implementation of soil and water conservation programs on key drainage basins. These key areas can be selected by their importance for hydropower generation and drinking water, as well as their past response to natural hazards. In addition, an accurate distribution of the forest resources at the drainage basin level will assist in the implementation of a more

comprehensive national water balance. Chapter 4 of this dissertation explores in detailed the results obtained at the watershed level of this forest assessment.

Climate Change: Carbon fluxes and stocks are essential for national inventories of greenhouse gases. In addition the rate of change and specially the type of change are essential variables to document emissions of trace gases such as N₂O (Keller et al., 1990; Velkamp, 1993). Keller et al.(1990) have concluded that the N₂O emissions are higher after deforestation and that they are reduced to pre-disturbance levels as pasture land become old. A regular forest assessment couple with current studies on spatial distribution of trace gases in Costa Rica is critical to understand the response of the natural system to LUCC, as well as provides important knowledge to the climate change community. Moreover, the information provide by this national forest assessment can help to fill a critical gap in terms of carbon estimates in Costa Rica, as well as to define a more concrete national baseline for the country's carbon storage.

Rates of forest loss. Results from this study contrast with those from FAO (1990). FAO results are base on official estimates of forest cover and forest loss provided by the Costa Rica's National Forest Services (Direccion General Forestal). Current estimates of ~4.0% per year between 1986 and 1991 for central Costa Rica contrast with a ~3% defined by FAO on its 1990 forest cover assessment (FAO, 1990). The main differences are due to book keeping records by FAO. FAO dependence on information not validated independently is the main source of disagreement. This research work has proved that only an accurate forest

assessment based on remote sensing information, coupled with state-of-the-art thematic and positional accuracy assessment, can provide with accurate estimates of forest loss at the regional and national level.

Accuracy assessment. During this research project, remote sensing and geographic information systems were combined to provide a forest cover map with quality control and accuracy analysis. Quality control is a critical issue in developing countries where different interpretations of forest/ non-forest can affect conservation policies. A semi-automated processing system, similar to the one used in this analysis, provides fast and accurate analyses of several satellite scenes in a short period of time. Thematic accuracy analysis provides confidence to decision makers concerned about resources assessment errors during the classification/interpretation phase, but also provides insight into how a monitoring program should be implemented. The analysis performed by integrating remote sensing information, GIS and GPS in conjunction with current state-of-the-art procedures, has allowed this research to go beyond a simple analysis of a contingency error matrix.

The integration of coefficients of agreement such as KHAT and Tau provided insights regarding the accuracy of the maps presented in this research. An overall accuracy of 94% and a Tau coefficient agreement of 89% indicates that forest classes were extracted with confidence. A Tau coefficient of 89% indicates that based on the data collected in the field, our assumptions of forest/non-forest definitions were correct 89% of the time.

The positional and thematic accuracy documented in this paper also has implications for research and development in remote sensing. The integration of remote sensing

information with aerial photography (used as a surrogate of upcoming high resolution satellites) has provided important information regarding the forest canopy closure mapped in this project. In addition, this analysis has established links for future analysis between Landsat data and < 1 meter new satellites. In general, the common assumption that the mapped forest cover represents an $x\%$ of forest cover canopy closure does not have any scientific meaning unless it is independently validated. The methodology presented in this chapter to estimate spatial errors provides a way to evaluate the uncertainty associated with the definition of percentage of forest closure (canopy closure).

The methodology designed to evaluate canopy closure has other applications. One is the possibility of using aerial photography, with high spatial resolution, to perform an independent evaluation of results obtained from supervised or unsupervised classification. In this study, results indicate that training sites selected to represent closed forest during a supervised classification were able to detect forest with a ~80% canopy closure. This was confirmed by integrating independent results with reference forest islands identified on both the remote sensing satellite scene and the aerial photography. A second issue of importance is the role that aerial photography can play in simulation of high resolution satellites. The possibility of simulating high resolution sensors is a first step in the integration of forthcoming high resolution remote satellites with current remote sensing platforms. The successful application of the methodology proposed in this chapter suggests that high resolution satellite information, which will be available in the near future, will play a critical role in the definition of boundaries between forest and non-forest classes. The results also suggest that the new high resolution sensors will contribute to a more accurate and detailed analysis of tropical

forests in the near future. This information will be crucial in refining past estimates of forest cover and deforestation in developing countries.

Technology, such as that implemented in this research, needs to be shared with developing countries. The implementation of remote sensing and geographic information systems on site, in conjunction with information from G.P.S. technology and national experts, is critical in implementing national deforestation monitoring programs and land use planning projects. In addition, these tools will allow researchers and policy makers to assess both old and new environmental problems, and to evaluate the interaction between society and the natural environment.

Future forest assessments. Results of this research can be extrapolated at the national and regional scale. Future forest assessments can provide important insights on the state of forest cover and forest fragmentation at the Central American level. In addition, a regional forest cover assessment using high resolution satellite data will provide information on the “state of the forest environment” for each central american country. The implementation of the forest assessment most considered selected those satellite scenes in the region that are significant and representative of LUCC process in the region. Selection of these scenes using stratified sampling rather than random sampling is the base of a sound monitoring system for the region. The stratification process must be based on persistence. Persistence is defined as an indicator of a temporal trend of LUCC process. Chapter 2 presents in detailed how stratified sampling based on persistence is a key component of any future monitoring program in Costa Rica and the Central American region.

Conclusions

1. The integration of remote sensing and geographic information systems in Costa Rica has proven to be an important tool. The approach presented in this study suggests that current mapping technologies are important not only for national deforestation studies, but also for providing valuable information related to the extent and level of forest fragmentation at the life zone level. This information is critical to research dealing with biodiversity impacts due to deforestation, and for the development of sound conservation policies in Costa Rica.
2. This present study has also documented the degree of forest fragmentation in Costa Rica. Results indicate that government practices directed to communicate the extension of Costa Rica's forest protection, are not accounting for the high degree of forest fragmentation. Even though the country has been able to protect 29% of the current forest cover, the 71% remaining is being fragmented with important consequences from the ecologic and hydrologic point of view.
3. The results suggest that the extent of tropical deforestation in Costa Rica goes beyond the estimation of total forest lost at the national level. The impacts at the national level have deeper roots when the data is also studied at the life zone level. The nearly complete disappearance of the tropical dry forest (bs-T) and the very-humid montane (bmh-M) present important issues of concern for current conservation policies.
4. In a country like Costa Rica, with high dependence on hydropower generation, the

degree of forest fragmentation in its most important drainage basins is an issue of concern for water managers and planners. These findings show that the Grande de Terraba and Reventazon drainage basins can be considered two of the most fragmented drainage basins in the country. Landscape fragmentation criteria such as those presented in this paper will help to identify and rank a national drainage system as a function of its degree of deforestation. The use of fragmentation indexes can also provide important information about the development and prioritization of drainage basins at the national level.

5. This study has also shown the role that < 1 meter new orbital satellites and Landsat from EOS can play when it is used to evaluate aerial accuracy. Integration of aerial photography (surrogated to simulated <1 meter satellite resolution) with Landsat TM makes it possible to conclude that the mapped forest represents in average ~80 canopy density. It is also suggested that the approach presented in this paper is a first step in the link between high resolution satellites (1m to 5m resolution) and current commercial platforms. These findings suggest that future high resolution satellites will provide valuable information to map tropical forests.

Table 1.1. Forest / Non-Forest threshold as a function of forest closure (%)

Digital Number	Percentage Forest Closure		
	90 (%)	80 (%)	70 (%)
Band 2	17	19	20
Band 3	12	13	14
Band 4	62	67	71
Band 5	45	47	49

Table 1.2. Costa Rica 1991 forest cover assessment, forest distribution by province.

Province	Forest (ha)	Non-Forest (ha)	F/NF ratio	% Forest cover	Total Area (ha)
San Jose	144587	252080	0.57	30	479511
Alajuela	127113	536319	0.24	16	779234
Cartago	208937	83537	2.50	68	308757
Heredia	109284	117490	0.93	41	264719
Guanacaste	28434	855565	0.03	3	886356
Puntarenas	202909	447007	0.45	19	1078393
Limon	540227	254424	2.12	60	898585
Total	1361491	2546423			4695555

Note: Forest represents those units with 80% or higher canopy closure.

Table 1.3. Costa Rica 1991 forest cover assessment, forest distribution by life zone.

Life zone Symbol	Life zone name	Forest (ha)	Non-Forest (ha)	F/NF ratio	% Forest Cover	Total Area (ha)
bs-T	Tropical dry forest	149	130714	0.00	0.1	130864
bh-T	Humid tropical forest	45493	706042	0.06	5.1	884376
bmh-T	Very-humid tropical forest	415152	357116	1.16	38.6	1076862
bh-P	Humid premontane	8955	499995	0.02	1.8	511542
bmh-P	Very-humid premontane	217906	662907	0.33	19.5	1119052
bp-P	Pluvial premontane	212286	69744	3.04	60.0	353675
bh-MB	Humid lower-montane	3784	20138	0.19	15.8	23929
bmh-MB	Very-humid lower-montane	51261	58865	0.87	45.1	113756
bp-MB	Pluvial lower-montane	290830	24494	11.87	83.9	346760
bmh-M	Very-humid montane	636	1049	0.61	36.8	1728
bp-M	Pluvial montane	114682	11128	10.31	89.8	127775
pp-SA	Pluvial Sub-alpine	358	4232	0.08	7.8	4590
	Total	1361491	2546423			4694907

*Note: 1. Forest represents those units with 80% or higher canopy closure
 2. Total area represented total sample area, this figure does not include areas with no data*

Table 1.4. Costa Rica 1991 forest cover assessment, forest distribution by life zone transition

Life Zone Symbol	Transition to	Forest (ha)	Non-Forest (ha)	F/NF ratio	% Forest Cover	Total Area (ha)
bs-T - H	To Humid	0	31126	0.00	0.0	31126
bh-T - D	To Dry	777	115250	0.01	0.7	116027
bh-T - PH	To Per-humid	2868	147252	0.02	1.9	150120
bh-T - PM	To Premontane	5238	58484	0.09	8.2	63722
bmh-T - PM	To Premontane	164915	140416	1.17	54.0	305331
bh-P - B	To Basal	3544	463238	0.01	0.8	466781
bmh-P - B	To Basal	98375	595090	0.17	14.2	693466
bmh-P - Pl	To Pluvial	17724	63606	0.28	21.8	81330
bp-P - B	To Basal	6284	31578	0.20	16.6	37862
bmh-MB - H	To Humid	1618	1417	1.14	53.3	3035
bp-M - LM	To Lower Montane	68341	9261	7.38	88.1	77603
Total		369683	1656718.78			2026401.8

Note: Forest represents those units with 80% or higher canopy closure

Table 1.5. Costa Rica 1991 forest cover assessment, forest island size distribution.

Class Ranges	# Islands	Total Area (ha)	% Total Area (ha)
3-50	7134	74530	5.5
50-100	370	25413	1.9
100-150	109	13237	1.0
150-200	73	12554	0.9
200-250	43	9537	0.7
250-300	27	7395	0.5
300-350	18	5807	0.4
350-400	19	7073	0.5
400-450	10	4277	0.3
450-500	6	2877	0.2
GT 500	80	1189662	88.0
Total	7889	1352363	100

Note: 1. Forest represents those units with 80% or higher canopy closure closure.

2. A total of 9128 ha representing forest with a MMU less than 3 ha is not presented

Table 1.6. Costa Rica 1991 forest cover assessment, fragmentation statistics by life zone

Life Zone Symbol	Total Area (ha)	Number of Islands	Patch Density (#/100ha)	Mean Patch Size (ha)	PSSD*	PSCV**
bh-T	884376	961	0.11	45.1	260.3	577.0
bmh-T	1076862	2572	0.24	160.1	1781.9	1113.3
bh-P	511542	265	0.05	32.7	113.8	347.8
bmh-P	1119052	3873	0.35	54.5	612.7	1123.5
bp-P	353675	742	0.21	284.3	2980.4	1048.3
bh-MB	23929	129	0.54	28.3	51.1	180.5
bmh-MB	113756	495	0.44	102.2	472.7	462.5
bp-MB	346760	271	0.08	1071.4	7950.0	742.0
bmh-M	1728	12	0.69	53.0	125.3	236.3
bp-M	127775	38	0.03	3016.2	12278.5	407.1
pp-SA	4590	8	0.17	43.7	52.2	119.6
Total	4564044	9366				

Note: 1. Because the tropical dry forest with 80% canopy closure represents only 0.1% of its total area, this class was not considered in the analysis.

*2. * Patch Size Standard Deviation (PSSD)*

*3. ** Patch Size Coefficient of Variance (PSCV)*

Table 1.7 1986 - 1991 Deforestation Analysis comparison between path 15 / row 53 Lansat TM scene, Island size distribution change.

Class Range (ha)	1986 # Islands	1986 Total Forest Area (ha)	1991 # Islands	1991 Total Forest Area (ha)	1986-1991 # Island Change	1986-1991 Forest Change (ha)
3-50	3341	36363	3865	41330	524	4967
50-100	175	12263	220	15036	45	2773
100-150	57	6940	56	6837	-1	-103
150-200	30	5108	42	7151	12	2043
200-250	22	4941	33	7323	11	2382
250-300	12	3339	15	4106	3	767
300-350	7	2319	11	3591	4	1272
350-400	5	1859	9	3307	4	1448
400-450	3	1282	4	1701	1	419
450-500	3	1437	3	1412	0	-25
GT 500	35	968341	50	727428	15	-240913
Total	3690	1044191	4308	819221	+611	-224970.42

Note: 1. Classes represent forest with an upper canopy closure of 80% or higher

Table 1.8 Remaining forest and deforestation rates in Costa Rica by life zone

Life zone Symbol	1986 Forest (ha)	1986 Number of Islands	1991 Forest (ha)	1991 Number of Islands	Rate of Change (% / yr)
bs-T	9	2	7	1	4.79
bh-T	10985	452	5530	257	9.93
bmh-T	395690	1133	282772	1488	5.71
bh-P	9531	249	5679	183	8.08
bmh-P	181326	1716	121203	2078	6.63
bp-P	132328	232	113939	414	2.78
bh-MB	4978	142	3648	129	5.34
bmh-MB	53366	369	44129	480	3.46
bp-MB	184363	116	173221	165	1.21
bmh-M	711	11	623	12	2.47
bp-M	70904	44	68271	29	0.74
pp-SA	837	10	200	7	15.22
Total	1044191	4466	819222	5243	4.31

Table 1.9. Costa Rica 1991 forest cover assessment, thematic accuracy assessment

<i>Reference Data</i>						
<i>Classified Data</i>	Forest	Non-Forest	Water	Row Total	Correct (%)	Commission (%)
Forest	28	4	0	32	88	13
Non-Forest	1	56	0	57	98	2
Water	0	0	0	0	N/A	N/A
Column Total	29	60	0	89		
Omission (%)	3	7	N/A			

Notes:

Omission: Refers to the samples of a certain class of the reference data that were not classified as such.

Commission: Refers to the samples of certain class that were wrongly classified

User's Accuracy: The probability that a pixel classified on the image actually represents that category in ground, also known as reliability. Error of commission.

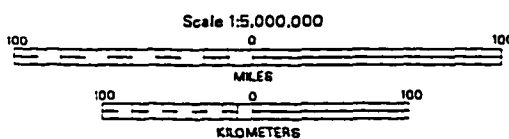
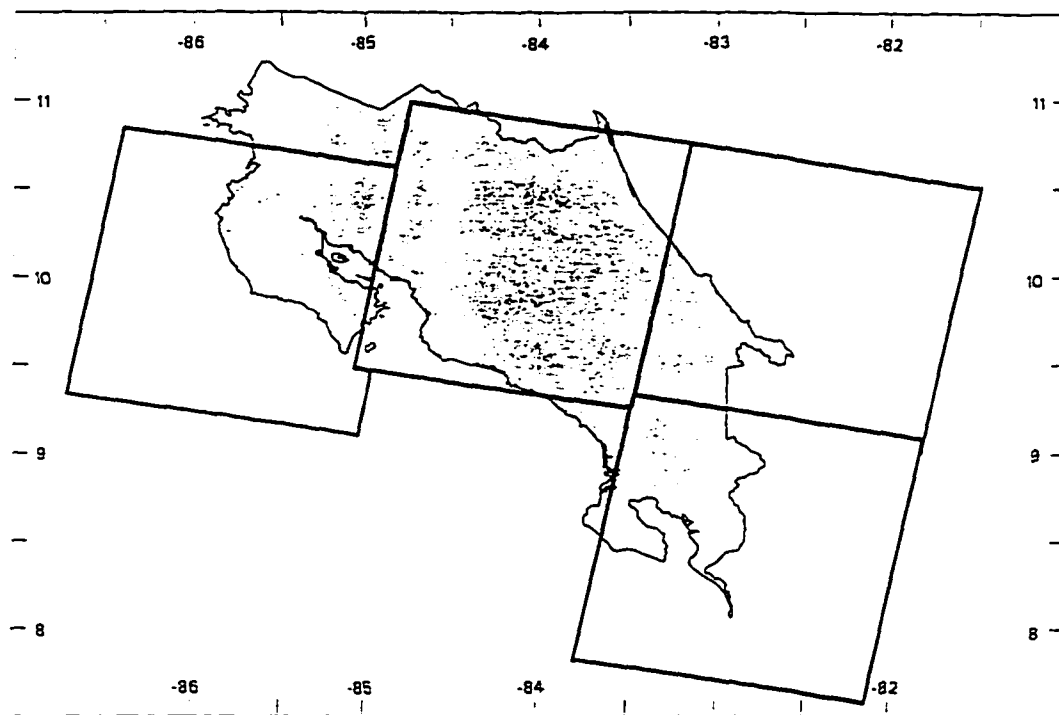
Producer's Accuracy: The probability of a reference pixel being correctly classified. Error of omission.

Table 1.10. Costa Rica 1991 forest cover assessment, Landsat TM sensitivity analysis

Canopy Closure (%)	Island 1			
	Area	Perimeter	Shape Index	Fractal Dimension
Reference	740882	7224	2.37	1.31
70%	1000692	20691	5.83	1.44
80%	<i>690413</i>	<i>10431</i>	<i>3.54</i>	<i>1.38</i>
90%	418309	12312	5.37	1.46

Canopy Closure (%)	Island 2			
	Area	Perimeter	Shape Index	Fractal Dimension
Reference	458109	4560	1.90	1.29
70%	713156	10488	3.50	1.37
80%	<i>378508</i>	<i>4446</i>	<i>2.04</i>	<i>1.31</i>
90%	307030	6954	3.54	1.40

Canopy Closure (%)	Island 3			
	Area	Perimeter	Shape Index	Fractal Dimension
Reference	336272	3249	1.58	1.27
70%	661984	8379	2.91	1.35
80%	<i>297284</i>	<i>3819</i>	<i>1.98</i>	<i>1.31</i>
90%	211185	6042	3.71	1.42



Name Code	Path	Row	Date	% Clouds
San Jose	15	53	02/06/86	10
San Jose	15	53	01/01/91	20
Limon	14	53	05/14/92	20
Osa	14	54	03/17/91	20
Guanacaste	16	53	03/25/92	10

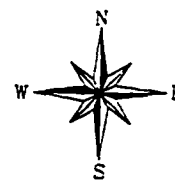


Figure 1.1. Costa Rica, location of Landsat TM scenes (WRS-2) tile systems used for the 1991 forest cover assessment.

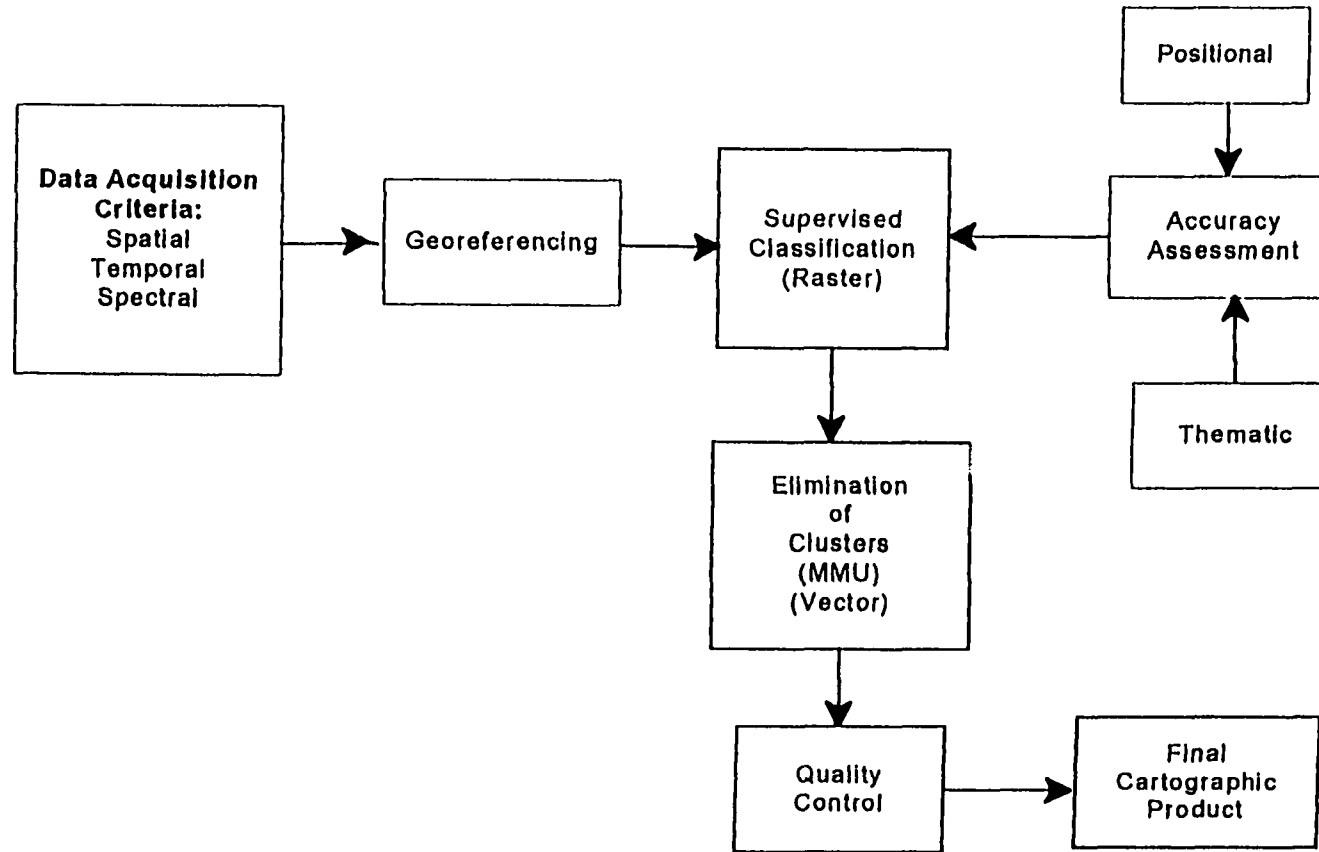


Figure 1.2. Costa Rica 1991 forest cover assessment, methodologic steps follow during the definition of primary forest cover.

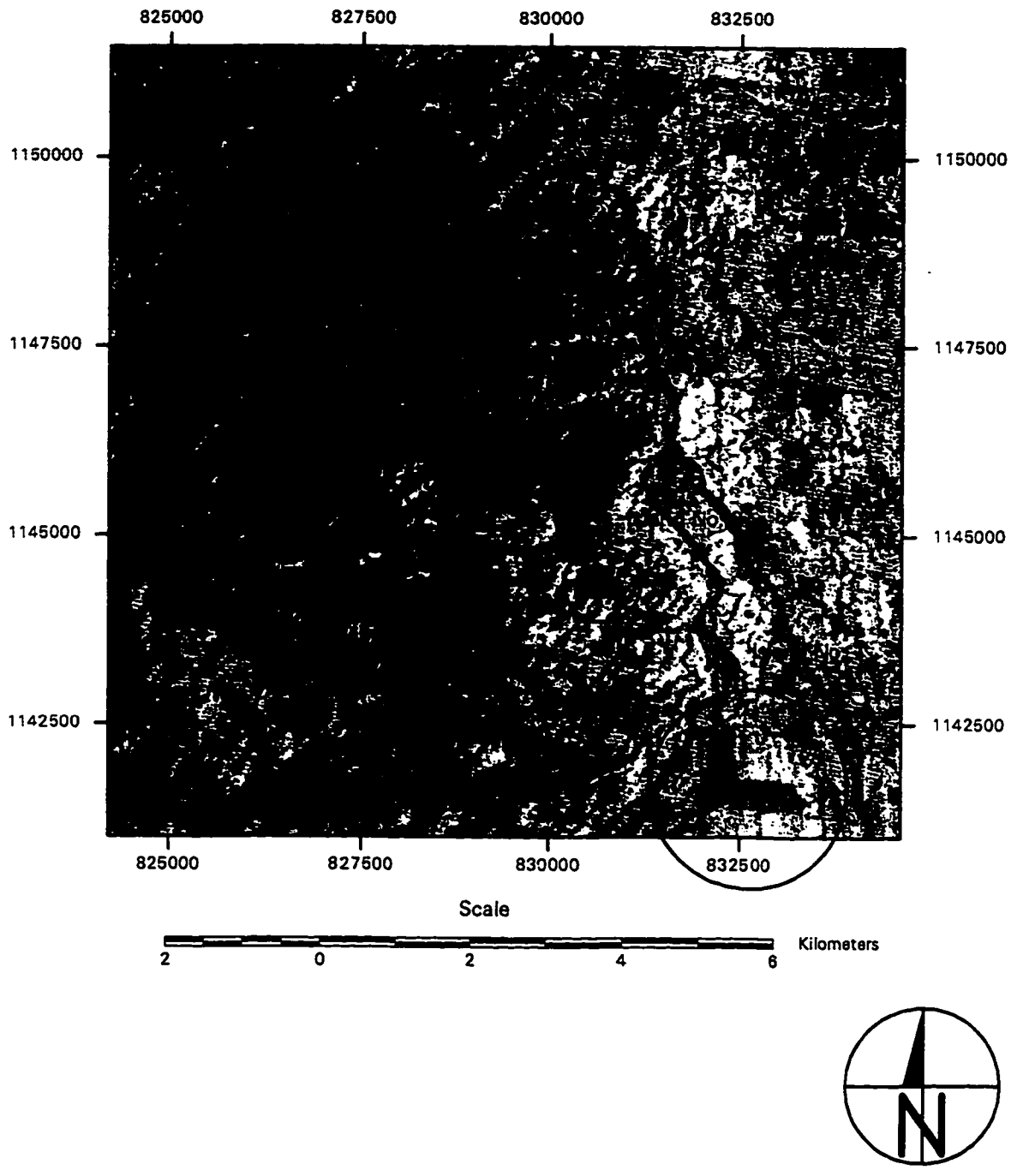


Figure 1.3. Puerto Viejo de Sarapiquí, location of sites for positional accuracy assessment.

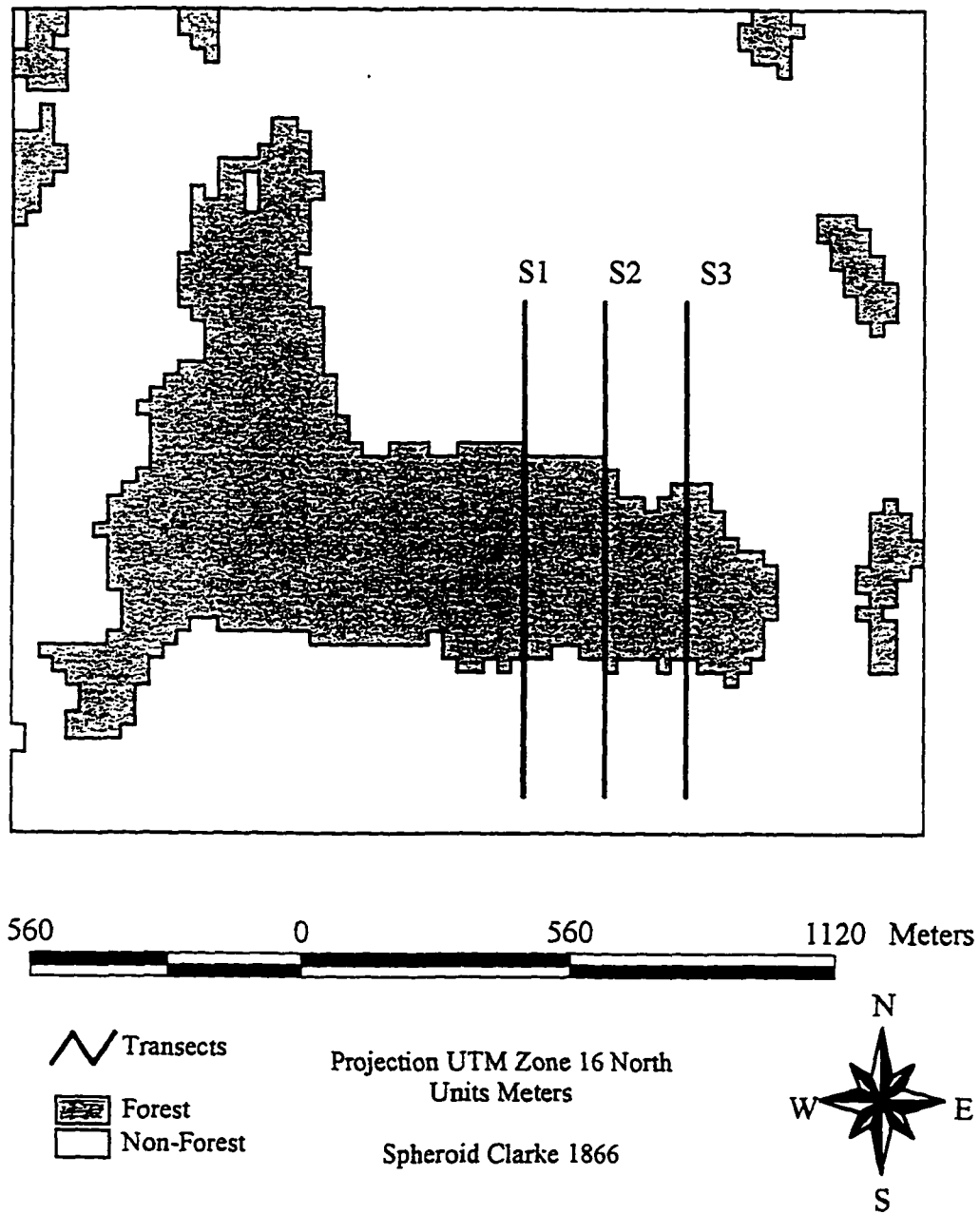


Figure 1.4. Puerto Viejo de Sarapiquí, location of transect for positional accuracy assessment.

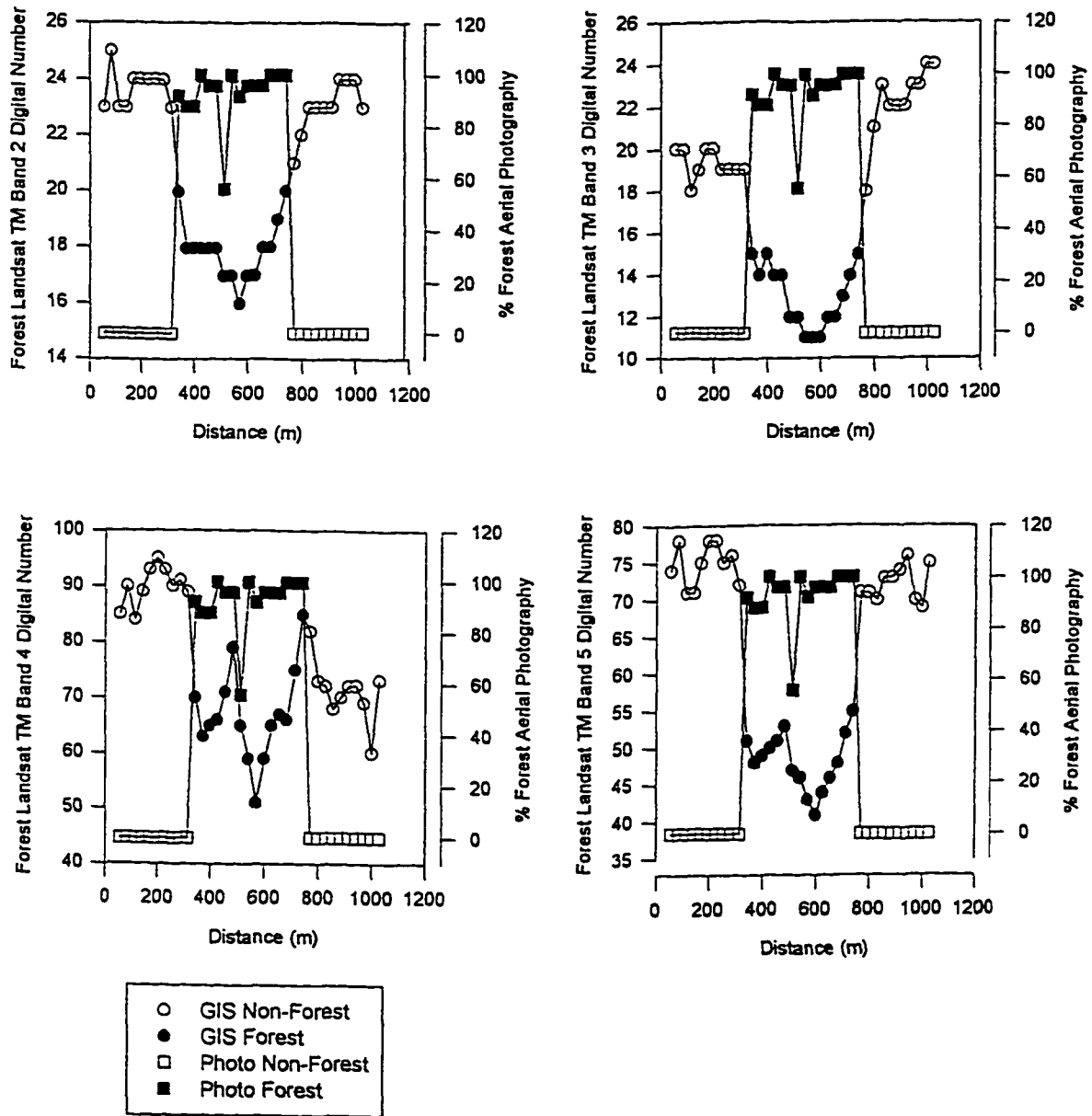


Figure 1.5. Correlation between transect extracted from the Landsat TM scene and the classification of the aerial photography.

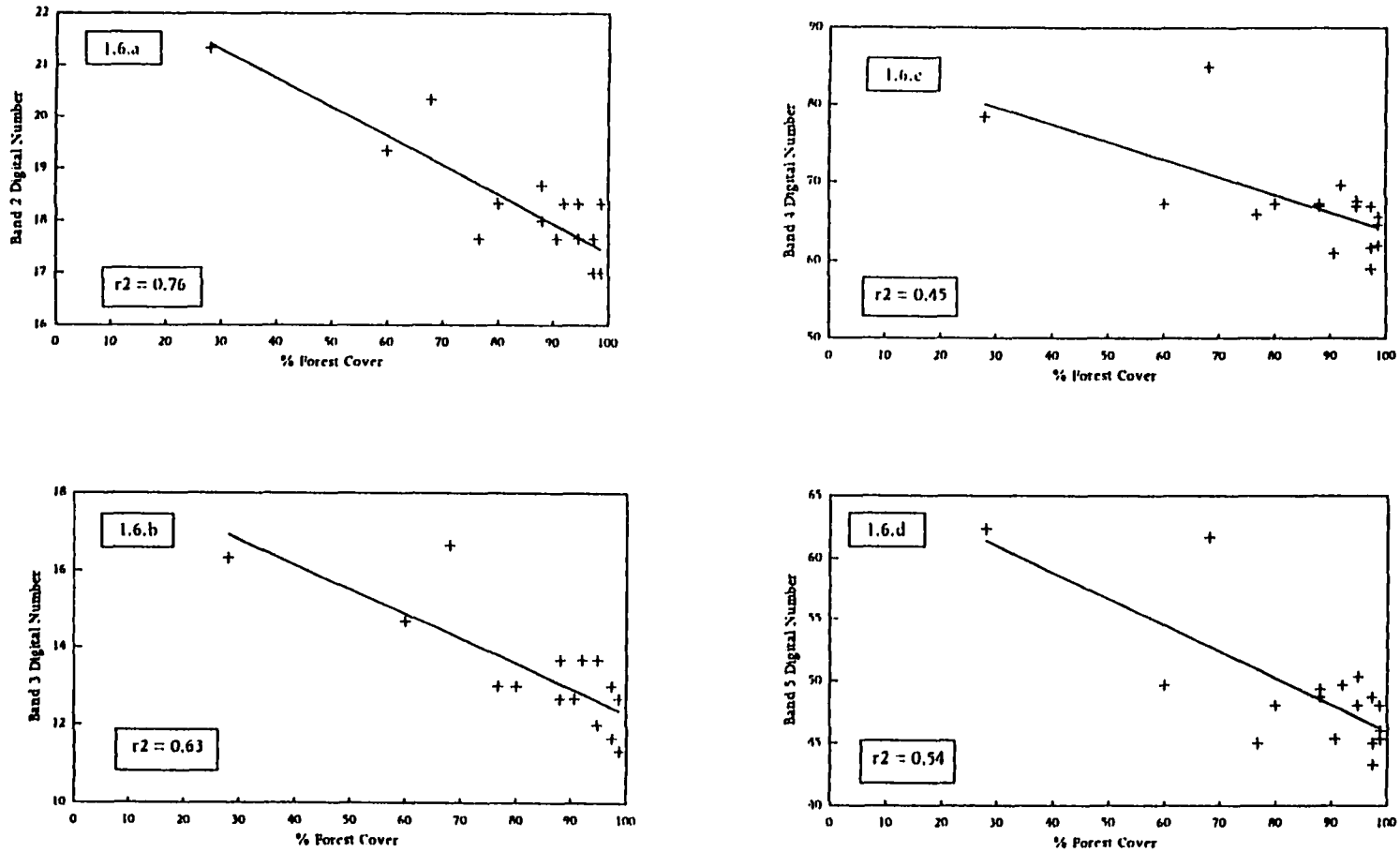


Figure 1.6. Correlation between percentage forest cover on a 5 x 5 kernel window from the aerial photography and its correspondent TM digital number for (a) band 2, (b) band 3, (c) band 4, and (d) band 5. Points represent the average of three transects.

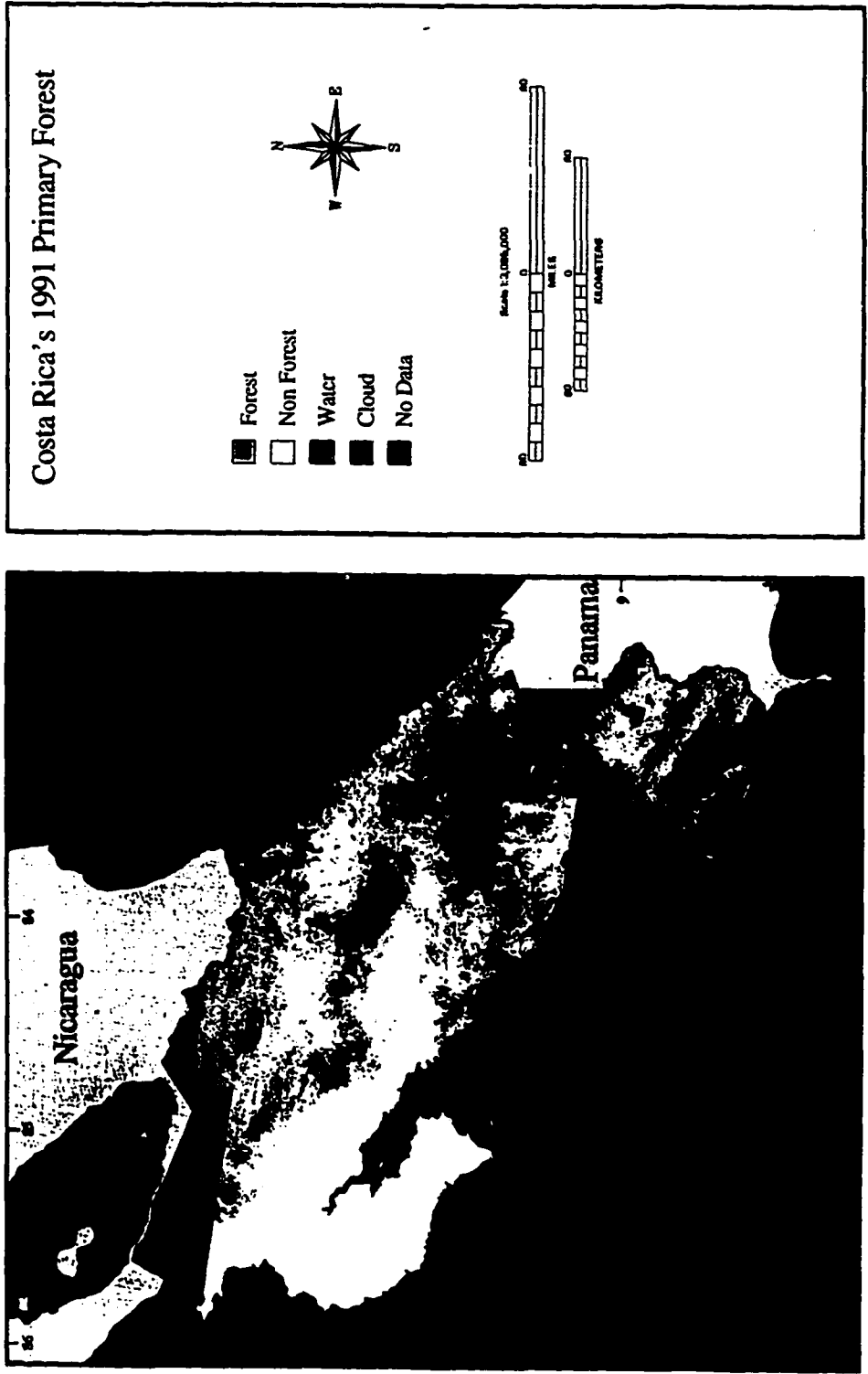


Figure 1.7. Costa Rica 1991 forest cover assessment, primary forest.

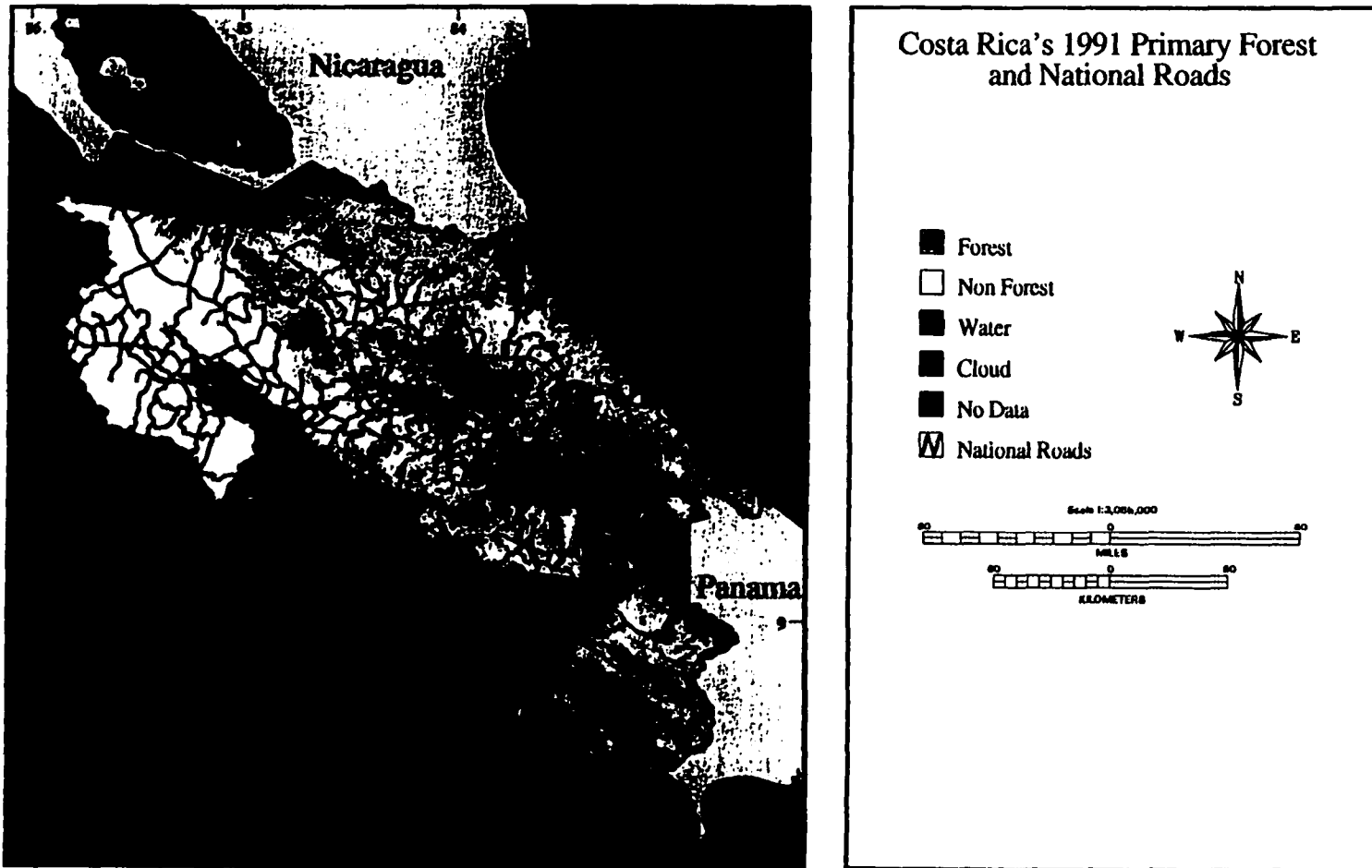


Figure 1.8. Costa Rica 1991 forest cover assessment, primary forest and national roads.

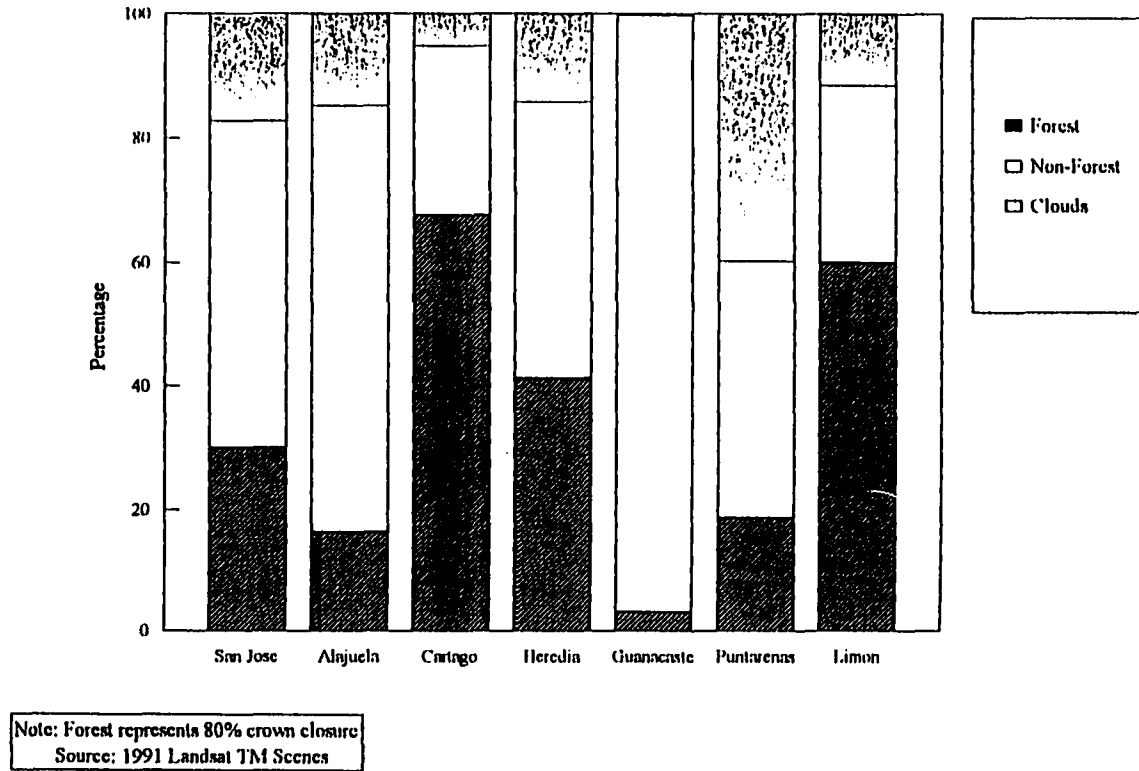


Figure 1.9. Costa Rica 1991 forest cover assessment, primary forest distribution by province. The Cartago and Limon province are the areas with less infrastructure (roads) development.

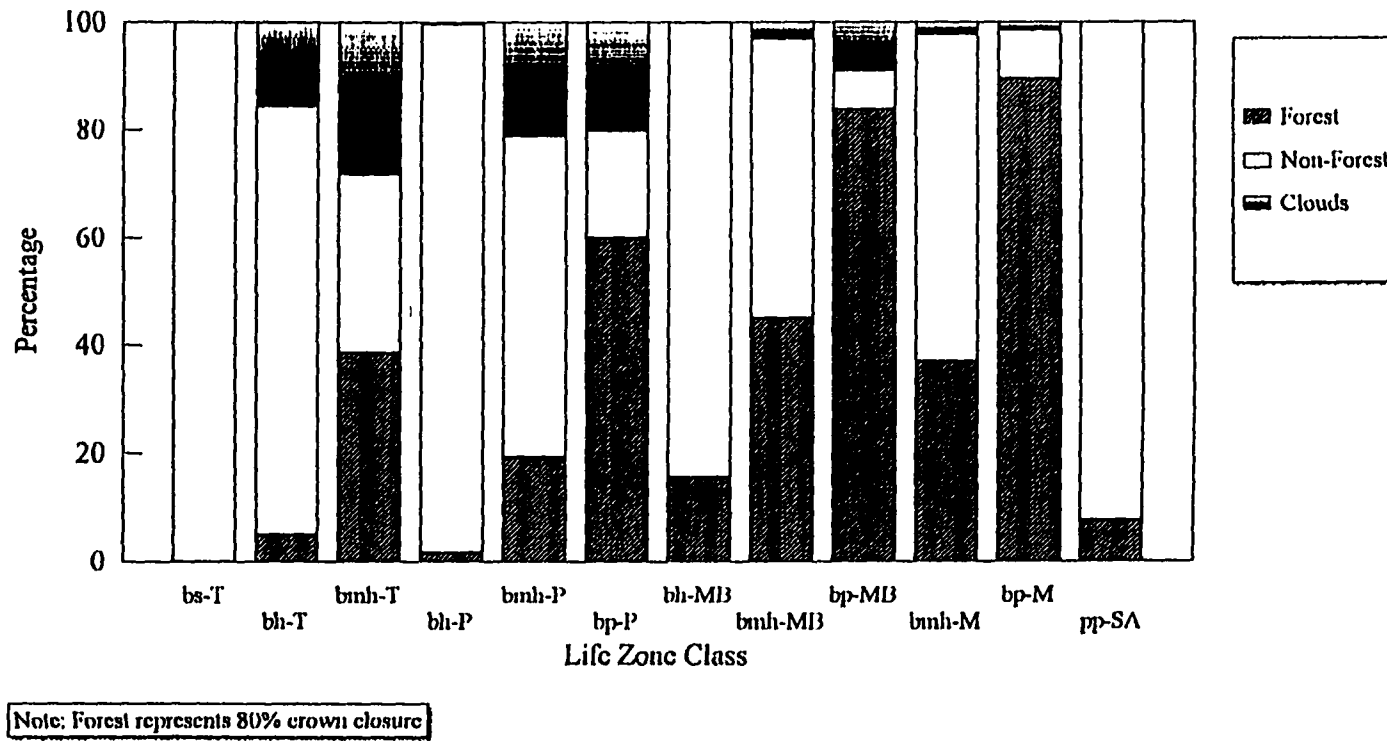


Figure 1.10. Costa Rica 1991 forest cover assessment, forest distribution by Holdridge life zones.

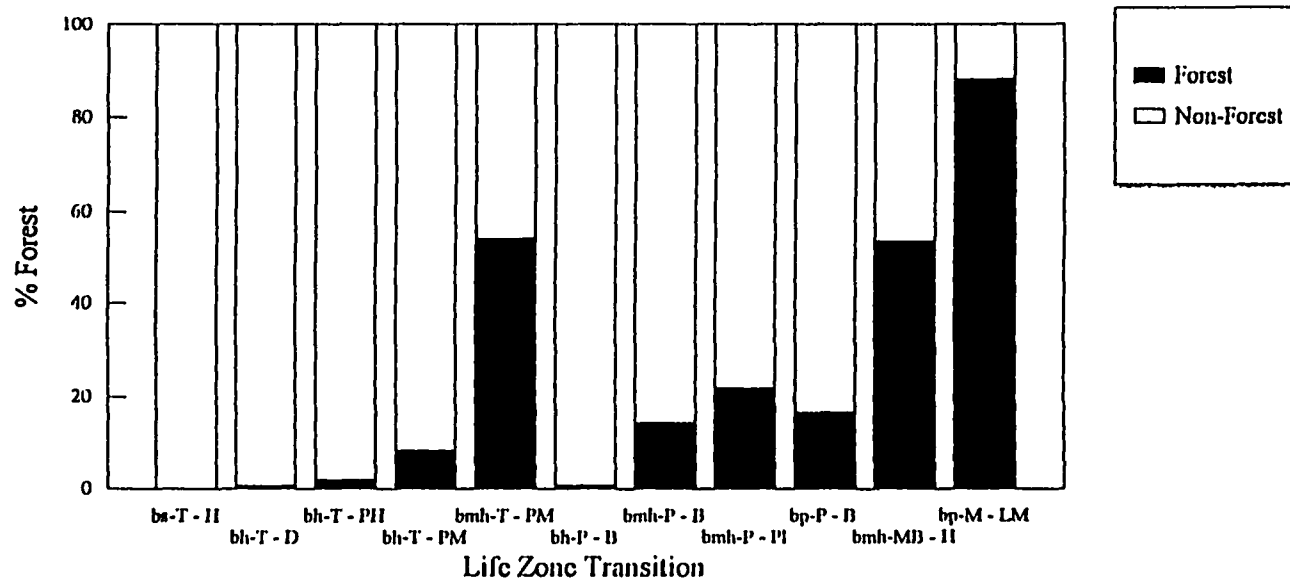


Figure 1.11. Costa Rica 1991 forest cover assessment, forest distribution by Holdridge life zone transition.

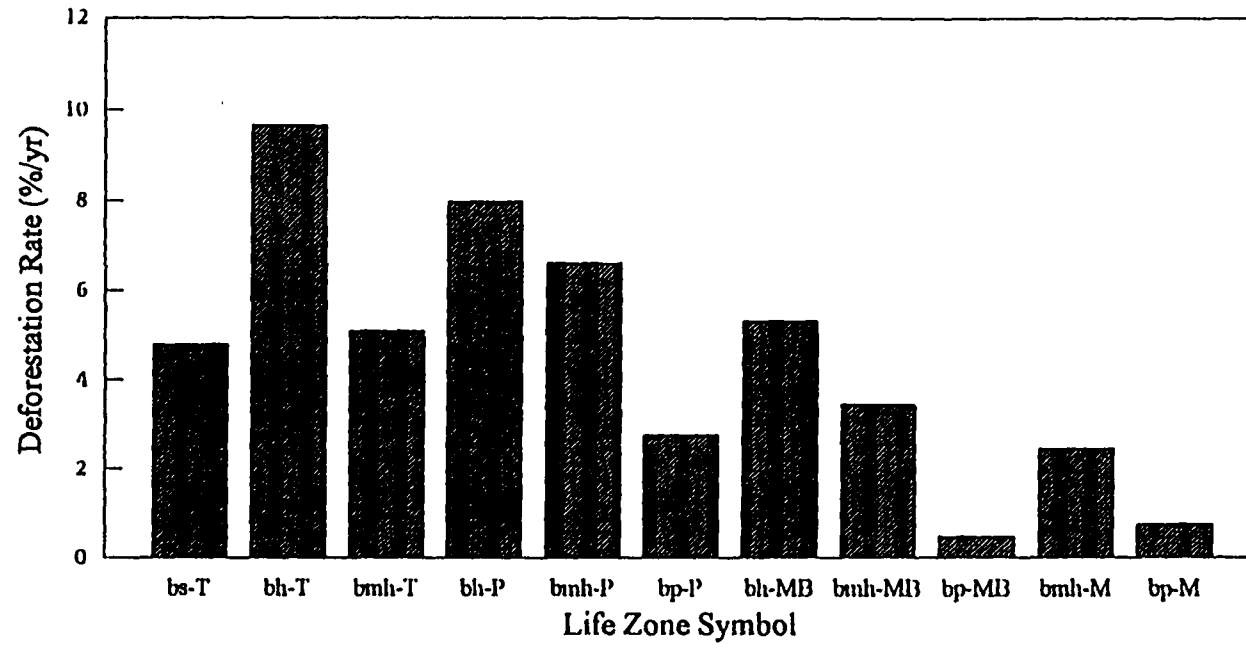


Figure 1.12. Costa Rica 1991 forest cover assessment, rate of forest loss at the Holdridge life zone level. Rates of forest loss is for Landsat TM scene path 15 / row 53 between 1986 and 1991.

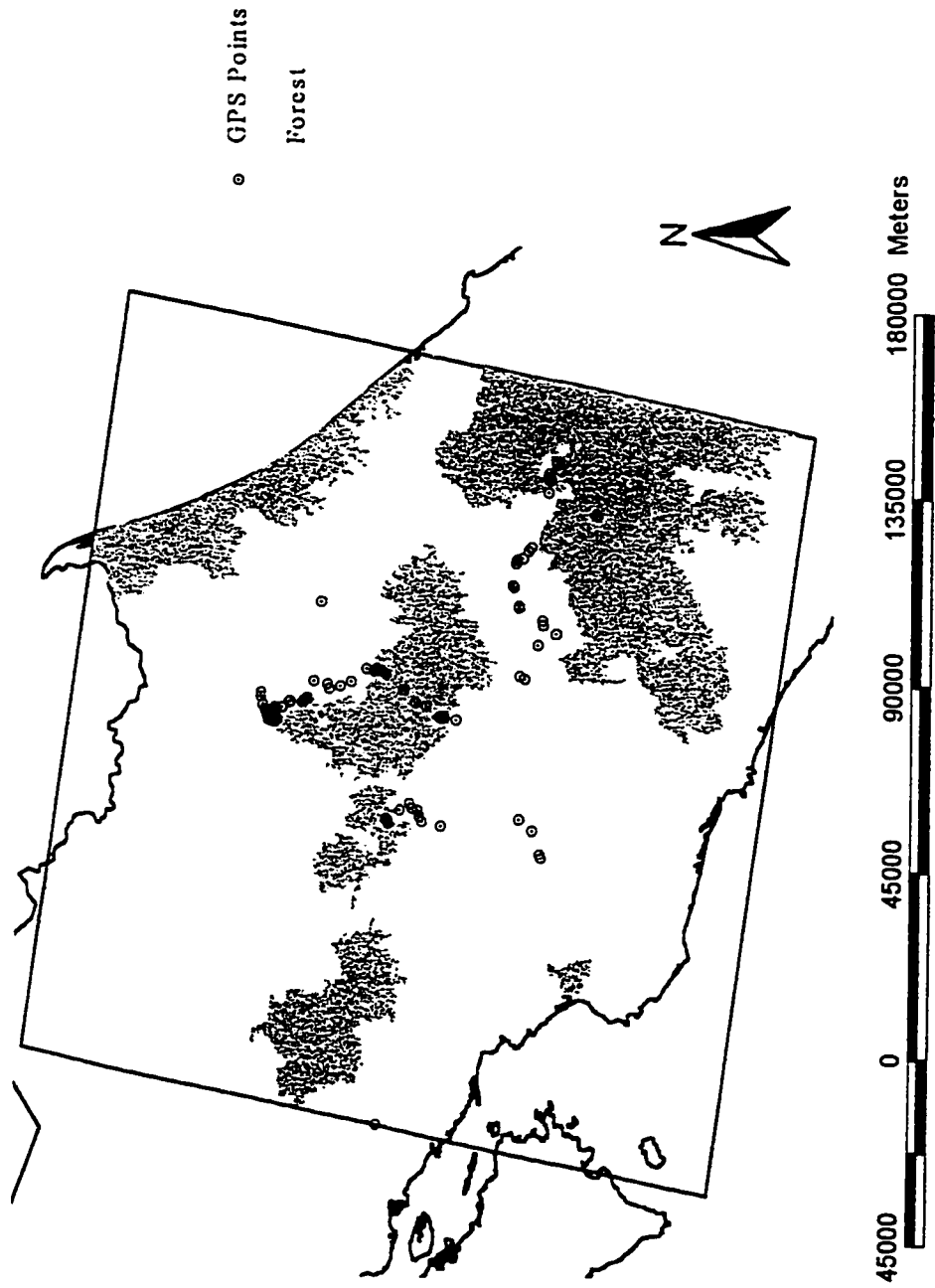


Figure 1.13. Location of ground control points for thematic accuracy assessment.

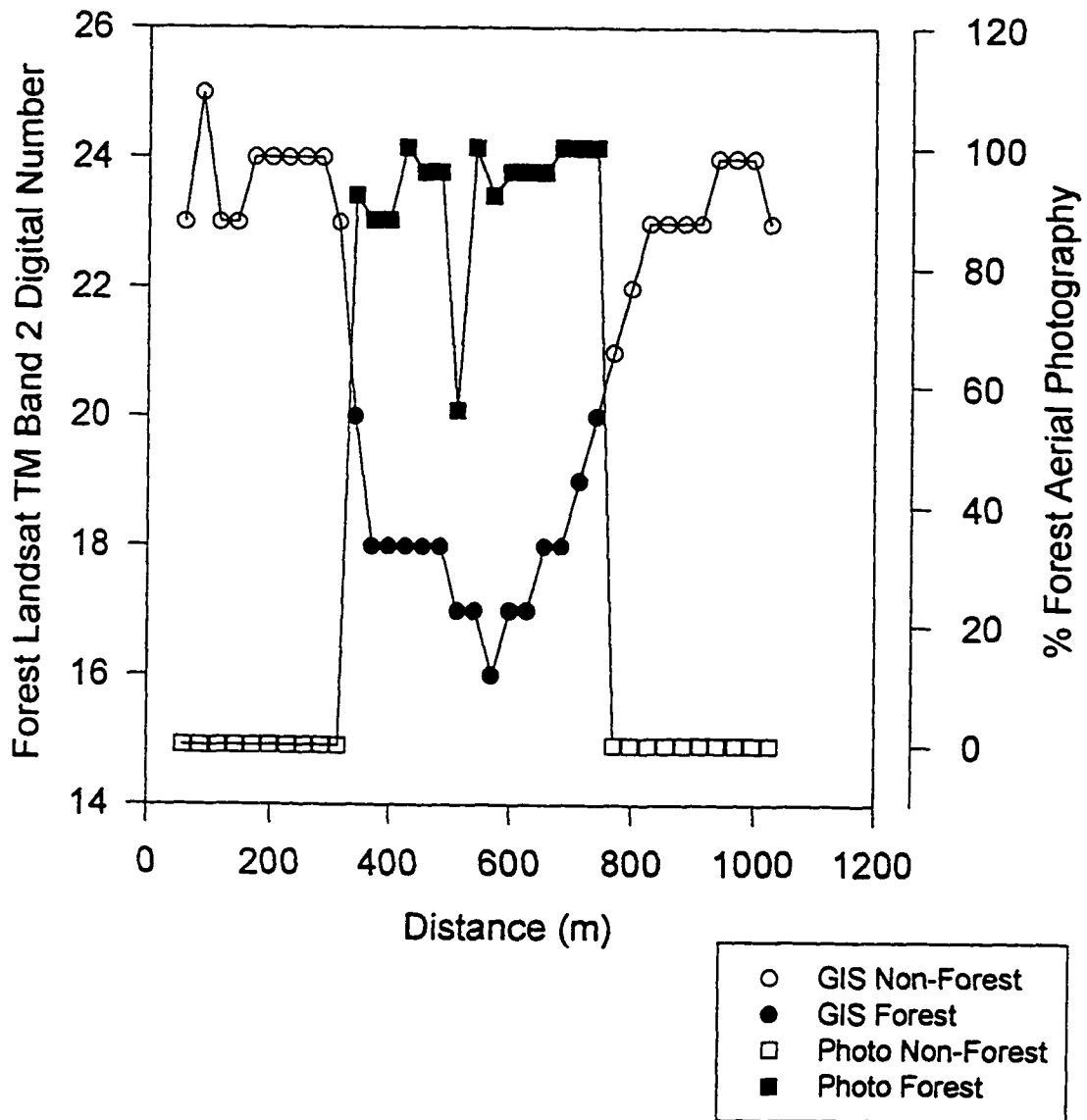


Figure 1.14. Correlation between Landsat TM band 2 digital number and % forest cover from aerial photography. A forest gap with a forest canopy closure of ~60% is observed in this transect.

CHAPTER 2

CAN STRATIFIED SAMPLING BE USED TO ESTIMATE TROPICAL DEFORESTATION?

Introduction

The worldwide lack of knowledge regarding total tropical deforestation and deforestation rates affects estimations of trace gas production. The dependency of current atmospheric and terrestrial models on the quality and quantity of information in tropical forest coverage is the main cause of uncertainty. Additionally, lack of information in forest coverage is also considered a major impediment to the development of regional and global budgets for a variety of nutrient species (Matson, Vitousek & Schimel, 1989). This lack of information is an important factor constraining the development of sound regional land-use / land-cover (LUCC) change policies in the tropics.

One of the concerns regarding transformation of land cover in tropical areas has been the large degree of uncertainty associated with both rates of deforestation over time, and total area deforested. Questions which remain include: What is the area of remaining tropical forests? Are existing estimates of national deforestation rates accurate? How can we use new technologies of remote sensing to get better estimates? How can we obtain representative samples that allow us to conduct an accurate assessment of total deforestation, and to define sound monitoring deforestation programs as part of national strategies for sustainable

development? Recent studies, when they are conducted on decade basis, have demonstrated that remote sensing data can help to answer the former questions (Skole & Tucker, 1993). But problems for annual appraisals and partial coverage still a limitation to the remote sensing technology.

The need for a statistical approach for sampling remote sensing data bases is crucial for LUCC research. The importance and need for developing a methodology for monitoring tropical deforestation and other more comprehensive LUCC processes is a critical issue. When there is no possibility of implementing a wall-to-wall deforestation or LUCC monitoring program partial sampling must be implemented. Sound partial sampling, taking into consideration the population of satellite scenes characteristics, is a key issue of monitoring tropical deforestation and its impacts on biodiversity, water resources, and the carbon cycle. Problems associated with partial sampling can be resolved by using adequate scene selection methodologies.

The premise of this paper is that any attempt to quantify tropical deforestation and deforestation rates, by randomly selecting sites within a population of satellite scenes, would require an overwhelming number of samples. Random sampling generally produces logistical problems and it has high economic costs. Hewitt et al. (1993) indicated that any attempt for "*fair sampling*" will need to optimize both the performance of statistical analysis and the amount of information obtained when compared against the cost of the study.

The following sections of this chapter suggest a methodological approach for sampling remote sensing data bases. The proposed approach can be used as an initial stage in a monitoring deforestation program in the tropics. In this chapter, the proposed method uses

the concept of stratification. Stratification is defined in this chapter as the set of criteria used to select the lowest and most representative elements from a population, minimizing the error, and producing less bias in estimation of a predictive variable. In this paper, it is suggested that stratification can be used for satellite scene selection for global data bases. The proposed methodology is expected to contribute to better design and implementation of long term deforestation monitoring programs in the tropics. It is assumed that stratification will contribute to producing better designed sampling strategies for deforestation studies.

Background

Global and Regional Monitoring Deforestation Projects

In global deforestation studies, sampling has often play an important role. Wall-to-wall interpretations of global deforestation can be time consuming and expensive. Even though it is important, wall-to-wall inventories of tropical deforestation and forest cover have not been accomplished until today. In most studies random sampling is used for scene selection. Because of the patchiness of the deforestation, random sampling can produce significant errors when the goal is to estimate total deforestation. Skole (1992) indicated that when random sampling of Landsat scenes was used for estimating deforestation in the Amazon basin errors were between 48% and 252% of the actual deforestation value.

Sample construction must use procedures that yield the best results at the minimum cost (sub-sampling). It is possible to obtain sound statistical samples if stratification is used as a data base developing tool. One attempt to develop a stratified data base with the purpose

of monitoring global deforestation in the tropics was implemented by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 1996). The FAO sample covers all the tropical regions. A population consisting of Landsat Thematic Mapper satellite scenes was used. The original sampling population was formed by those scenes with a minimum land area of 1 million hectares and a forest cover of 10% or more. The area represented 62% of the total tropical land area, and 87% of all tropical forest.

FAO's scenes were selected using a two-stage stratified random sampling:

Stage 1: Stratification was based on geographical continuity by dividing the survey area into sub-regions.

Stage 2: Stratification was based on forest cover and forest dominance.

The sampling selection was achieved by overlaying a sampling frame, vegetation data, and an eco-floristic zone map. FAO's survey consisted of a sample of 117 satellite Landsat TM scenes. These scenes represented 10% of the total remote sensing data base. The distribution of the scenes by region was 47 in Africa, 30 in Asia and 40 in Latin America. Sample size was selected to represent a standard error of less than $\pm 5\%$. FAO's survey indicates that the former procedure *"minimizes the sampling error by utilizing all the existing information and available knowledge on sampling techniques"*. Selected scenes were visually classified for two different time periods. Forest / non-forest classes were the main attributes of this data base. Total global deforestation and deforestation rates were then extrapolated between 1980 and 1990.

Regional wall-to-wall studies have been developed for the Amazon Basin (Skole & Tucker, 1993). Skole and Tucker's (1993) assessment was performed for the legal Amazon

basin. This area included the states of Acre, Amapá, Amazonas, Pará, Rondônia and Roraima, plus parts of Mato Grosso, Maranhão and Tocantins. A total of 228 Landsat scenes were used. The study area covered an area of ~5,000,000 km² (~4,090,000 km² forest, and ~850,000 km² “cerrado” or tropical savanna, and ~90,000 km² in water). Satellite and GIS techniques were used to stratify the Amazon basin on the basis of cover types. The study reports that total area deforested increased from 78,000 km² in 1978 to 230,000 km² in 1988. A deforestation rate of ~15,000 km² per year is also reported in the same study. Since this analysis includes two time periods with complete coverage by all 228 Landsat scenes for the Brazilian Amazon, it forms an ideal data set with which it is possible to compare various sampling schemes against the entire population.

The Sampling Design

Chatfield (1988) indicated that the main goal of sampling design *“is to select a representative sample, avoid bias and other non-sampling errors, and achieve maximum precision for a given outlay of resources.”* Two different kinds of sampling procedures can be identified: *random sampling and quota sampling*. During random sampling, each sample is pre-selected from the population under the same probability of being selected. In quota sampling, selection of sampling units is weighted so that the sample is representative of the different groups that are part of the population. Quota sampling is also known as *weighted sampling*.

Random sampling involves selecting a sample of size n units from a population of size N units without replacement. Under random sampling conditions, all possible samples of size

n have an equal chance of being selected. A modification of random sampling is presented when the data is selected from an stratified population (*stratified random sampling*). The use of stratified random sampling has been suggested as an important tool for climate change research (Matson, Vitousek & Schimel, 1989; Stewart, 1989; and Aselmann, 1989). During stratified random sampling, the population is divided into distinct subgroups, called strata, and then a simple random sampling is taken from each stratum to form a sample.

Chatfield (1988) notes that stratified random sampling better than random sampling must be selected for the following reasons:

- (1) It uses the researcher's knowledge about the population to make the sample more representative and hence improve the precision of results.
- (2) It permits information to be obtained about subgroups of the population when they present issues of interest for the ongoing research.

The methodology presented in this paper is based on stratified random sampling without replacement of a population of Landsat satellite scenes from the Brazilian Amazon. Sampling without replacement means that each satellite scene in the data base is not replaced after being selected. The first item is selected in " n " ways, the second in " $n-1$ ", and so on, until the r^{th} is selected in " $n-r-1$ " ways. The following rules also apply:

1. Each stratified population selected for sampling must have the same probability distribution as the original population.
2. The process of sampling is independent.
3. Sampling without replacement is required to avoid repetitions and bias.
4. The probability of selecting a sample unit from the population is the same for all the

units in the population.

The former rules ensure that a random scene is one that is selected in such a way that any other scene could have resulted with equal likelihood. Non-randomness of sample selection may well be reflected in a lack of independence of the items or in heterogeneity of variances. Moreover, the order of occurrence of the data is not important. Only the data value is important.

Methods

The Reference Data Set and Sampling Frame

The Landsat tile system or World Reference System 2 (WRS-2) was used as a sampling frame. The WRS-2 is the standard reference system for Landsat Thematic Mapper (TM) and Multi-Spectral Scanner satellite scenes (MSS). This reference system has been in place since the launch of the Landsat Mission Four in July, 1982 (Jensen, 1986). The WRS-2 system codes the location of Landsat TM and MSS into path/row maps. The WRS-2 provides a convenient description of the geographical distribution of satellite scenes and is a ready-made sampling frame for the selection of remote sensing data (FAO, 1996).

A remotely sensed data set, linked to the WRS-2 systems and developed at the Institute for Study of Earth, Ocean and Space (EOS) of the University of New Hampshire was used as a sampling frame (Figure 2.1). The data set is the result of a wall-to-wall assessment of deforestation for the legal Amazon Basin (Skole and Tucker, 1993). Spatial location of scenes forming this data base are coded using the WRS-2 reference system. The

Amazon basin is the largest continuous tropical forest in the world (6,248,373 km²). Deforestation of the Amazon basin accounts for a large fraction (12-20%) of the global estimate (~15,000 km²/year). The Amazon basin is important in terms of global carbon flux and other trace gas emissions (Keller et al., 1991; Harriss, 1989).

The database used consists of land cover change information (i.e. deforestation) extracted from 228 satellite scenes for 1978 and 1988. Each scene represents (approximately) 185 x 185 km in size. Deforestation, primary forest, clouds and naturally occurring non-forest (know as "cerrado" or tropical savanna) are the main topological attributes. Results from these data bases indicate a total deforestation of 78,271 km² and 230,324 km² for 1978 and 1988, respectively.

The Stratification Scheme

This studies follow a three step procedure for selection of a stratified population for random sampling (Figure 2.2). During the process of creating a sampling population, the entire original population was defined as un-stratified-population (*level 1*). The application of a satellite scene selection criterion to generate a new sample from it, produced a *level 2* stratified-population. Application of a additional criterion, over the level 2 stratified-population, generated a level 3 stratified-population. This last population was used for random sampling and estimation of total deforestation.

Stratification of a the un-stratified-population (*level 1*) to level 2 used the percentage of tropical savanna as a basic criteria. Stratification from a level 2 to a level 3 used two different sets of criteria: persistence and the rate of forest change by scene. First, persistence

is defined as an indicator of deforestation dynamics at the scene level. Under the concept of persistence, scenes presenting some degree of deforestation on time T_i , will present more but no less deforestation on time T_{i-1} . Persistence was calculated as the correlation coefficient (r^2) between time T_i and time T_{i-1} of total deforestation. As time between sampling population increases, and the patchiness of the deforestation also increases, persistence (r^2) will also decrease. Secondly, the rate of change of total deforestation change (as a percentage) for each satellite scene between 1978 and 1988 was used as stratification criteria. Scenes with deforestation changes of 5% and 10% were used to create the sampling populations. Total change in total deforestation at the satellite scene level was estimate as follows:

$$DC = \frac{F_i - F_{i-1}}{F_i} * 100 \quad (2.1)$$

where DC is deforestation change, and F_i and F_{i-1} is the total deforestation in time I and I+1, respectively.

Sampling and Comparison of Results

Sampling from the level-3 stratified-population was performed for several density classes in order to identify the optimum sample size. Density class was defined as the percentage of satellite scenes from the total stratified-population-*level I* used to generate a given sub-sample (e.g. a sample size of $n = 20$ scenes from a 202 population will represent ~10% density class). Bros and Cowell (1987) recommended that the number of random

draws n made from a finite population be, at least 10% of the original population.

Comparisons of results for each sample density was performed under standard conditions. In this specific case we have used a normalized standard deviation as a comparison between sampling densities. A decrease of the normalized standard deviation is a function of an increase of information out of the finite population-level-I. A graphical comparison of sample trial density against the normalized standard deviation was performed (Figure 2.3). The normalized standard deviation was defined as:

$$NSD_j = \frac{TV_{d,n} - \gamma\sigma_i}{TV_{d,n}} \quad (2.2)$$

where NSD_j is the normalized standard deviation for a j sampling density, $TV_{d,n}$ is the known value of deforestation of a sample of size n , γ is the number of standard deviations departure from the mean (1,2 or 3), and σ is the individual standard deviation for a sample trial of density I . Figure 2.4 presents a flow diagram related to process of random sampling and comparison of results.

Results

Stratification and Sampling

Stratification level 2. The original population was stratified by eliminating all scenes with an area of more than 30% of non-natural forest area (cerrado). A new stratified-population-level 2 consisting of 202 scenes was produced. Both 1978 and 1988 data sets accounted for 89% of the total Amazon basin's area. Both data sets also accounted for 96% and 97% of the total

reported deforestation, respectively (Table 2.1). Frequency distribution of these two populations (Figure 2.6) were similar to the original population (Figure 2.5). Most of the scenes eliminated from the original population had total deforestation ranging from 0 to 500 km². None of the scenes with higher deforestation were eliminated from the data set.

Stratification level 3. A second stratified-population-level 3 was created by using the concept of persistence on the 202 scenes. Scenes presenting a departure from the 1978-88 regression line were selected (Figure 2.7). For the 1975-78 period, the correlation between the data is estimated to be 0.81. The high correlation for the 1975-78 data represents a less intense process of deforestation in the Amazon. Therefore, there is more clustering along the regression line. The correlation for the 1978-88 data set is estimated to be 0.63. As deforestation becomes dominant as a spatial process over time, more dispersion and less clustering is observed around the regression line, therefore decreasing persistence.

The use of persistence allowed for the identification of 71 of the 202 scenes (Figure 2.8). The selected 71 were identified from the 1978 data set in order to estimate total deforestation in 1988. The frequency distribution of the 1978 selected scenes followed the same probability distribution as the original population (Figure 2.9). The selected scenes accounted for 31% of the total study area, and 94% of all the 1978 deforestation.

Sampling: A random sampling without replacement at 5% sample size density was applied to the two stratified data sets (Level 2 and 3) (i.e. for 202 scenes, only 10 scenes will be sampled at 5% density). Sampling was performed 100 times for each sample density in order

to ensure that no bias was present in the estimation of the average total deforestation. Comparisons of results for each sampling experiment was performed under standard conditions. Normalized standard deviations were calculated and compared (Figure 2.3).

Figure 2.3 indicates that for the stratified-population-level 2 there is no gain in precision by random sampling without replacement the 202 original data set (FAO approach). It is also concluded that there is no gain by increasing the sampling density. Minimum normalized standard deviation is reached when sample density is equal to 100%. Behavior of the normalized standard deviation as a function of sampling size is the same for the 1978 and the 1988 populations. For example, if a random sample consisting of 50% of each original population is selected to estimate total 1978 and 1988 deforestation, on the average, the estimated error will be $\pm 30\%$ (for the 1988) and $\pm 35\%$ (for the 1978) of their original total deforestation.

A considerable gain is observed when persistence is used as a tool for stratification. The use of persistence decreases sampling error significantly. For this case study, the standardized error regarding estimation of tropical deforestation for the whole Brazilian Amazon Basin (at the 5% sample density) drops from 2.38 (in 1978) to 1.35 (persistence 1978-88). In addition, minimum standard error is reached at a 35% sample density. When the minimum standard error is reached using the stratified-population-level 3, sampling from stratified-population-level 2 from the 1978 and 1988 data sets reports a $\pm 40\%$ level error. Our results indicated that random sampling from a stratified/persistence data base can perform better than simple random sampling from a finite population.

Rate of change: Figure 2.10 presents the rate of change for 228 satellite scenes in the Amazon Basin. Percentage of change in the amount of reported deforestation was estimated by comparison of two independent estimations of total deforestation between 1978 and 1988. Rates of change of 5% or more, and 10% or more were used as criteria for scene selection. The application of this technique (equation 2.1) yields the selection of 33 and 14 on 1978 and 1988 as reference scenes for monitoring and further sampling (Figure 2.11 and Figure 2.12).

The most important limitation of this method was that the scene selection process violates the same probability distribution assumption. An inspection of figure 2.13 indicates that the selected scenes using the threshold criteria do not follow the original frequency distribution. Therefore, sampling was not performed in this data set. The used of the former two level-3 population will produce bias results.

Conclusions

1. Results of our study on the impacts of stratification as a scientific tool for estimation of global deforestation are encouraging. Our estimates indicate that stratification based on persistence contributes to the reduction of error regarding estimation of total deforestation when it is contrasted against stratified level one data bases (random sampling without stratification). The results of this work also indicate that more accurate estimations of deforestation can be obtained if persistence is used to select sampling elements for deforestation studies. Use of persistence, for construction of sampling databases, could be possible only if current efforts to map tropical

deforestation are product of wall-to-wall reference data sets.

2. Results indicate that random sampling (from stratified populations level 2) has the potential for extreme over or under estimation of total deforestation. Reductions in error are achieved only when very high sampling densities are attained. If a new level of stratification is applied, very accurate estimates of the total area deforested can be obtained using low sample densities.
3. Stratified sampling based on persistence can help to develop more sound monitoring deforestation programs at the global or national scale in the future. Sound sampling methods are necessary to monitor current efforts regarding the effect of mitigation/adaptation policies and programs (i.e. those new programs which are part of the Joint Implementation projects in the area of sustainable forest management).
4. The results from this research can be extrapolated from global deforestation estimates to more regional analysis. In those cases where there is a lack of good satellite imagery, the spatial dimension of the sample element can be reduced, so that multi-temporal aerial photography data bases can be selected as a sampling element. This alternative could permit to national governments and international organizations to implement regional or national LUCC programs bases on inexpensive and available aerial photography data sets.

5. More accurate information on the current extension of tropical forests and the dynamics of deforestation processes can facilitate the refinement of global carbon budgets and models. The results of this study indicate that more accurate assessment of deforestation at global levels can be accomplished through the development of scientifically-based monitoring methods based on stratification. The use of random sampling for original data sets is not encourage.

Table 2.1 Amazon Basin, number of scenes selected from different stratification criteria.

Criterion	Year	Number of Scenes	Total Area (km²)	Total Deforestation (km²)	% of Total Area	% of Total Deforestation
Level 1 Whole population	1978	228	6284373	78271	100	100
	1988	228	6284373	230324	100	100
Level 2 Forest zone % Non-Natural Forcst >= 60%	1978	202	5583378	74875	89	96
	1988	202	5583378	223543	89	97
Level 3 Persistence	1978	71	1952114	73723	31	94
Level 3						
1978-88 Percentagc Change >=5%	1978	33	904524	50523	14	65
1978-88 Percentagc Change >=10%	1978	14	382517	32312	6	41
1978-88 Percentagc Change >=5%	1988	33	904524	169231	14	73
1978-88 Percentagc Change >=10%	1988	14	382517	112438	6	49

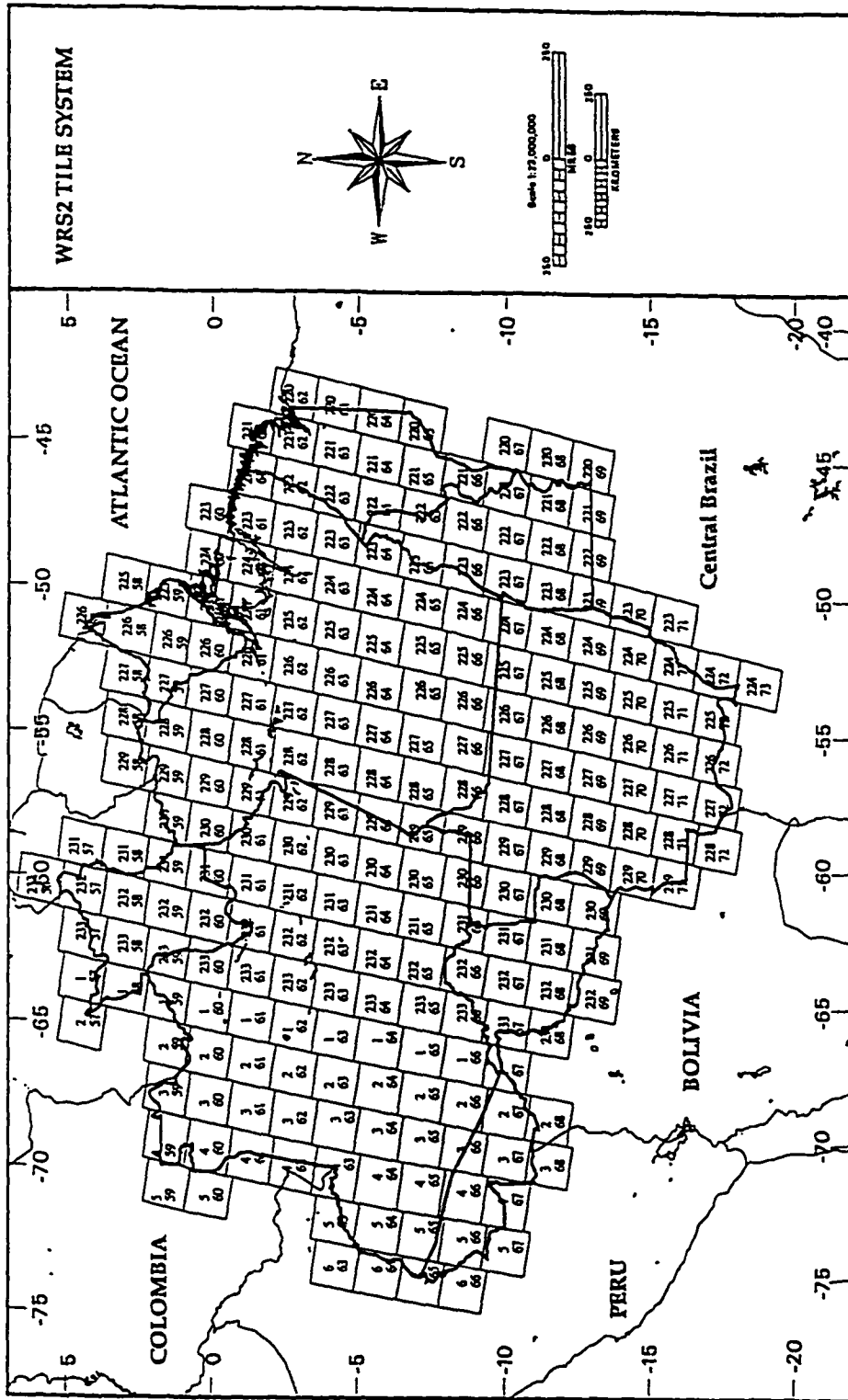


Figure 2.1. Distribution of satellites scenes for the Amazon Basin.

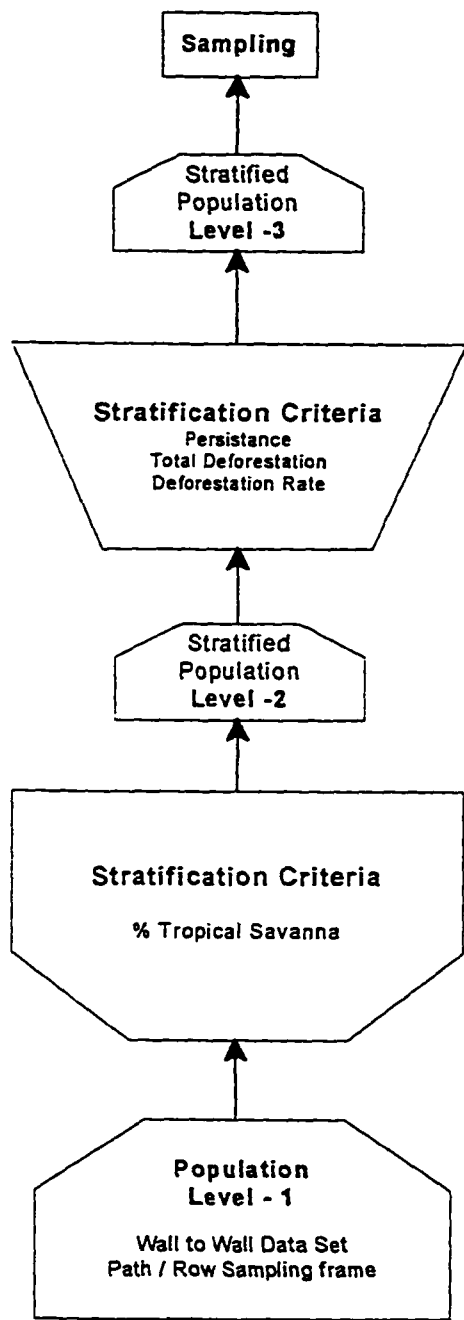


Figure 2.2. Stratification scheme follow to generate a stratified population Level-3 for random sampling

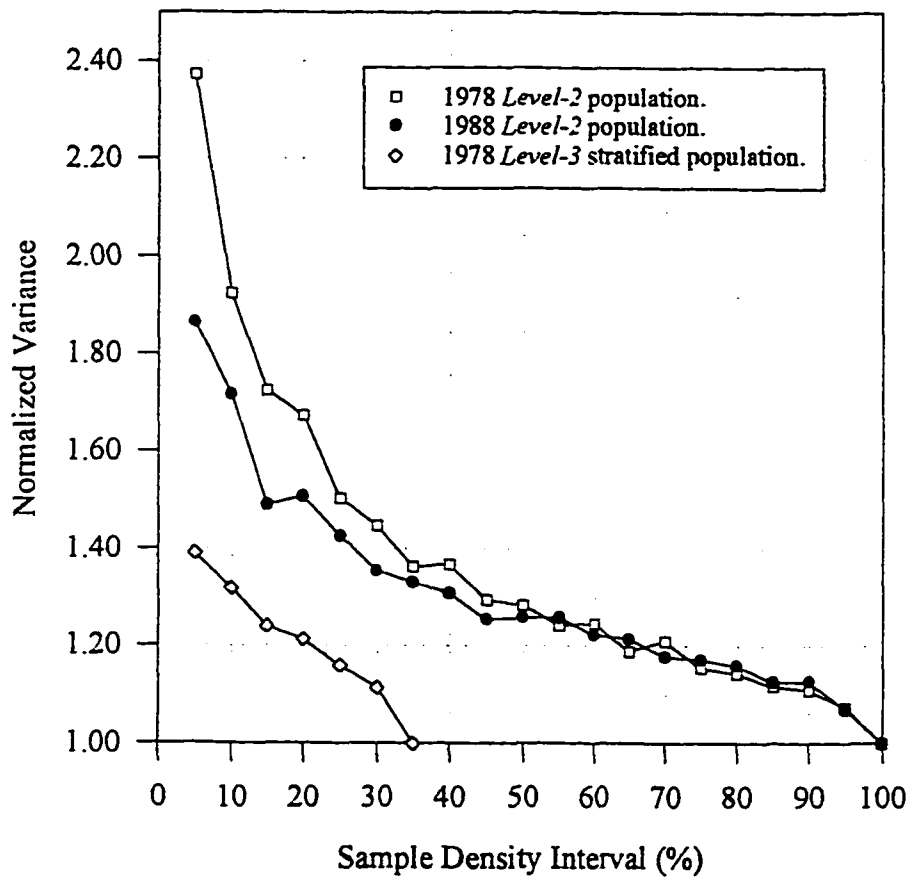


Figure 2.3. Comparison of normalized variances for level-2 stratified populations (1978, 1988 data sets) and level-3 stratified population. The level-3 population was generated by using persistence.

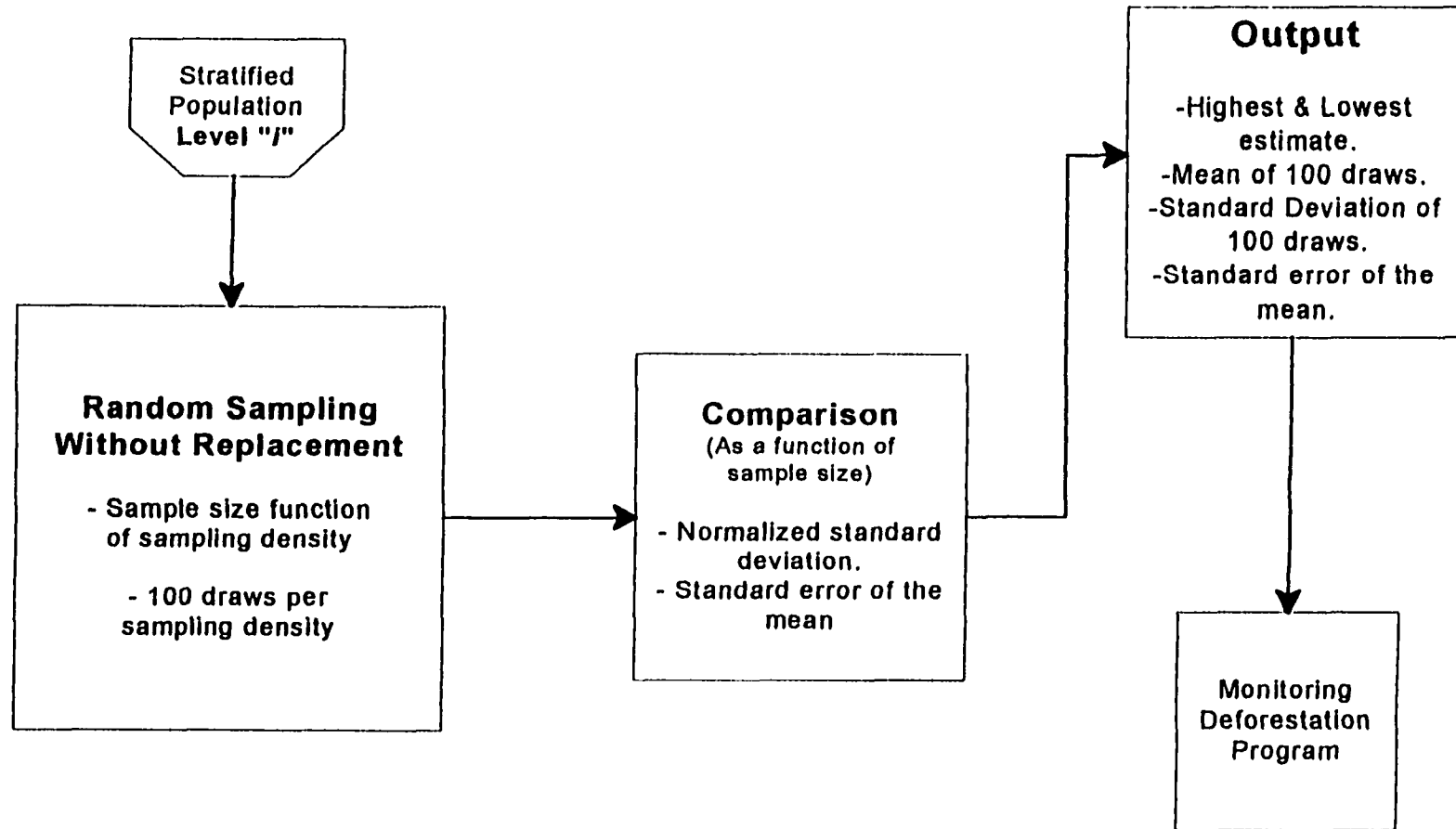


Figure 2.4. Random sampling procedure on a stratified population level-3.

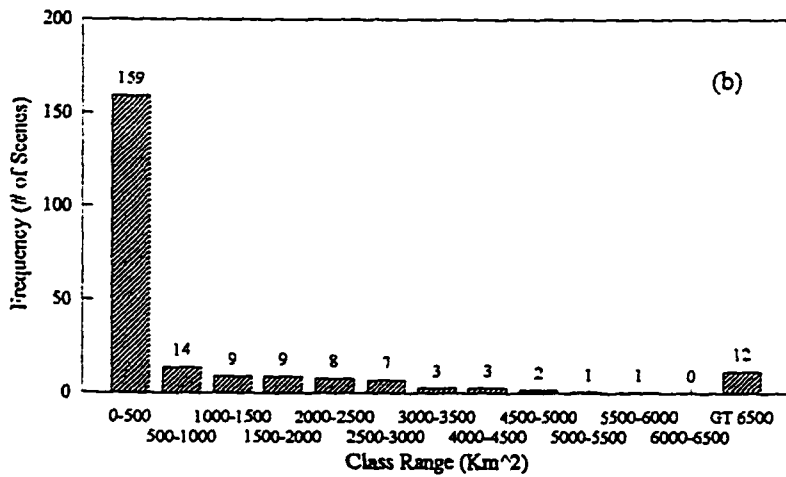
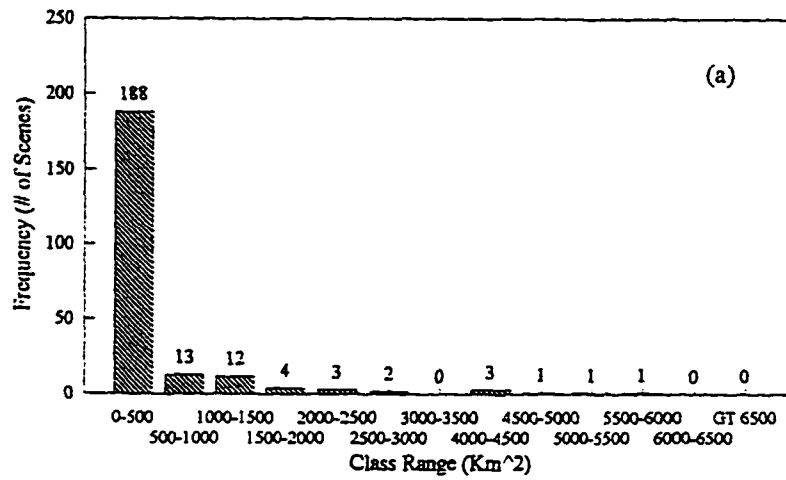


Figure 2.5. Frequency distribution for the original satellite scene sampling population (a) 1978, and (b) 1988.

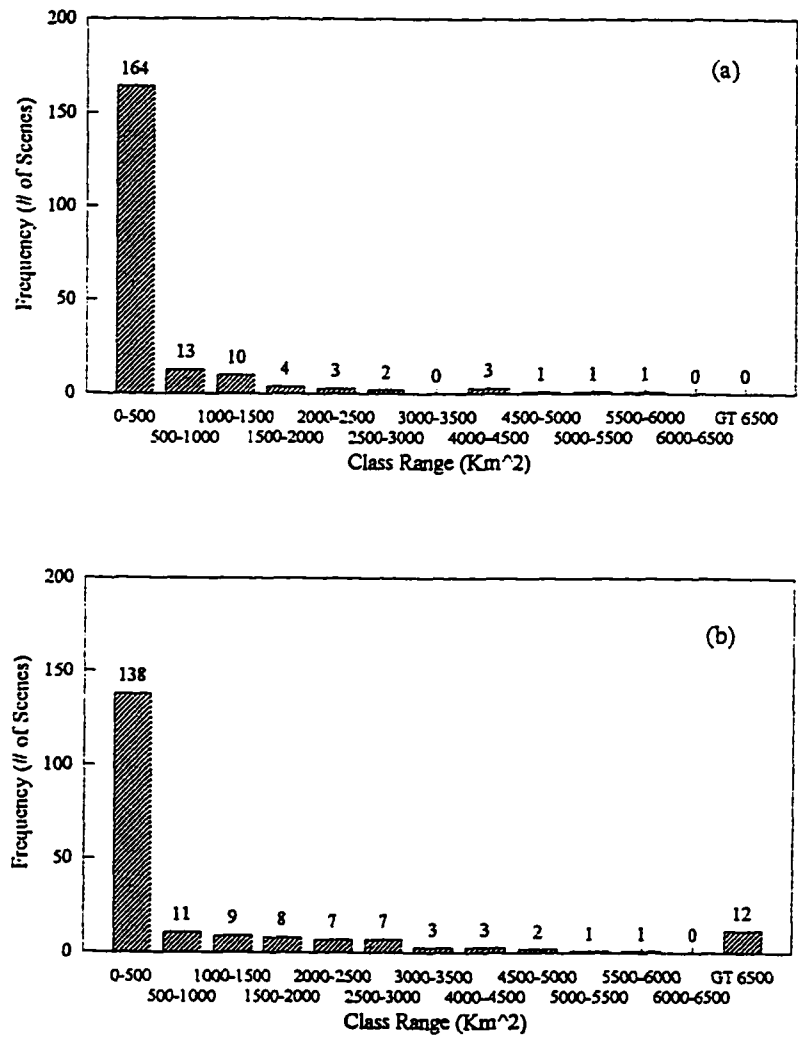


Figure 2.6. Frequency distribution for level-2 satellite scene population (a) 1978 and (b) 1988.

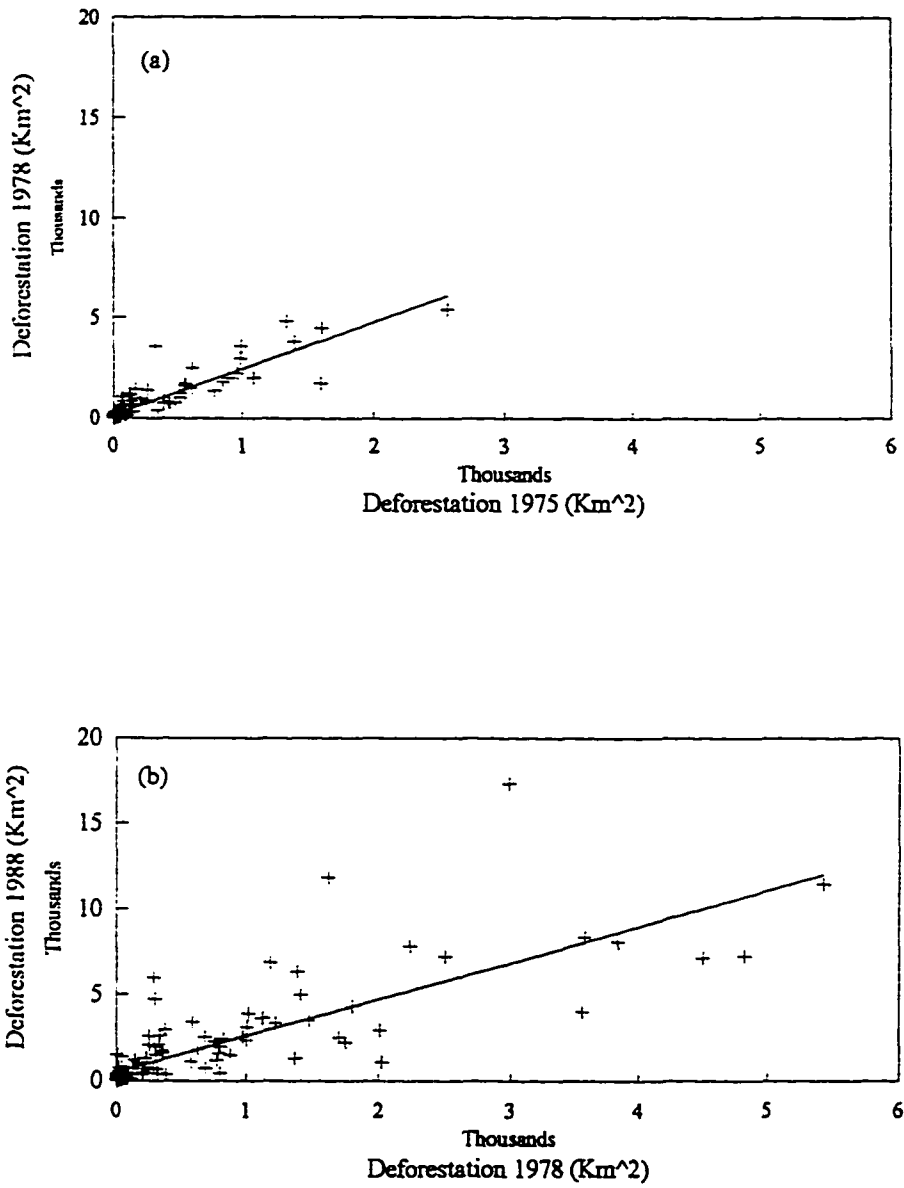


Figure 2.7. Persistence analysis for three time periods, (a) 1975-1978 ($r^2 = 0.81$) and (b) 1978-1988 ($r^2 = 0.63$). Persistence decreases over time as deforestation patchiness increases.

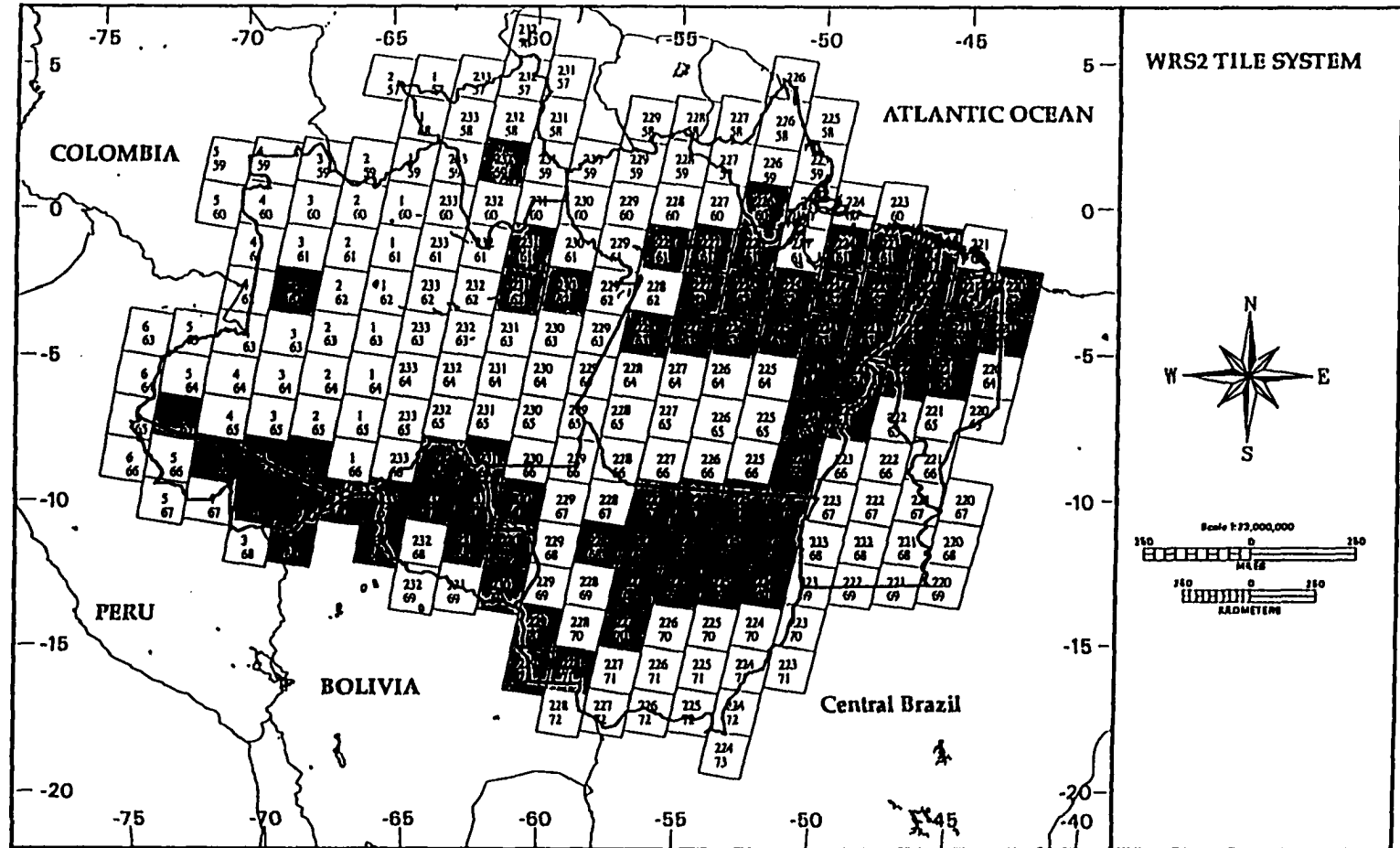


Figure 2.8. Selected satellite scenes by using persistence.

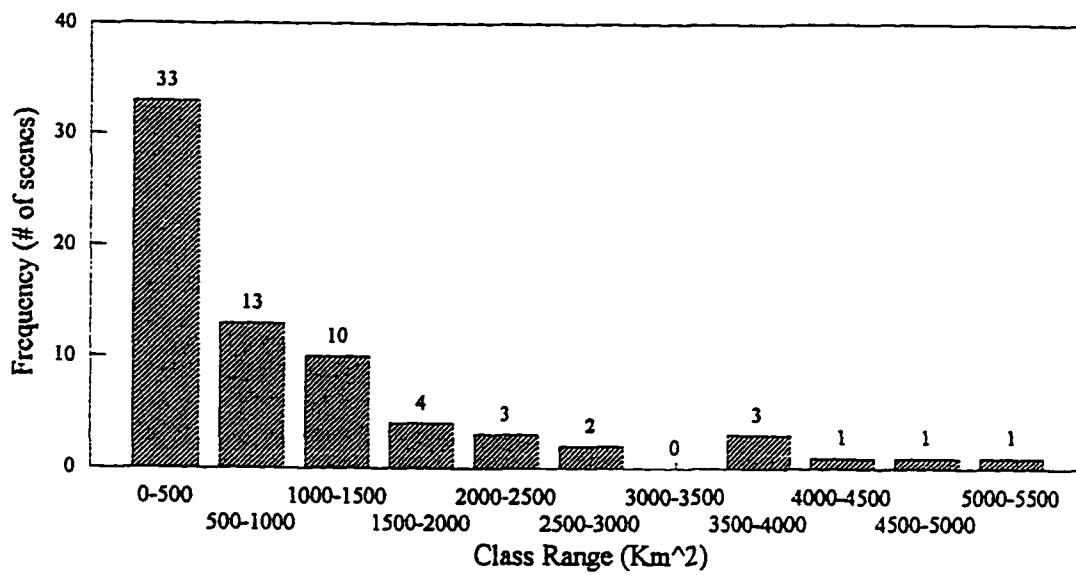


Figure 2.9. Frequency distribution of selected satellite scenes using persistence. The level-3 population has the same frequency distribution than the level-1 population.

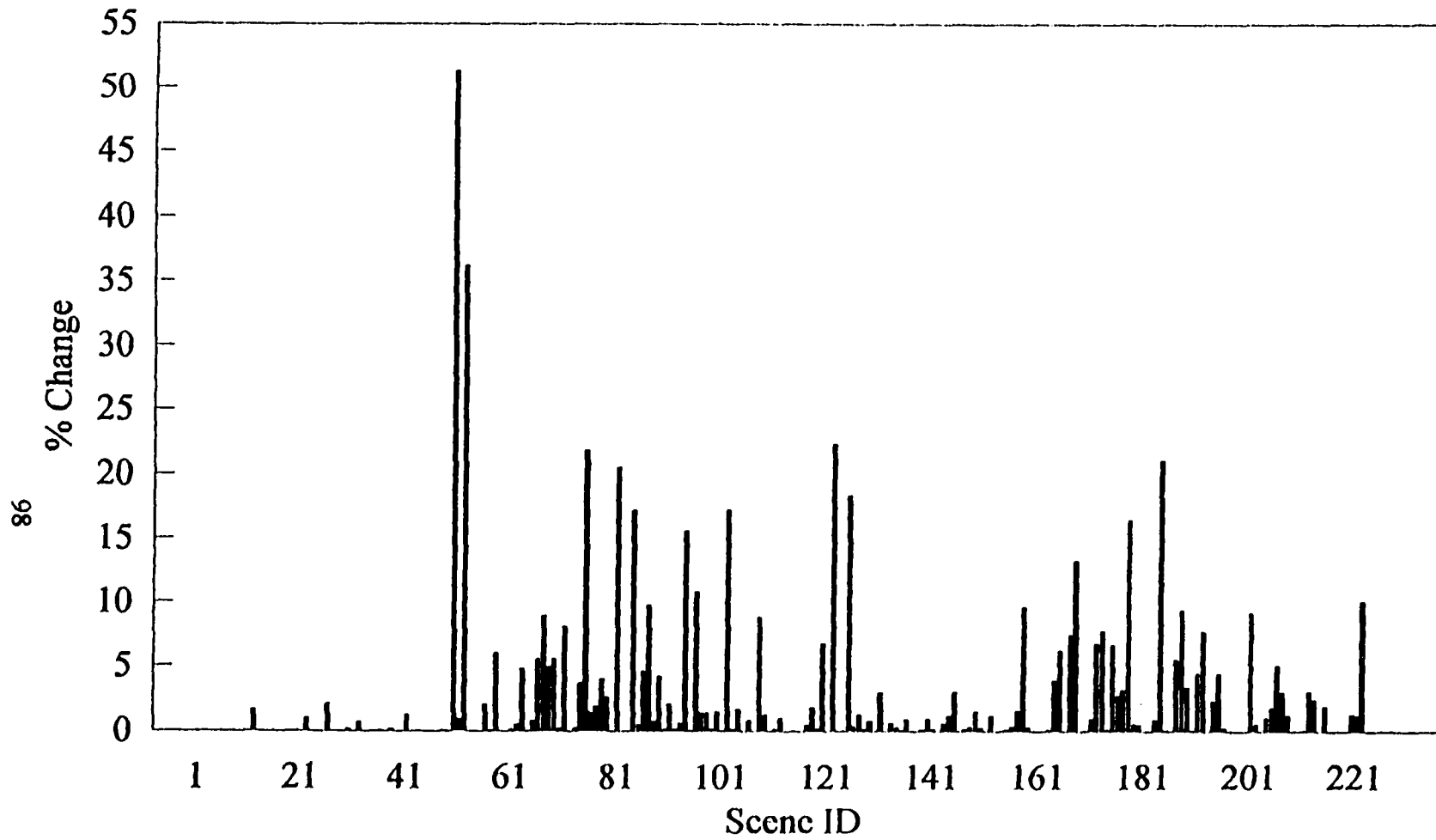


Figure 2.10. Rate of forest change between 1978 and 1988 for 202 satellite scenes at the Amazon basin. A total of 33 and 14 scenes were selected for a 5% and 10% change, respectively.

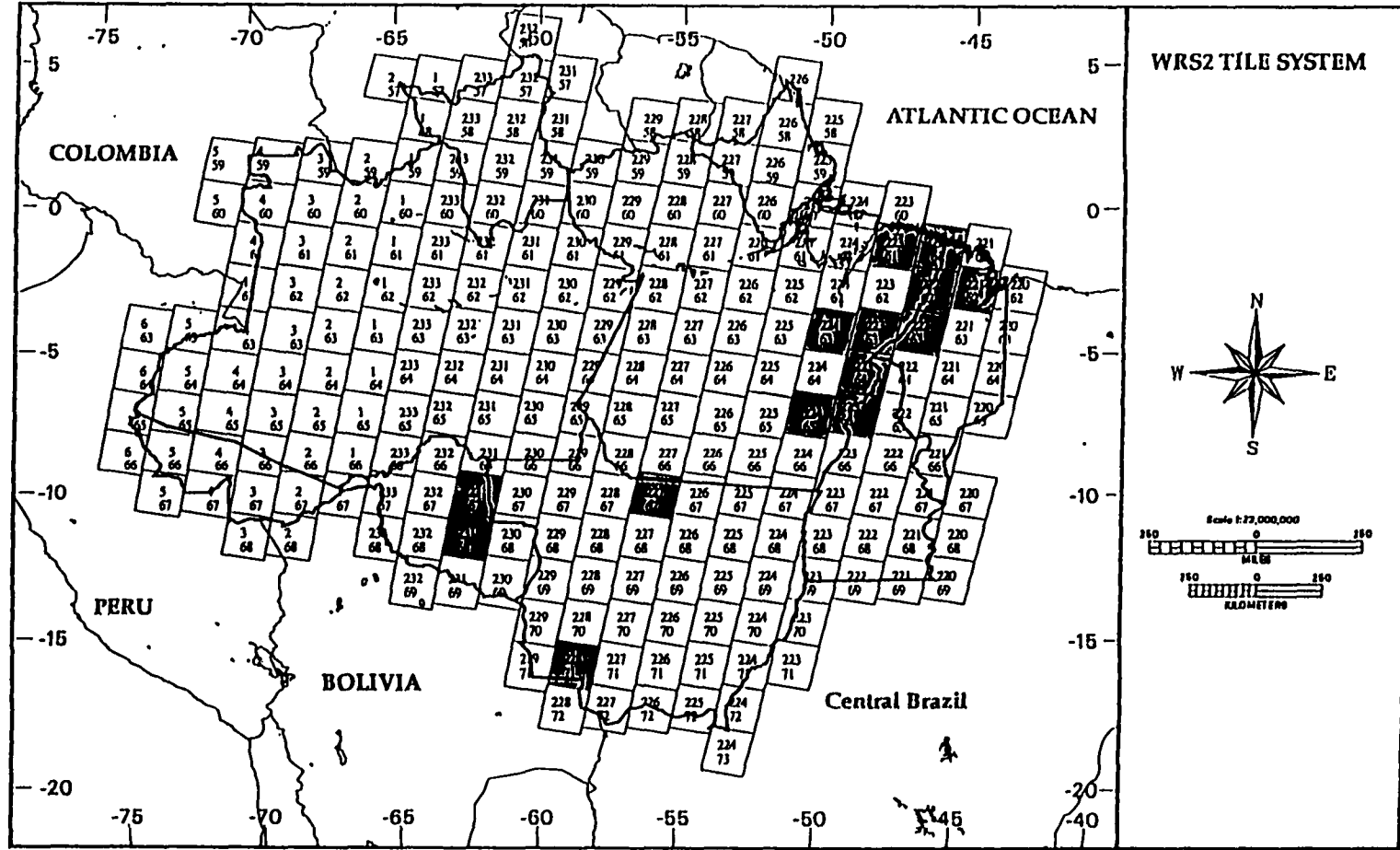


Figure 2.11. Location of selected scenes using a 10% forest change threshold.

100

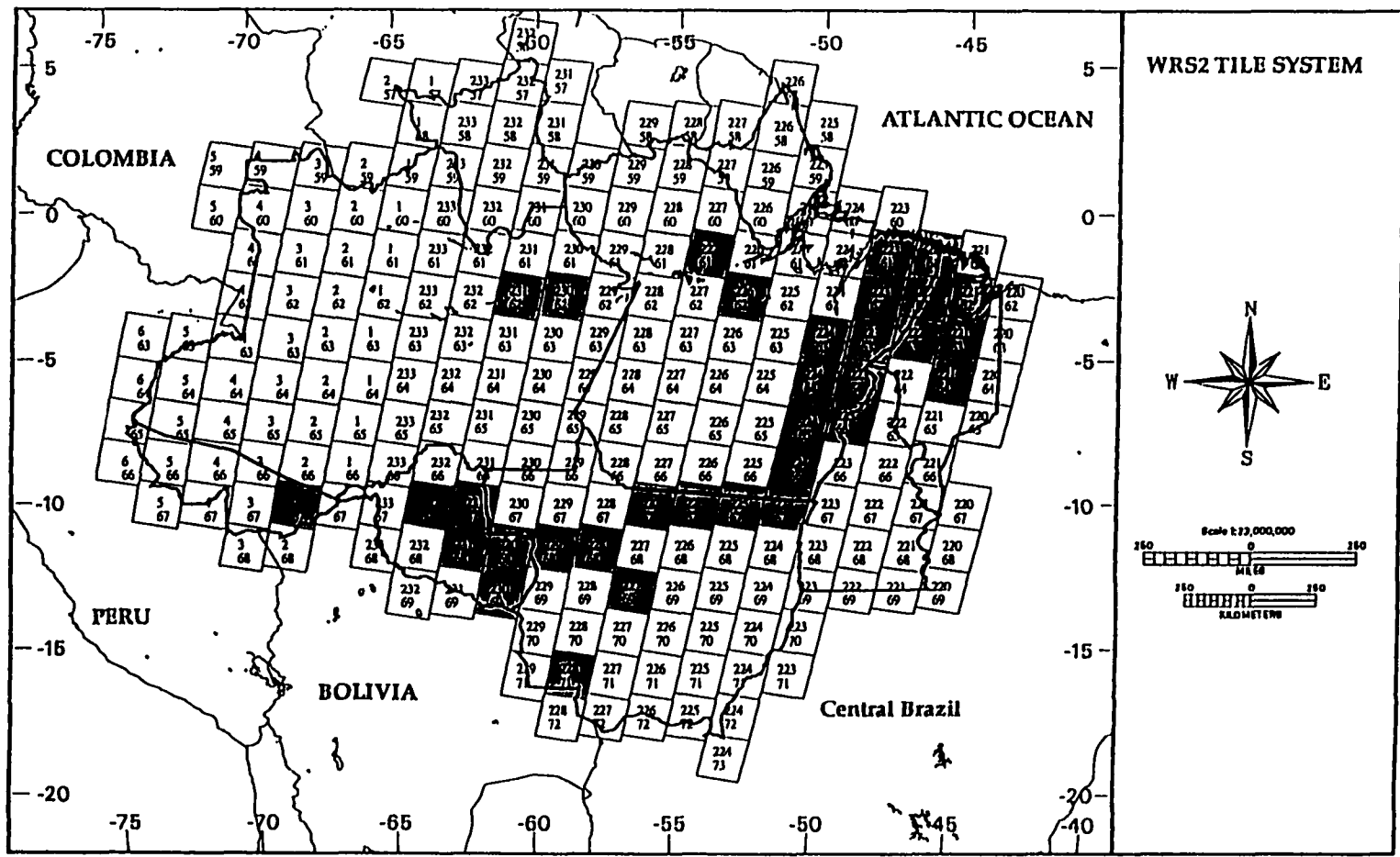


Figure 2.12. Location of selected scenes using a 5% forest change threshold.

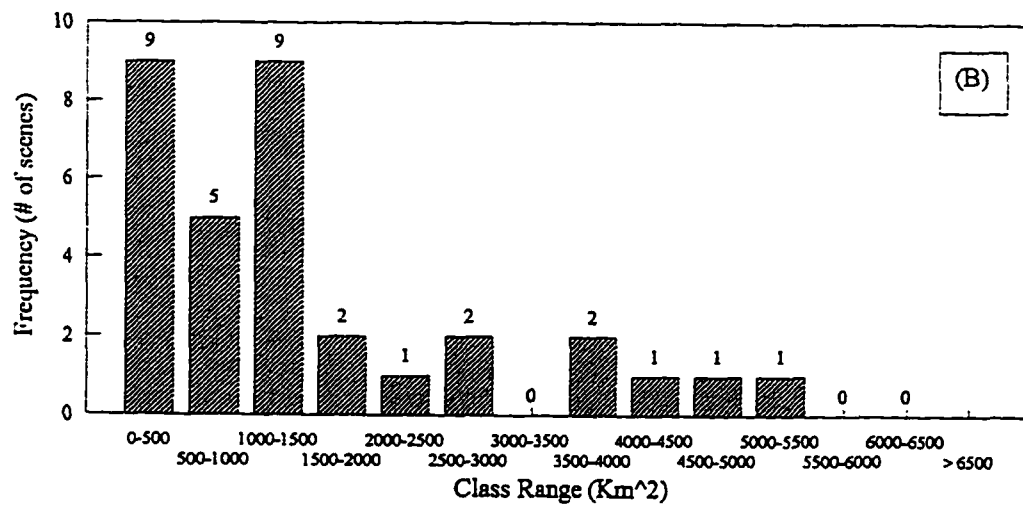
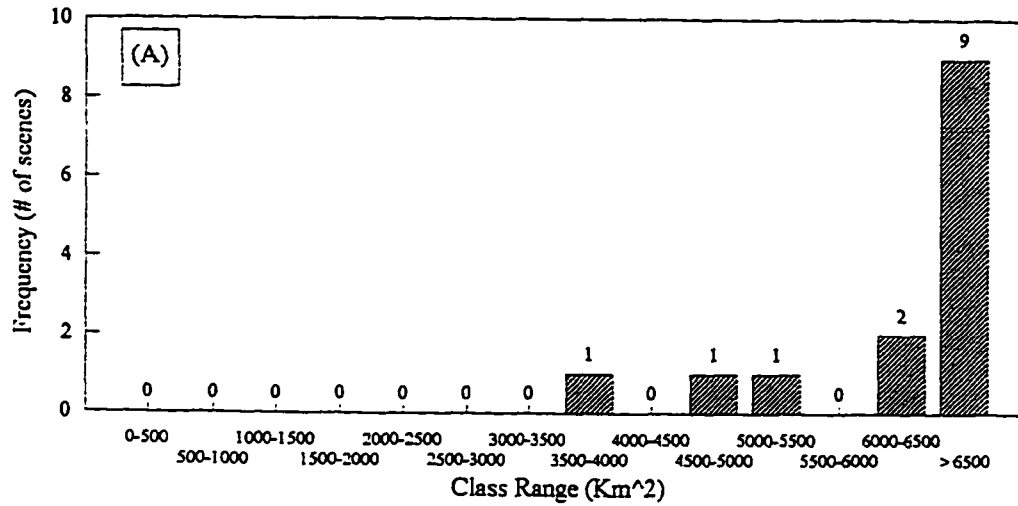


Figure 2.13. Frequency distribution for scenes selected using (a) 10% change and (b) 5% change. None of the selected samples follow the original frequency distribution.

CHAPTER 3

A REVIEW OF FACTORS WHICH HAVE CONTRIBUTED TO LAND USE/COVER CHANGE IN COSTA RICA

Introduction

Developing countries are beginning to invest in systematic studies of land use and land cover change (LUCC) to take inventory of natural resource assets. Costa Rica has one of the most comprehensive resource inventory programs. Tropical deforestation has been reported as one of Costa Rica's most important LUCC issues (Sader & Joyce, 1988, Centro-Cientifico-Tropical, 1982). Some authors suggest that the loss of tropical forest will have a damaging impact on Costa Rica's economy (Quesada-Mateo, 1990; Solorzano et al., 1991). Such landscape modifications result in the loss of biodiversity and scenic values, increases in erosion and reservoir siltation, and loss of agricultural top soil.

Quesada-Mateo (1990) note that deforestation is one of the most important causes of environmental degradation in Costa Rica. The primary causes of deforestation were identified as: (1) Expansion of the agricultural frontier in critical and fragile forested areas, producing increased soil erosion, siltation of hydropower reservoirs, and changes in biodiversity; (2) Urban expansion into high productivity agricultural soils.

LUCC trends reflect expansion of the agricultural and urban frontiers, in a country with high rates of population growth (2.6% per year). Significant links exist between LUCC

and processes of environmental degradation. This is especially important in a country with a high dependency on multiple uses of water resources for irrigation, domestic consumption, recreation, and hydropower generation.

By 1982, the Tropical Science Center reported that 17% percent of the country was experiencing erosional processes caused by humans, and that 24% of the country's surface was eroded due to LUCC processes. Costa Rica was estimated to be losing an average of 680 million tons of soil per year (Centro-Cientifico-Tropical, 1982). This erosion, occurring in both the Pacific and Atlantic watersheds, is jeopardizing Costa Rica's future agricultural productivity and its water resources infrastructure. The decline in these resources restrict future options for development. Understanding of LUCC driving forces and their impacts on natural and managed systems is critical for the sustainable development in Costa Rica.

Costa Rica has taken important steps toward environmental protection of representative areas of valuable natural and scenic habitats. Currently, 29% of Costa Rica's territory is under some degree of protection (Chapter 1). Costa Rica's protected areas encompass more than 70 sites, including national parks, biological reserves, wildlife refuges, protected zones, and forest reserves (Umaña & Brandon, 1992). However, concerns remain regarding how land is managed outside national parks. Ramirez and Maldonado (1988) concluded that although a good national park system is in place, LUCC trends outside of the protected areas are unsustainable. Their 1988 report concluded that the expansion of the agricultural and cattle frontier, illegal deforestation, and squatter settlements are having detrimental impacts on the country's natural resource base.

Methods

To further study LUCC and its effect on the natural resource base, a geographic information system (GIS) with a comprehensive natural resource and socioeconomic data set was developed. Agricultural census data for cattle and pasture lands were integrated into a common data set for the entire country. Additionally, data on head of cattle, area in pasture land, area in sugar cane, and area in coffee were aggregated at the province level (Figure 3.1). The main source of information were the 1950, 1955, 1963, 1973 and 1984 agricultural census (Costa Rica, 1950; 1955; 1963; 1973 & 1984).

Annual growth rates in these variables were computed (Table 3.1 to Table 3.4). Information for banana was not available during this study. Official Costa Rican census data were last issued in 1984. The failure to complete a census in 1994 has resulted in a serious gap in understanding of LUCC information. In addition, the 1984 official land use cover map from the National Geographic Institute was integrated into the GIS as an independent validation of the forest cover assessment presented in the agricultural census (Instituto Geografico Nacional, 1984). A complete description of the GIS and its data sets is presented on Appendix B.

Results

LUCC Dynamics in Costa Rica (1950-1984)

LUCC dynamics in Costa Rica for the last 30 years have been driven by expansion of the agricultural and cattle frontier, and urbanization (Centro-Cientifico-Tropical, 1982; Harrison, 1991; Quesada-Mateo, 1990; Ramirez & Maldonado, 1988). This LUCC process

was encouraged by legislation which placed low value on forest and encouraged agricultural development (Gaupp, 1992). Tropical deforestation, associated with expansion of this agricultural land base through national and international loans, was considered a necessity. In general, deforestation was used as a tool to expand grazing land without regard for potential environmental degradation. By 1980, the Tropical Science Center reported that as much as 76% of all land with potential for growing annual crops was occupied by pastures (Centro-Cientifico-Tropical, 1982).

The concept of using the forest as an open-access resources have produce high deforestation rates during the last 20 years. FAO (1990) have reported that Costa Rica deforestation rate of 2.9% ranked the country 5th in the world. For much of the period 1950-1984, Costa Rica's deforestation rate has been estimated to be 3.9% per year (Leonard, 1987). Deforestation trends between 1940 and 1983 estimated by Sader and Joyce (1988) resulted in the loss of 50% of the 1940 primary forest cover (primary forests are considered here to be relatively undisturbed forest with an upper canopy covering more than 80 percent of the surface area) (Figure 3.2).

Economic Development Policies and LUCC: Data from the agricultural census allows for the analysis of the influence of economic development policy on LUCC dynamics. LUCC processes in Costa Rica (1950-84) appear to be correlated to phases in the country's economic development. During the 1950-1984 period, five different economic phases can be identified (Aguilar., 1982; Quesada-Mateo, 1990): 1) *A shift from an agrarian to an international export-economy* (1950-1963); 2) *Expansion of the internal market to regional*

agricultural trade markets (1963-1973); 3) Import substitution and industrial development (1974-1978); 4) an important period of economic crisis (1978-1982); and 5) post-crisis economic recovery (1983-1989).

Figure 3.3 indicates that the relative contribution of the agricultural sector to the national GNP was reduced from 41% in 1950 to 20% in 1984. During the 1950s, the country's economic model was dependent on expanding the production of a few commercial crops such as coffee and sugar cane. These two crops experienced high growth rates during the 1950s (5.1% coffee, 5.7% sugar cane). In 1950, Costa Rica's coffee, banana and cocoa represented 51% of the national production (Costa Rica, 1995a). Exports of these three agricultural products accounted for 91% of the total export revenue (Costa Rica, 1995a).

Our analysis of Costa Rica's agricultural census during the study period indicates that the percentage of the land dedicated to permanent crops and annual crops have been constant (Figure 3.4). This a result of a complex interaction of government policies policy and technologic advances which have maintained high production yields. At the same time pasture land as expanded as a result of the existence of an cattle sector based on extensive exploitation of the resource rather than intensive use of the land. Forest has been the main resource used to support the expansion of the extensive-cattle growth industry.

Between 1950 and 1960, cattle were introduced as part of a new production structure. Sugar cane and cattle production for meat exports became the main factors driving LUCC. In 1960, sugar cane and meat represented 14.3% of the country's national production (\$ as GNP). By the end of the 1960's, the total contribution to the agriculture fraction of the GNP from coffee, banana and cocoa was reduced to 44% from 51% in 1950.

In 1963, Costa Rica became part of the Central America Common Market (MERCOCEN). At that time, new policies promoting industrialization were implemented. Between 1963 and 1978, policies aimed at transforming the national economy from agrarian to industrial were implemented (e.g. investment credits, fast depreciation rates, low taxes for imported capital goods, etc.). During the period 1970-79 the contribution of the agricultural sector to Costa Rica's GNP declined from 22.5% to 19%, while the industrial sector annual growth rate was 9.6%, the agricultural sector grew much slower at 5% per year.

The different economic development policies implemented between 1950 and 1978 are reflected in different growth rates for the agricultural sector. This sector grew 3.2% per year between 1950 and 1962, 5.6% per year between 1962 and 1972, and 2.6% per year between 1972 and 1978 (Costa Rica, 1995a). The exact reasons are complex but Aguilar et al. (1982) concluded that the decrease observed after 1972 is related to four factors (1) price increases in fertilizer and chemical additives derived from petroleum, (2) new taxes on banana production, (3) restrictions on expansion of coffee plantations, and (4) increased emphasis on industrial expansion.

Costa Rica's agricultural census (Costa Rica, 1995a) indicates farmland transformation growth at 0.2% per year between 1910 and 1950. The change was highest between 1950 and 1963 when farmland area increased at 1.3% per year. This rate dropped to 0.9% per year between 1963 and 1973. Most of the 1950-63 high growth rate was due to land reclamation not directed at expanding agricultural land. During this period land reclamation policies by Costa Rica's Land Colonization Institute (ITCO) promoted most of the shifting from forest cover land to other uses.

Pasture and Cattle Expansion

Historically, the expansion of cattle, and therefore pasture land has been driven by external forces outside of Costa Rica. Schelbas (1991) indicated that *"expansion of cattle pasture was driven by the increased U.S. demand for low grade beef and by the financing of cattle expansion by the international development banks in an effort to diversify Costa Rican exports beyond coffee and bananas."* Similar conclusions have been reached by several authors (Quesada-Mateo, 1991; Hedstrom, 1993).

The period between 1950 and 1963 was characterized by an annual growth rate for cattle of 5.6%, 6.1% between 1963 and 1973, and 0.8% between 1973 and 1984 (Table 3.1). This rate was driven by a rapid increment in meat prices (2.7% per year) (Figure 3.5.b).

After Costa Rica's industrial transformation period (1973-1978), there was an important reduction in the cattle growth rate (0.8%) (Table 3.1). Meat exports represented only 8% and 10% of all exports by 1975 and 1979, respectively. This small growth rate can be related to several related factors such as the elimination of government supported loan programs during the 1970's, and changes in the international price of meat (Figure 3.6).

During the 1974-79 period, meat prices dropped 30% and 20% for internal and international consumption, respectively. The 1973 inflation phenomenon in the United States is identified as the main force behind the 20% reduction in international meat prices (Leon et al., 1982). Because Costa Rica sold most of its production into the U.S. market which offered import incentives, Costa Rica's meat price avoided a major drop. During the 1974-79 period, meat prices dropped more than 60% relative to the 1973 price, meanwhile other international markets dropped between 40 to 50% of the 1973 price (BIRF, 1971). The

impact of this price drop did not affect the total production which continued to grow (Figure 3.6). This continuous growth was a result of government incentives to the cattle sector in form of loans (Luzt & Daly, 1990). Luzt & Daly note that of the total amount of money given by the government as agricultural loans, more than 50% was taken by cattle ranchers. This group only represented 5% of the total people who got benefits.

Annual growth rates of pasture land have been estimated to average 8.8% between 1950 and 1963, 4.1% for the 1963-73 period and 0.5% between 1973 and 1984 (Table 3.2). During the first two periods, all of the provinces experienced high annual growth rates in pasture development.

Most of Costa Rica's deforested land between 1950 and 1973 was turned into pasture (1,558,000 ha) (Costa Rica, 1950; 1973). Figure 3.4 indicates that pasture area changed from 34% to 50% during this time period. By 1973, 80% of all agricultural land was used for cattle ranching, and one-half of all farms were dedicated to this activity (Leon et al., 1982). The dynamics of this LUCC process took place in all provinces (Figure 3.1.b).

Expansion of pasture land and its direct relationship with the increase of international meat prices can be divided into the following development periods (Leon et al., 1982):

- a. 1950-1955: During this period, the demand for pasture land exceeded supply. Farms dedicated to other less productive agricultural uses were transformed into pasture land. During this period, pasture land increased at 1.92% per year. A total of 98,000 ha were transformed into pasture land, 30% from deforestation of primary forest and 70% from transformation of previous deforested land (Table 3.5). The meat price index for internal consumption (price per kilogram of standing cattle)

hardly changed during this period (Figure 3.5.b).

b. *1955-1963*: For this period, 16% of remaining primary forest were converted to crops and pasture. Twenty-eight percent of the total area deforested was dedicated to pasture. The meat price index changed for internal consumption from 1.18 in 1955 (constant 1966 colones) to 1.43 in 1963. International meat index prices changed from 1.09 to 1.72 during this period.

c. *1963-1973*: During this period, a further 9% of remaining primary forest land was converted to agriculture. At the same time, land used for cattle growth increased 14%. Of this total, 25% (150,000 ha.) was created from transformation of previous deforested land. The international meat index price changed from 1.72 to 3.19, while the internal market price index increased from 1.43 to 2.66.

d. *1973-1984*: During this period pasture land change from 3.9%, even though total meat production, population and the number of heads of cattle continue to increase. This small growth rate can be related to the variations on the international price of meat during this period (Figure 3.5.b).

A multi-regression analysis of pasture land for 1950, 1955, 1963, 1973 and 1984 presents high correlation with Costa Rica's population ($r^2= 0.95$) and total meat production ($r^2= 0.97$). High correlations are more evident when total production is divided down into

production for internal consumption and production for exports ($r^2= 0.97$). A multi-regression analysis indicates that total meat production is a highly predictable ($r^2= 0.96$) on variables such as Costa Rica's population, and the international and internal meat prices. The regression equation is:

$$TMP = -40,677 - 0.101 CRP - 14,902 INTMP - 4,678 INTLMP$$

where TMP is total meat production (MT), CRP is Costa Rica's population, INTMP is the normalized index of meat prices for internal consumption, and INTLMP is the normalized index of meat prices for exports. Meat prices are normalized to 1966 (real) colones.

Figure 3.6 indicates that even though internal prices of meat increased during the study period, the rate of growth on the international price of meat changed at a higher rate producing a steady drop in the percentage of the total market share by this sector. Market share of meat production change from 100% of the total production on 1950 to 50% on 1969. At the same time, meat exports increased surpassing the total meat production for internal consumption during 1970. The 1970-1982 presents a higher sharing of the meat market for exports rather than internal consumption. This situation changed after 1982 due to drops on the international price of meat and contractions of the local economy.

At the same time that meat exports increased, pasture land also increased. A multi-regression analysis indicates that pasture is highly correlated ($r^2= 0.97$) with Costa Rica's population, total volume for exports (MT), and total volume for internal consumption (MT). The regression equation is:

$$PL = 658,946 - 0.63 CRP - 25.5 VE - 17.2 IV$$

where PL is the total pasture land (ha) for year "I", CRP is Costa Rica's population on the "ith" year, and VE and VI are the total volume for exports and internal consumption (MT), respectively. It is important to indicate that internal and international meat prices were not considered because their correlation with VI and VE, respectively (Table 3.6).

The former correlations must be taken with caution because meat prices for export were sustained artificially by government incentives. These incentives helped to avoid a major drop between 1972 and 1976. In addition, the rate of growth of Costa Rica population and its internal consumption did not change, allowing for a sustained the growth trend of the total meat production (Figure 3.5.a).

Permanent Crops

Sugar Cane Production: Sugar Cane production presented high annual growth rates (5.9%) between 1950 and 1963 (Figure 3.7, Table 3.3). Production changed from 38.2 MT/ha in 1955 to 46.3 MT/ha by 1963 due to the application of new technologies which increased production (Barboza et al., 1981). After this period of rapid growth, rates dropped to 1.1% per year between 1963-73 and 2.0% between 1973 and 1984. However, sugar cane production changed from 46.5 MT/ha in 1963 to 72 MT/ha by the 1980's. Sugar cane yield in Costa Rica is being estimated to be 66.3 MT/ha, which is above the world average of 53.5 MT/ha (Barboza et al., 1981).

The number of farms used for sugar cane production decreased from 11,000 farms in 1950 to 9,500 farms by 1973. The total area of sugar cane production increased by 19,000 ha during the same period. Annual growth rates for sugar cane planted area was 7.0%

between 1955 and 1963. Between 1963 and 1973, the increase in land dedicated to sugar cane slowed to approximately 1% per year (Barboza et al., 1981). By 1984, a total of 47,286 ha (7,373 farms) were dedicated to sugar cane production (Costa Rica, 1984)

Sugar cane production occurs primarily in the Alajuela and Guanacaste provinces. Alajuela contributed more than a third of the total national production of sugar cane for the 1950-73 period. After 1973, a production shift from Alajuela to Guanacaste occurred due to the creation of CATSA (Central-Azucarera-del-Tempisque, S.A.) which started to exploit sugar production in the Tempisque river valley. By 1984, more than a third of the national sugar cane production was located in Guanacaste. The Guanacaste irrigation project has been partially responsible for this regional growth.

Coffee Production: Currently, coffee plantations are located in Costa Rica's central region (68%), the South Pacific Region (14,2 %), the Central Pacific (12.7%) (Figures 3.8.a and 3.8.b) . The remaining 3.1 percent are distributed across the national territory. A more detailed analysis of spatial trends related to coffee plantation has been presented by Aguilar et al. (1982). Expansion of coffee plantations was a driving force in Costa Rica's central valley during the early colonization (Schelas, 1991). Seligson (1984) indicates that the number of coffee plantations started to multiply by 1820, mainly as a result of the aggregation of small farms into larger coffee plantations. During the 19th century, coffee production was the fundamental element of Costa Rica's internal economic growth.

Costa Rica's efficiency in coffee production has been increasing and is presently the highest in the world (6.3 MT/ha vs. 2.8 MT/ha worldwide). The increase in coffee production

between 1950 and 1973 (Table 3.4) has been estimated to be 5.1% between 1950 and 1973, 0.4% between 1963 and 1973, and 0.7% between 1973 and 1984. The small growth rates between 1963 and 1984 are explained by government policies aimed at controlling the extension and growth of coffee plantations (Aguilar et al., 1982).

Costa Rica's agricultural census indicate that the total number of farms used for coffee production doubled between 1950 (15,222 farms) and 1963 (32,353). The average farm size was less than 10 ha. Total area grew at 2.4% percent per year between 1950 and 1973, and the total area changed from 48,885 ha in 1950 to 83,407 ha by 1973. Between 1973 and 1984, few changes were observed in both the total number of farms (34,464 farms) and their total extension (89,881 ha).

Discussion

Role of Remote Sensing and GIS for Policy Making in Costa Rica

Remote sensing and geographic information systems are important tools in communicating spatial and/or temporal trends to policy makers. Remote sensing information can provide a wide range of thematic information over a region. This information can be later integrated into a geographic information system (GIS) and linked to other relevant in situ data sets.

Although the integrated data base presented in this paper is useful to identify past LUCC trends, it has limited applications for understanding impacts and consequences of LUCC because of the nature of the original data sets, and the process of sampling. Detected inconsistencies on the extension of forest cover questions the accuracy of pasture land

presented on Figure 3.4. A comparison between the reported forest cover in the agricultural census and the official Costa Rica land use map provide additional information regarding the quality of the collected data (Figure 3.9). Costa Rica's official land use map was prepared on 1984 by Costa Rica's National Geographic Institute (Instituto Geografico Nacional, 1984). The IGN map is an interpretation of aerial photography and infra-red aerial photography in several scales (Elizondo, 1995). The IGN map scale is 1:200,000.

The premise of this comparison was that if there is agreement between the agricultural census and the reported forest cover on the official land use map, total reported forest at the county level will plot along 1:1 line. Points under the 1:1 line will indicate under-estimation and points over the 1:1 line will represent over-estimation of the agricultural census. Figure 3.9 indicates that, with few exceptions, the forest cover in Costa Rica is under-estimated by the agricultural census. For example, for the Perez Zeledon, San Ramon and San Carlos counties, forest cover is under-estimated by 65,518; 49,180 and 90,486 ha, respectively. A correlation (r^2) between the agricultural census and the IGN map at the county level is only 0.42. This comparison explains the significant differences in total forest area between the Agricultural Census information and Sader and Joyce (1988) satellite estimates (Figure 3.10 and Table 3.7). Moreover, this comparison questions the accuracy of all previous agricultural census data. The causes for under-estimation can be attributed to a lack of a statistical sampling scheme for census site selection.

The accuracy of Costa Rica's National Geographic Institute (IGN) forest cover maps was check by comparing them against the forest cover map generated for 1986 using a Landsat Thematic Mapper (TM) scene (Chapter 1). Figure 3.11 indicates that there is a high

correlation ($r^2 = 0.87$) between the IGN's land use maps and the information derived from remote sensing information. Differences are observed on those counties which presented high cloud cover.

Remote sensing data set will be valuable to enhance understanding of both spatial and temporal trends in LUCC. Thematic remote sensing information should be analyzed for the year in which the agriculture census is collected (e.g. 1984, 1996, 2006, etc.). The thematic information must have classes similar to the agricultural census (coffee, banana, pasture land, annual crops, forest, etc). This will allow for refinement of collected census information at the spatial scale by means of remote sensing data such as Landsat Thematic Mapper (TM). In addition, inter census year information can be generated from the same satellite sensor. This information will quantify trends in LUCC more accurately in both time and space. Selection of study sites can be accomplished by using partial sampling at the scene level (Chapter 2).

Agricultural census provides aggregated information at the county or district level, without spatial variability of the different land use/cover types (e.g. spatial distribution of coffee presented on Figures 3.8.a and 3.8.b). A second generation GIS data base will provide information regarding the spatial variability of crops and pasture land, granting more detailed information over the agriculture census.

Potential applications of the proposed second generation data set will make it possible not only to identify potential regional conflicts between water resources development and LUCC, but will also to have a more quantitative understanding of the spatial distribution of ongoing LUCC in a region (district, watershed, etc).

This data base can also be combined with other topologic information such as slope distribution, precipitation fields, roads and river networks, life zone classification, etc. This will help in assessing the impact of several land use policies on the natural environment. Results such as those presented by Sanchez-Azofeifa & Harriss (1994) will be able to be reproduced in all drainage basins within the nation. The integration of this GIS/RS information within the objectives of national development programs will allow for more scientific decision making.

Conclusion

1. The analysis of the agricultural census data for a 34 year period documents how variable land cover/use change is over time. It also indicates that such change can be episodic, depending on social, economic, and technological factors. A better understanding of forces, trends and spatial distribution of different land/cover changes can be achieved by integration of remote sensing derived information and geographic information systems.
2. Improved decision making can be achieved if remote sensing information is integrated with agricultural census data. The creation of a second generation data base is recommended as part of a more comprehensive operational plan for LUCC monitoring in Costa Rica. This data base must integrate current available information in GIS format and remote sensing thematic information. The remote sensing information must use the same classification scheme as the agricultural census. The

remote sensing information must also be generated from a complete coverage of satellite scenes in the same year that the agricultural census is developed. The information produced from the proposed second generation GIS, will provide a valuable independent data set for calibration and validation of land use change models such as USTED (Sustainable Land Use Development) (Stoorvodel, Schipper and Jansen, 1995).

3. The second generation GIS data base proposed in this paper, will also help to make it possible to study several aspects related to watershed management. It will help in quantifying changes in land cover (e.g. deforestation) on a specific drainage basin, in addition of being source of basic information for watershed characterization, prioritization and land use planning by the Costa Rica's Electricity Institute.
4. The success of future land use / cover change planning in Costa Rica will depend on accurate resource inventory. This paper has demonstrated that forest information generated from agricultural census is not accurate and that differs from independent estimates carry-on by other government agencies in Costa Rica. In addition, it has been demonstrated that forest cover information derived by means of remote sensing approaches estimates done by the Costa Rica's National Geographic Institute.
5. It is suggested to generate a first generation GIS system for the other Central American countries. This systems can follow the same approaches used to build the

Costa Rica's one. The application of the first generation GIS data base will have important regional considerations at the Central American level. Agricultural censuses are being collected in most of the countries, and National Geographic Institutes have their own political boundary information. The generation of this first generation data set can be easily accomplished for each Central American country through their national government agencies, national universities or regional development agencies such as the Central American Commission for Environment and Development (CCAD), the Central American Committee for Water Resources (CRRH) or the Central American Project for Climate Change (PCCC).

Table 3.1. Costa Rica's Cattle Annual Growth Rates (%)

Province	Growth Rate 1950-63	Growth Rate 1963-73	Growth Rate 1973-84
San José	4.7	3.5	0.3
Alajuela	5.4	5.8	3.7
Cartago	0.7	3.3	-0.7
Heredia	5.9	5.4	5.6
Guanacaste	4.9	6.5	-1.8
Puntarenas	11.5	7.7	0.5
Limón	8.9	8.4	9.0
Country	5.6	6.1	0.8

Source: Dirección General de Estadísticas y Censos, 1993. San José, Costa Rica.

Table 3.2. Costa Rica's Pasture Land Annual Growth Rates (%)

Province	Growth Rate 1950-55	Growth Rate 1955-73	Growth Rate 1973-84
San José	5.91	3.82	-0.31
Alajuela	6.26	5.23	3.12
Cartago	4.83	0.09	-1.54
Heredia	1.99	10.18	5.13
Guanacaste	9.83	3.07	-1.93
Puntarenas	13.36	6.81	1.19
Limón	17.30	4.01	6.40
Country	8.79	4.11	0.47

Source: Dirección General de Estadísticas y Censos, 1993. San José, Costa Rica.

Table 3.3. Costa Rica's Sugar Cane Annual Growth Rates (%)

Province	Growth Rate 1950-63	Growth Rate 1963-73	Growth Rate 1973-84
San José	1.07	-4.26	0.18
Alajuela	5.91	1.76	-2.33
Cartago	5.30	2.10	-2.09
Heredia	-3.60	2.51	-4.05
Guanacaste	12.31	2.73	27.93
Puntarenas	27.53	-1.51	2.95
Limón	15.14	-32.05	4.20
Country	5.86	1.09	2.00

Source: Dirección General de Estadísticas y Censos, 1993. San José, Costa Rica.

Table 3.4. Costa Rica's Coffee Annual Growth Rates (%)

Province	Growth Rate 1950-63	Growth Rate 1963-73	Growth Rate 1973-84
San José	3.19	0.69	-0.15
Alajuela	11.99	0.87	1.31
Cartago	1.79	0.32	1.57
Heredia	2.35	-1.48	-0.66
Guanacaste	6.36	-2.08	-1.36
Puntarenas	54.40	2.67	2.12
Limón	42.79	-0.86	8.31
Country	5.11	0.39	0.71

Source: Dirección General de Estadísticas y Censos, 1993. San José, Costa Rica.

Table 3.5. Costa Rica: Source of land use to expand pasture area

Period	Type A (ha)	Type B (ha)	Type C (ha)	Type D (ha)
1950-1955	68,000	30,000	98,000	39,000
1955-1963	N.D.	229,000	229,000	816,000
1963-1973	150,000	451,000	601,000	455,000

Source: Leon, J.; Barboza, C.; Aguilar, J. (1982). *Desarrollo Tecnológico en la Ganadería de Carne*. CONICIT.

Notes:

Type A: Increment from lands already transformed into farms or already deforested.

Type B: Increment due to deforestation of primary forest.

Type C: Total Increment on pasture land.

Type D: Total increment on farm area.

Table 3.6. Correlation between pasture area (1950, 1963, 1973 and 1984) and other socio-economic variables

	Pasture	Costa Rica Population	Volume of Exports	Volume for Internal	Total Volume	% Volume Internal	% Volume Exports
CR population	0.951						
Vol Exports	0.969	0.938					
Vol Internal	0.785	0.900	0.705				
Vol Total	0.965	0.996	0.949	0.893			
% Volume Internal	-0.870	-0.795	-0.942	-0.511	-0.826		
% Volume Exports	0.870	0.795	0.942	0.511	0.826	-1.000	
Heads of Cattle	0.983	0.985	0.976	0.840	0.994	-0.878	0.878

Table 3.7. Comparison of forest cover estimates from different sources and methods.

Source	Year	Method	Scale	Forest Area (ha)
DGES, 1950 Agricultural Census	1950	Survey	N/A	577,000
DGES, 1955 Agricultural Census	1955	Survey	N/A	542,000
DGES, 1963 Agricultural Census	1963	Survey	N/A	819,000
DGES, 1973 Agricultural Census	1973	Survey	N/A	716,000
DGES, 1984 Agricultural Census	1984	Survey	N/A	492,000
Sader & Joyce, 1988.	1940	Aerial Photo. Inter.	1:1,000,000	3,420,600
Sader & Joyce, 1988.	1950	Aerial Photo. Inter.	1:1,000,000	2,864,200
Sader & Joyce, 1988.	1961	Aerial Photo. Inter.	1:1,000,000	2,303,500
Sader & Joyce, 1988.	1977	MSS Interpretation	1:1,000,000	1,615,400
Sader & Joyce, 1988.	1983	MSS Interpretation	1:1,000,000	871,100
Sanchez-Azofeifa, 1996	1991	TM Interpretation	1:250,000	1,359,000

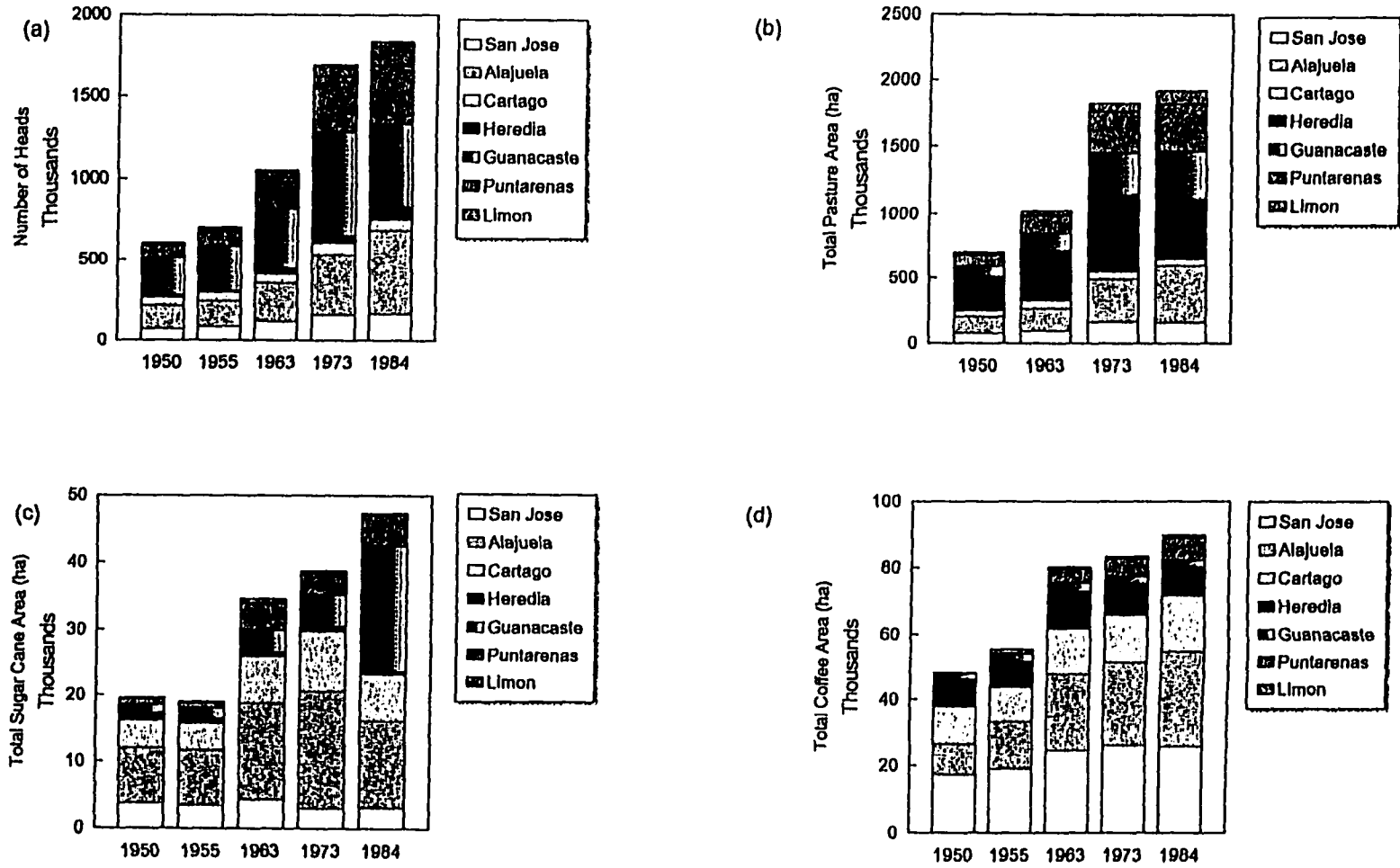


Figure 3.1. Aggregated agricultural census data by province. (a) Cattle, (b) pasture area, (c) sugar cane area and (d) coffee area.

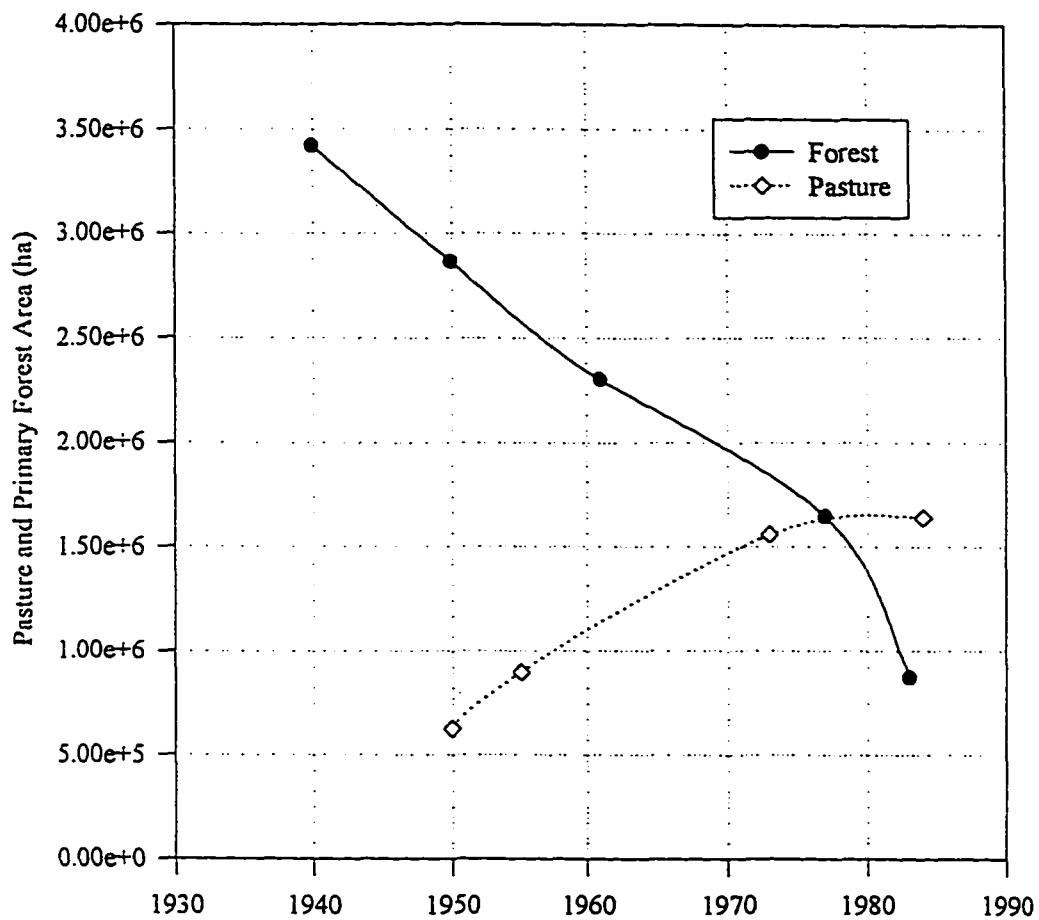
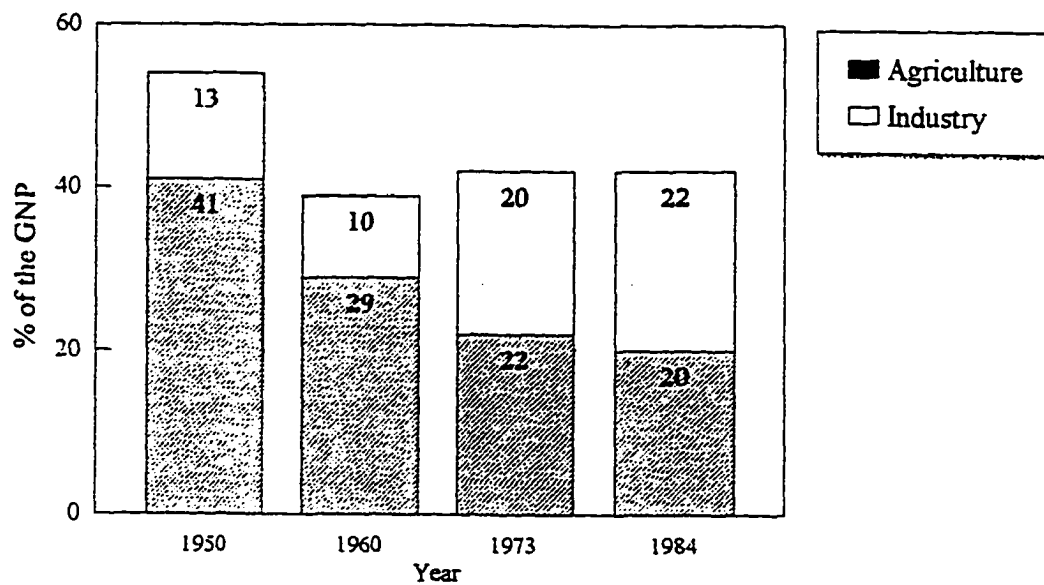


Figure 3.2. Primary forest cover (from Sader & Joyce, 1988) and pasture area (from agricultural census) in Costa Rica between 1940 and 1984.



Source: Banco Central de Costa Rica, 1995.

Figure 3.3. Relative contribution of the agriculture sector to Costa Rica's gross national product (GNP). Agriculture's contribution to the GNP drops from 41% (1950) to 20% (1984) as a result of a transformation of the country's production system.

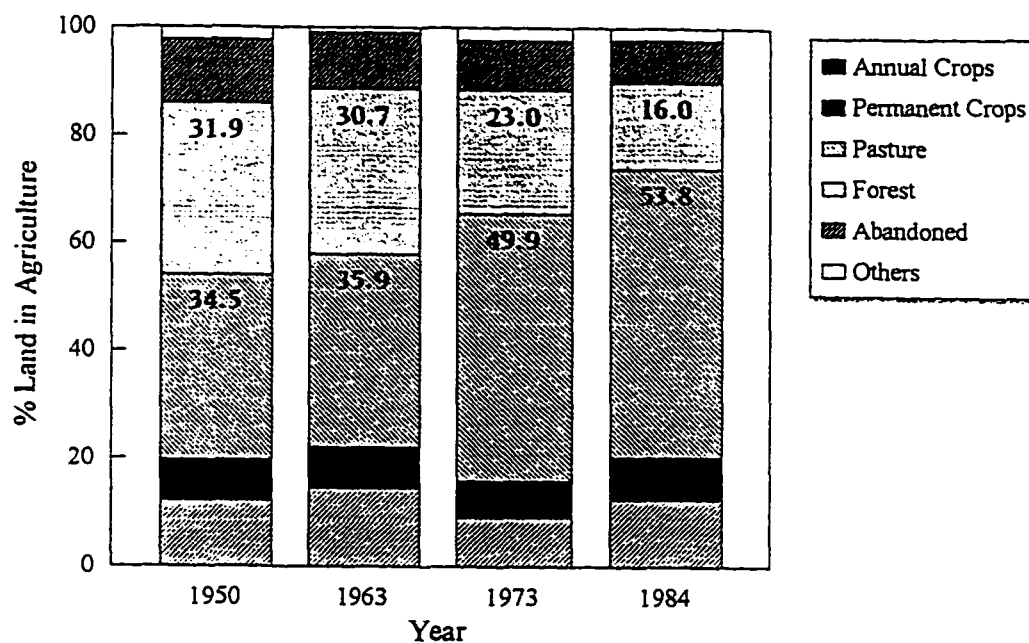


Figure 3.4. Percentage of Costa Rica's national territory occupied by annual and permanent crops, pasture, forest, abandoned land and other uses. Information generated from 1950, 1963, 1973 and 1984 agricultural census (Source: Direccion General de Estadisticas y Censos, 1950; 1963; 1973 and 1984).

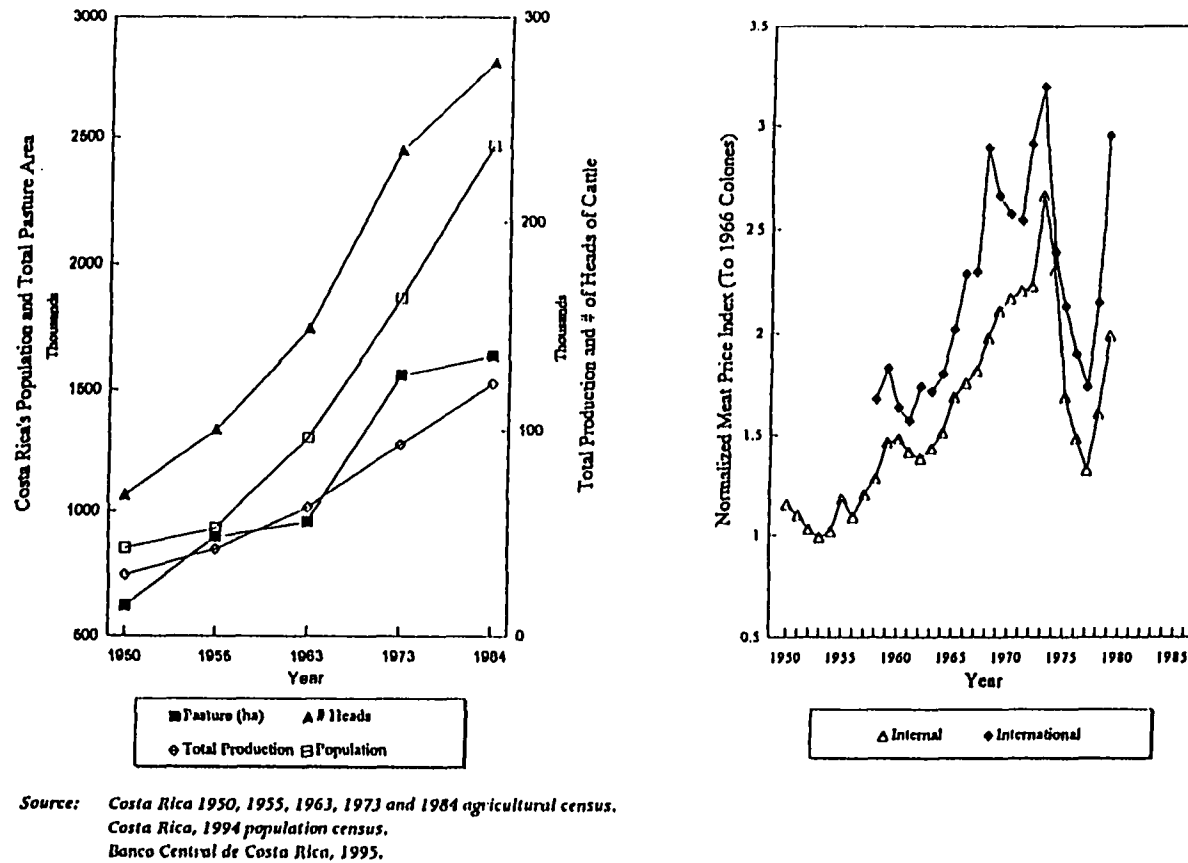


Figure 3.5. (a) Growth of pasture land, number of heads of cattle, total meat production and other population in Costa Rica, (b) change in normalized (constant 1966 colones) standing meat prices in the international and internal market.

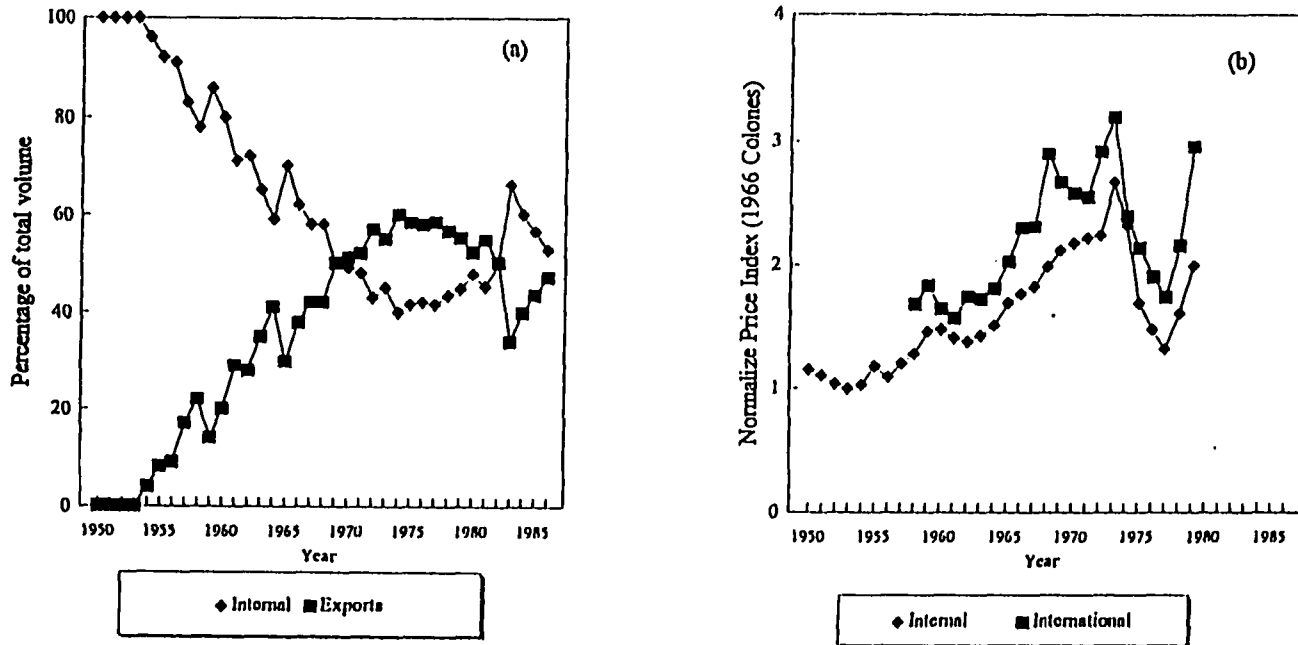


Figure 3.6. (a) Percentage of the total meat production used for internal consumption and exports, (b) change in normalized (constant 1966 colones) standing meat prices for the international and internal market.

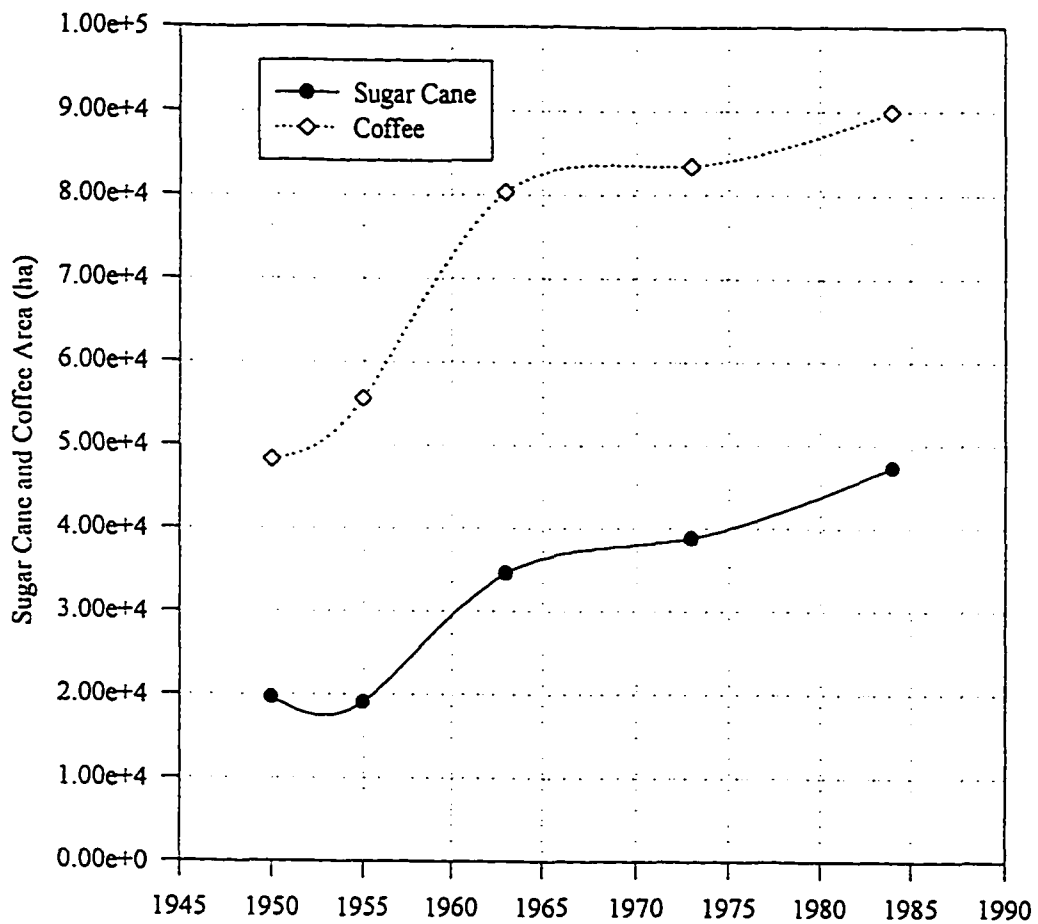


Figure 3.7. Sugar cane area and coffee plantations area growth in Costa Rica between 1950 and 1984. (Source: Direccion General de Estadisticas y Censos, 1950; 1963; 1973 and 1984).

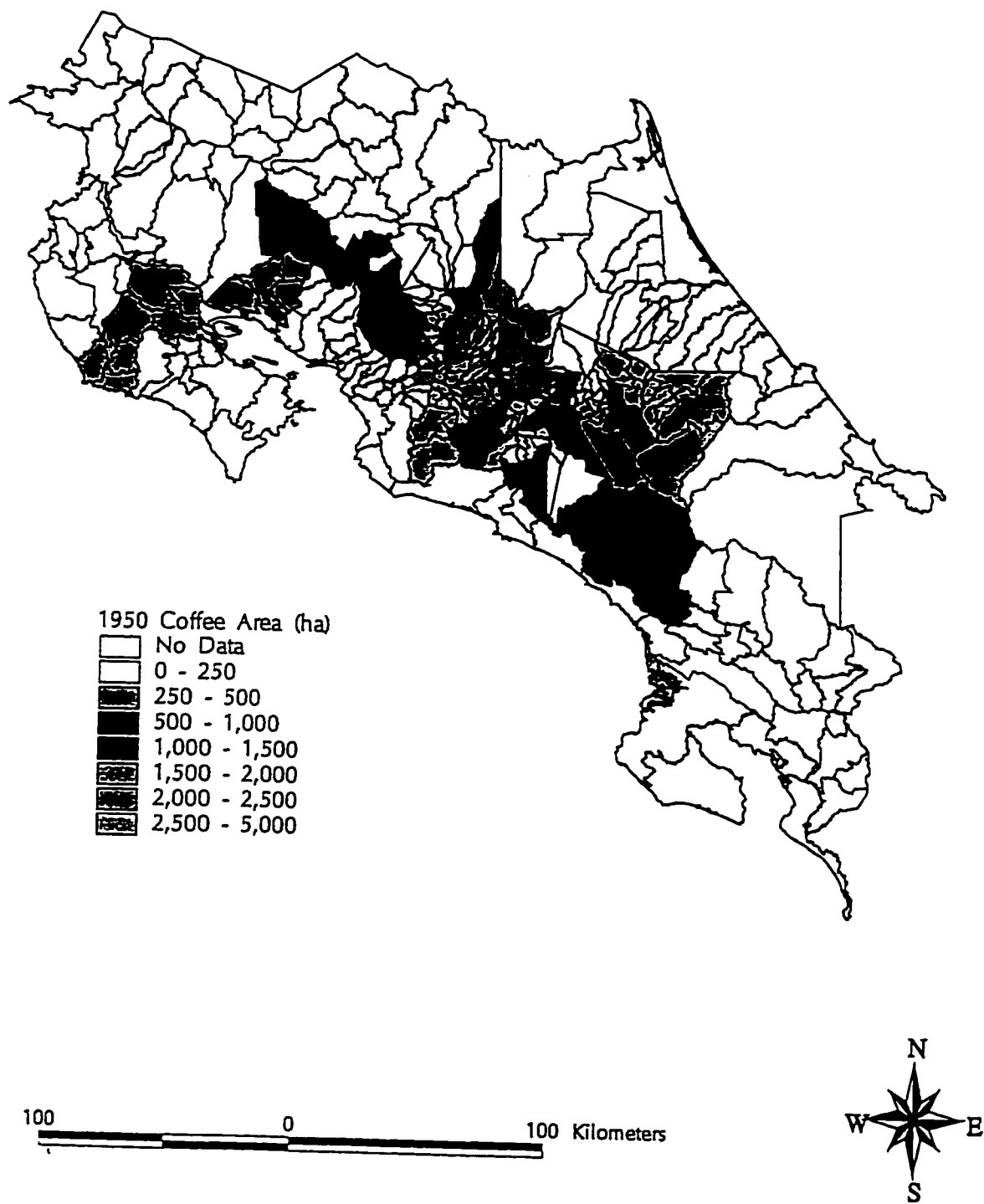


Figure 3.8.a. Spatial distribution of coffee plantation in Costa Rica, reference year is 1950.
Source: Direccion General de Estadisticas y Censos, Costa Rica (1950).

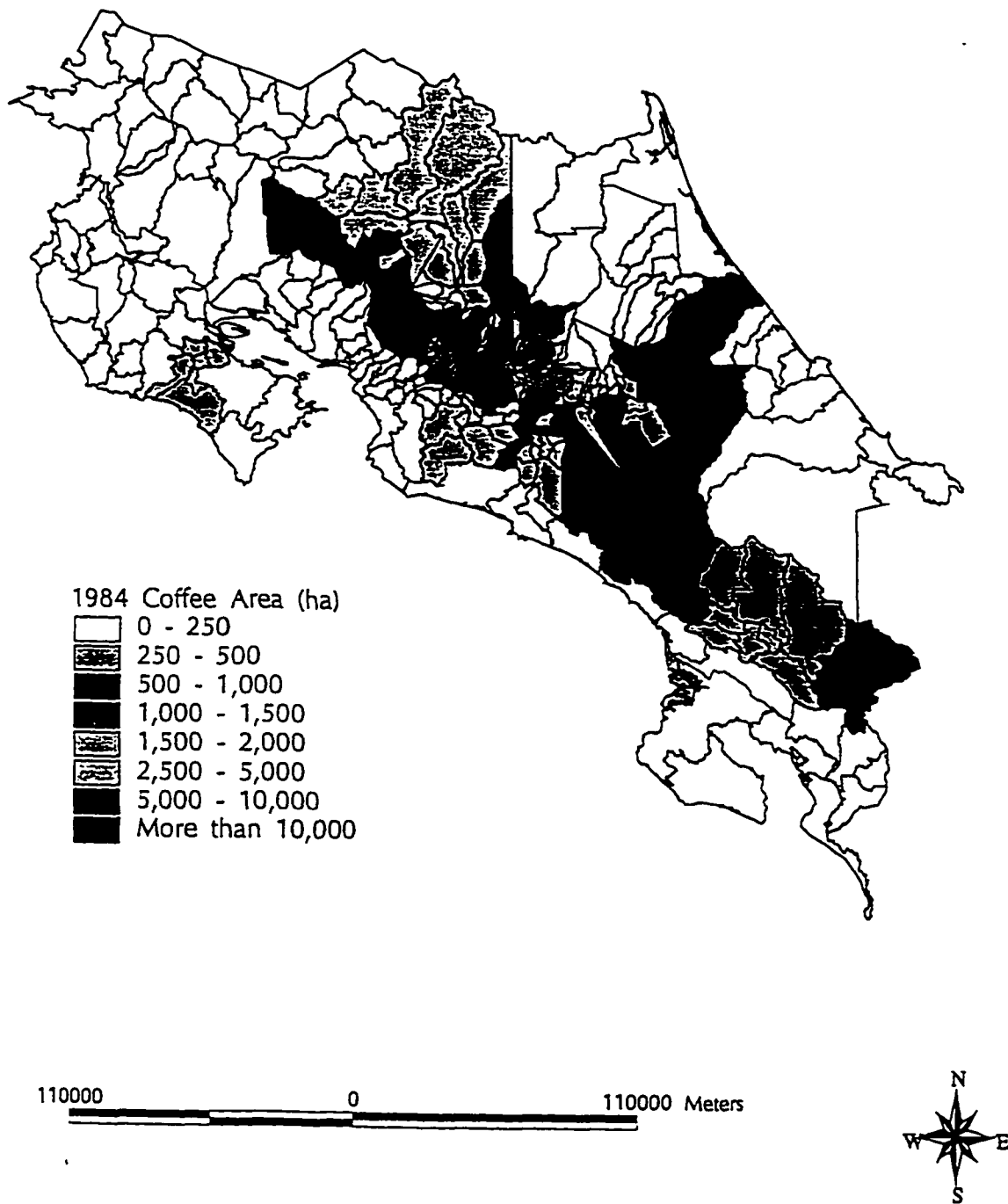


Figure 3.8.b. Spatial distribution of coffee plantation in Costa Rica, reference year is 1984. An expansion of coffee plantation outside the Central Valley (San Jose City) is observed. Source: Direccion General de Estadisticas y Censos, Costa Rica (1950).

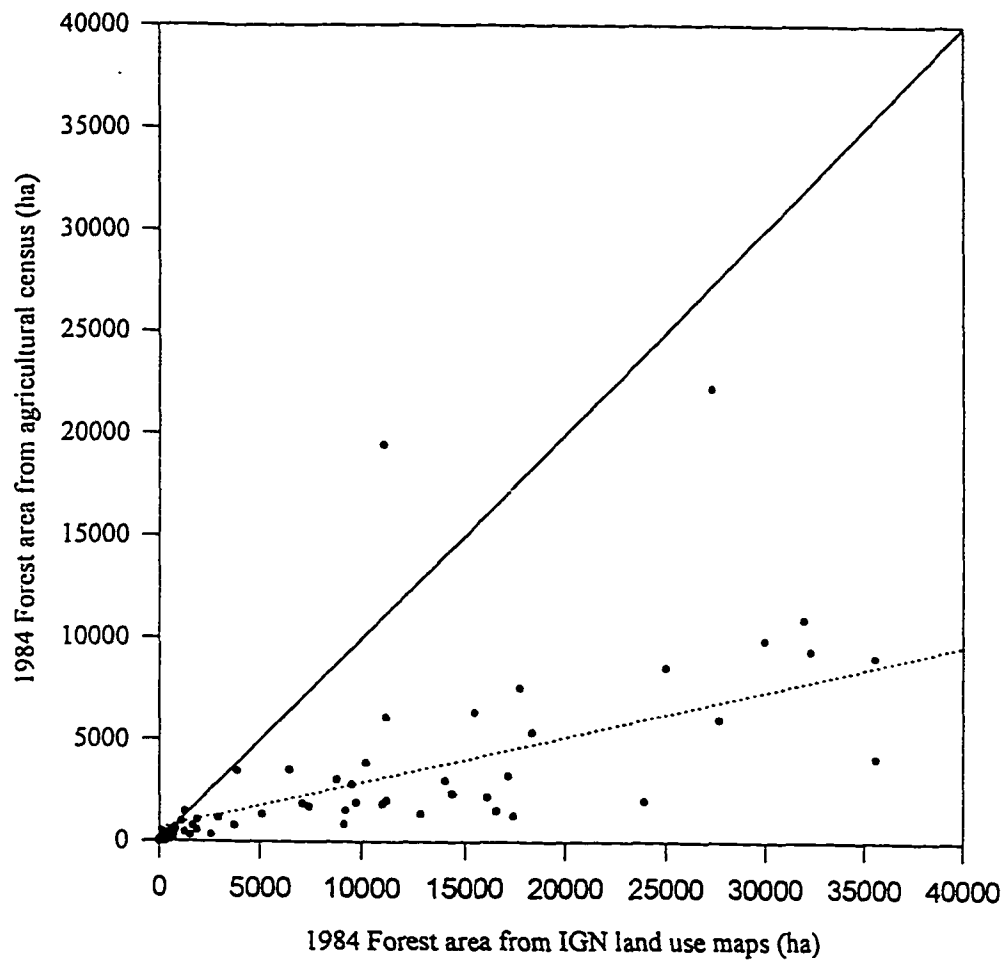


Figure 3.9. Comparison between forest cover information from the 1984 agricultural census and the 1984 National Geographic Institute land use map. Forest cover from the agricultural census is been systematically under-estimated by the current sampling scheme.

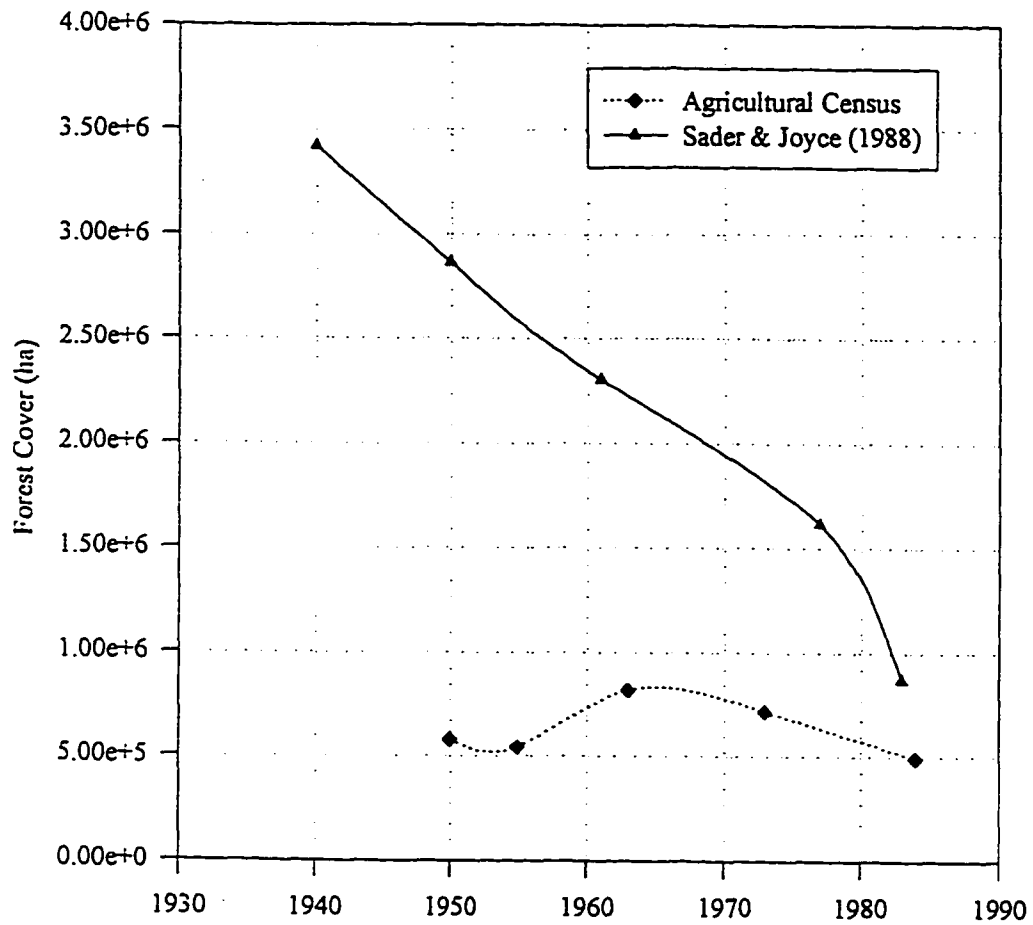


Figure 3.10. Comparison between forest cover information from several agricultural census and work performed by Sader and Joyce (1988). Forest cover is systematically underestimated by the agricultural census.

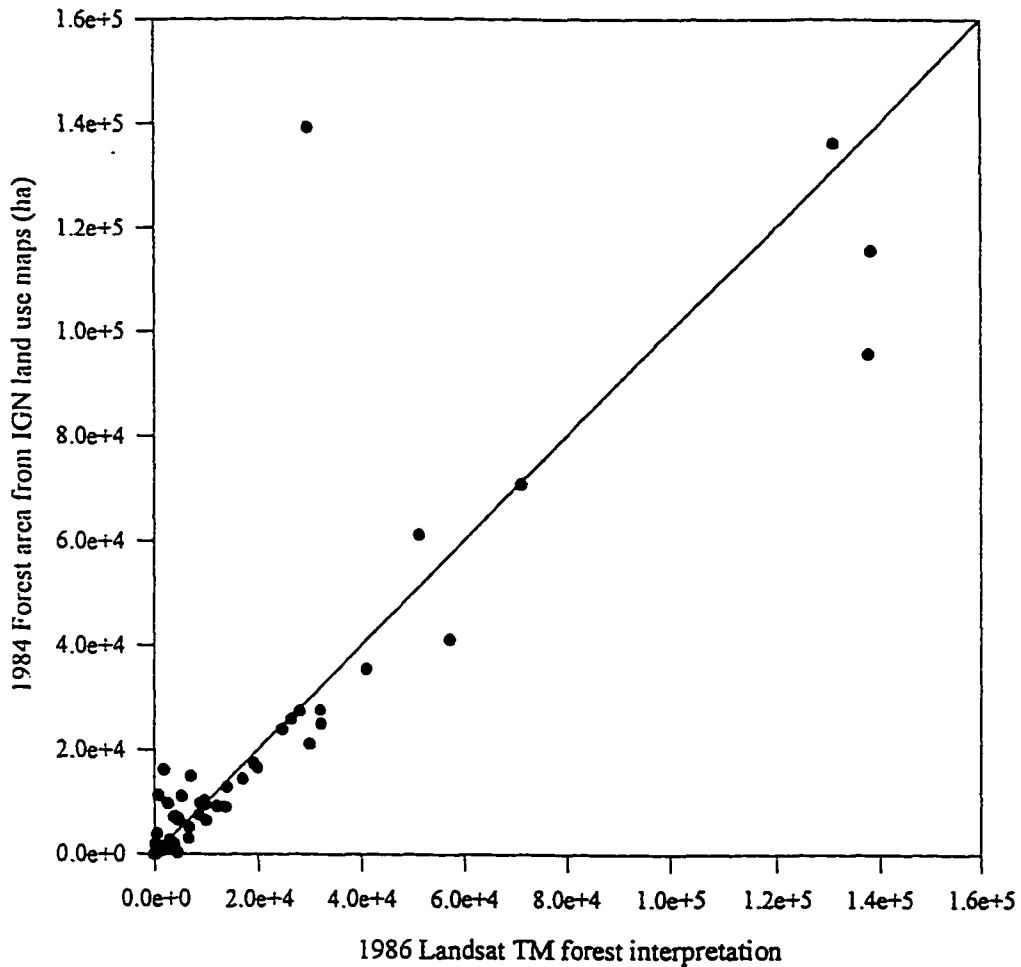


Figure 3.11. Comparison between 1984 forest cover from Costa Rica's National Geographic Institute (IGN, 1984) and forest cover derived from a 1986 Landsat TM scene (path 15 / row 53) acquired on February 6th, 1986. The high correlation ($r^2 = 0.87$) between the IGN information and the Landsat TM classification indicates that agricultural census are underestimating current forest cover in Costa Rica.

CHAPTER 4

IMPLICATIONS OF LAND USE/COVER CHANGE TO HYDROPOWER PRODUCTION IN COSTA RICA

Introduction

Water is becoming a source of conflict in Costa Rica. To some degree agricultural production, hydropower generation, and demand for clean drinking water have been major, competing socio-economic forces for decades, but now take on an added sense of urgency in the face of un-controlled urban development and growing tourism. These conflicts are critical to those sectors which play key roles on Costa Rica's economic growth.

Currently, ~90% of the electricity demand is generated from hydropower. This high dependency on hydropower generation makes this sector a priority in the national resource management arena. The rest is supplied by a combination of fossil fuel generation, geothermic and wind generation sources (Costa Rica, 1995b). For example, during the day of highest electricity consumption in 1993 (November 24), more than 95% of the total demand (13249 MWh) was satisfied by hydropower generation, with a small contribution of fossil fuel energy (2.47%, 328 MWh) and imported energy from other Central American countries (2.10%, 277 MWh) (Costa Rica, 1995b). This high dependency on hydropower generation changes during the dry season (December to May) due to reduction in reservoir storage.

A total hydropower potential of 8,742 MW has been identified for projects capable of producing 20 MW or more. An additional 1,500 MW has been also identified for projects capable of producing less than 20 MW. By 1994, 13% of the total estimated available hydropower potential was being utilized. From 1972 to 1992, total energy consumption for Costa Rica rose from 41,646 TJ to 84,172 TJ. Energy consumption per capita changed from 24.1 TJ to 26.6 TJ (per 1000 persons.), while energy efficiency (TJ / \$C) declined from 7.5 to 6.3, and public investment in energy generation changed from 16.6% to 45.1% of the total amount of the GNP dedicated to energy generation. By 1992, the external debt of the energy sector represented 14.4% of the national external debt and 17.8% of the internal debt (Costa Rica, 1995b). Since 1950, hydropower generation capacity has increased 20 times, and projections of sustained energy demand growth rate of 6% per year increased to 8% per year 1991 (Quesada-Mateo, 1990).

Hydropower generation is a resource that can be strongly affected by land use and cover change. LUCC processes are producing direct impacts on critical Costa Rican watersheds emptying into both the Pacific Ocean and Caribbean Sea. Previous studies by Mojica (1972), and Rodriguez (1989) have suggested and documented the relevance of the LUCC processes in Costa Rica. These studies analyzed linkages between LUCC and sediment transport, deposition and increased costs for hydropower generation. Uncontrolled and unsustainable LUCC practices can produce important hydrologic and soil erosion impacts on reservoir operation. This is especially true in the Grande de Terraba, the Reventazon, the Grande de Tarcoles, and Sixaola drainage basins.

Linkages between increasing sediment production and LUCC for the Reventazon

Basin have been studied in detailed by Sanchez and Harriss (1994) . Their study used double-mass curves for monthly and annual suspended sediment loads at the upper Reventazon basin (Figure 4.2). Annual double-mass curves indicated a larger sediment export at La Troya sub-watershed. Distinct changes in slope were observed in September 1975 and September 1984. The 1975 shift has been associated by Quesada-Mateo (1992) with deforestation in a very localized area of the La Troya drainage basin. Additionally, the authors document that 64% of all the sediment delivered to the Cachi reservoir is from areas under the constant process of shifting-agriculture. The study concluded that the “La Troya” watershed, with 34% of crop agriculture and 43% of pasture on slopes greater than 30%, exported 64% more suspended sediment in stream discharge per year than did an adjacent forest watershed.

The enhanced erosion rates from shifting agriculture and deforestation add significant costs to downstream hydropower generation (The Cachi reservoir). In the Reventazon drainage basin, the Cachi reservoir needs to be flushed once a year in order to remove sediment accumulated from the upper part of the Basin (Rodriguez, 1992). Annual losses attributable to sedimentation at the Cachi reservoir amounted to \$287,000, equivalent to 13 percent of the annual production value. Of this amount, \$169,600 per year are related to maintenance costs due to sedimentation, \$38,200 per year are related to losses due to reduction of energy attributable to diminished flow at the dam (and accounted as an increased demand for fossil fuel and electricity imports), and U.S. \$74,400/yr are losses from work stoppages at the plant dredging (an average of 15 days/yr) (Rodriguez, 1989).

In the Grande de Terraba drainage basin, where the controversial Boruca hydropower project is under consideration, new pasture areas (primary by deforestation of primary forest)

have increased on average 16% per year during the last 40 years. The Grande de Terraba basin currently has a total sediment production of 180 MT per year, the highest in the Pacific region (Sanchez-Azofeifa & Harriss, 1996).

The Grande de Tarcoles drainage basin is subject to urbanization as a result of the expansion of San Jose and adjacent satellite cities. Total sediment production which is the second highest in the region (154.8 mT of sediment per year). In addition, more than 500,000 people depend on drinking water from inter-basin water transfers from the Orosi reservoir in the Upper Reventazon drainage basin. Costa Rica's Drinking Water Institute (AyA) had estimated that 55% of the water for the San Jose Metropolitan area comes from the Orosi reservoir. Sediment problems affecting water collecting sites at the Orosi reservoir have produced critical shortages of drinking water for the urban population of San Jose and Cartago.

Finally, in the Sixaola drainage basin, where a set of chain hydropower plants are under consideration, annual sediment production has been estimated to be 360 mT per year (Sanchez-Azofeifa & Harriss, 1996). Cattle population growth rate rose approximately 18% between 1973 and 1984, and the pasture land growth rate was estimated at 23% per year for the same period. These trends could lead to potential socioeconomic and political conflicts between LUCC and hydropower development in Costa Rica's Atlantic region.

The purpose of this paper is to evaluate the implications of LUCC on two important variables: forest cover at the drainage basin level, and regional sediment production. The status of thirteen of the most important drainage basins in the country for hydropower generation will be explored in terms of forest cover and forest fragmentation. Sediment data

sets, collected by Costa Rica's Electricity Institute (ICE, 1993), will also be analyzed for linkages between LUCC and sediment transport.

Methods

Forest cover and forest fragmentation: For this study remote sensing- derived forest cover information for the whole country was integrated into a GIS. This GIS consists of a full coverage of Costa Rica's drainage basins. Forest cover for each drainage basin as well as two fragmentation indexes: mean patch size (MPS) and patch density (PD) were estimated.

The use of a fragmentation index, such as the MPS or PD, can provide insights into the level of forest fragmentation at the drainage basin level. The former fragmentation indices can be used as a good indicator of environmental degradation, as well as to rank those drainage basins that have greatest potential for the economic development of Costa Rica as function of forest fragmentation. Mean patch size (MPS) (ha) was estimated as:

$$MPS = \sum_{j=1}^n \frac{a_j}{n_j} \left[\frac{1}{10,000} \right] \quad (4.1)$$

where a_j is the area (m^2) of each individual forest fragment, and n_j is the number of forest fragments.

Patch density (PD, ha/100 islands) is considered a fundamental variable of landscape structure. Patch density expresses the number of patches per unit-area basis. McGarigal & Marks (1994) indicated that the PD concept facilitates comparisons between landscapes of variable size. PD for vector representations of the landscape is calculated as:

$$PD = \frac{n}{A}(10,000)(100) \quad (4.2)$$

where A is the total landscape area (drainage basin area, m^2).

Sediment production: Annual sediment production data sets for the Pacific and Caribbean river networks (ICE, 1993) were analyzed to study the implications and linkages of sediment production with variables such as “El Niño”, earthquakes and deforestation trends.

Sediment sampling in Costa Rica has been carried out by Costa Rica’s Electricity Institute (ICE) since 1971. The monitoring sediment program is part of a Central American hydro-meteorological monitoring program sponsored by the World Meteorological Organization (WMO). The sampling procedure followed by ICE is sporadic rather than systematic. Sampling is done by following the Inter-Agency Sedimentation project procedures under the U.S. Water Resources Council. Samples are coded as U.S. D-49 and U.S. DH-48. A detailed description of ICE’s methodology has been provided by Sanchez-Azofeifa (1993).

The Mann-Whitney Rank Sum Test (MWRST), a non-parametric procedure which does not require the assumption of normality or equal variance was used to elucidate the impacts of “El Niño” on sediment production. In general the rank sum test (MWRST) should be used when:

- a. There is a need to find out if the medians of two different samples are significantly different,

b. The samples are not drawn from normally distributed populations with the same variances, or the user does not want to assume that they were drawn from normal populations.

For the sediment data sets used in this analysis, a normality test known as the Kolomogorov-Smirnov test, was used to check for normal distribution.

Results

Deforestation and Watershed Protection

From a watershed perspective, remaining forest areas play a key role in the country's hydrology. Figure 4.1 presents the remaining forest masses in relation to Costa Rica's mayor drainage systems. Main river headwaters draining into the Caribbean have the most remaining primary forest protection in most cases, in contrast with watersheds draining to the Pacific Ocean. Table 4.1 presents the percentage of forest remaining for each drainage basin. These patterns of remaining forest have become important to the hydropower potential that Caribbean watersheds have for present and future hydropower generation. Caribbean watersheds will hold more than 50% of all hydropower plants to be constructed in Costa Rica in the next few years.

Table 4.1 indicates that the key drainage basins for hydropower generation and drinking water such as the Reventazon, Tarcoles, Terraba and Sarapiqui have less than 50% of forest cover. Forest cover has been estimated to be 49%, 13%, 33%, and 42% respectively. Watersheds with few infrastructure development such as the Pacuare and

Sixaola present the highest forest cover; 73% and 85% respectively.

The degree of forest remaining above the 1000 and 2000 m elevation for the 13 most important drainage basins have been estimated (Table 4.1). These drainage basins were selected because of their current and potential hydropower generation (Costa Rica, 1995b). Results indicate a good level of forest remaining at the 2000 and above elevation level. In contrast, between the 1000-2000 elevation levels the degree of remaining forest varies from 28% (Savegre drainage basin) to 95% (Sixaola drainage basin).

The Grande de Tarcoles basin is a clear example of the process of deforestation in high mountain watersheds. Remote sensing interpretation indicated that only 20% of the total watershed area above the 1000 m elevation level has forest protection. Deforestation is concentrated in the upper part of the basin despite the existence of protected areas. Deforestation in the upper Tarcoles river basins has occurred without regard for community concerns and the existence of important groundwater recharge areas for San Jose, Costa Rica's capital city.

In this study, we have ranked the 13 most important drainage basins in the country as a function of their degree of forest fragmentation (Table 4.2). Based on Patch Density (PD), basins with the highest degree of forest fragmentation are: The Grande de Terraba (PD = 1.3), Parrita (PD = 0.79), Naranjo (PD = 0.52), Reventazon (PD = 0.48) and Barranca (PD = 0.44). Watersheds with less forest fragmentation are the Chirripo (PD = 0.11) and the Sixaola (PD = 0.09).

Important concerns arise from the former analysis for the Grande de Terraba and Reventazon drainage basins. The Reventazon drainage basin has three operating hydropower

plants and one more under construction. Meanwhile, at the Grande de Terraba, the Boruca Hydropower Plant is still under consideration. The Boruca is considered the biggest in the Central American region and the second earth largest dam in the world.

Regional Sediment Production in Costa Rica

Soil loss due to erosion can reduce fertility and increase costs of agricultural production. Soil erosion also increases the costs of hydropower reservoir management through siltation (Jansson and Rodriguez, 1992). Cut and burn techniques, cultivation on steep slopes, soil erosion due to slope wash, landsliding and other forms of degradation contribute to soil loss in Costa Rica (Sanchez-Azofeifa & Harriss, 1994). In the last 20 years, Solorzano et al. (1991) have estimated that soil depreciation amounts to almost 10 percent of Costa Rica's annual agricultural production.

Solorzano et al. (1991), using the Universal Soil Loss Equation (USLE), indicated that even though pastures are the largest component of agricultural land use at the national level, they contribute less to total erosion than do annual crops. The authors have estimated that on average, pasture lands erode at an estimated average rate of 33.8 mT/ha/yr, compared to the 289 mT/ha/yr for annual crops. Additionally, their study concluded that 2.2 billion tons of soil have been eroded from 1970 to 1989 (61% from annual crops, 33.8% from pasture land, and 5.1% from permanent crops). The authors stated that total soil losses account for between 6.5% and 13.3% of the annual value added to GNP from agriculture.

Soil erosion rates and total soil loss estimated by Solorzano et al. must be interpreted with caution. The main limitation of the soil loss estimates by Solorzano's et al. (1991) is the

failure of the "universal" term used by the USLE. Vahrson (1989) and Mora (1989), studying the applicability of USLE in Costa Rica, concluded that the equation does not have applicability in the tropics. The USLE is based on empirical data derived from temperate environments, that was later extrapolated to tropical latitudes, where climatic, geologic, geomorphologic and edaphic characteristics differ greatly from those from which the equation was originally developed (Sanchez-Azofeifa, 1993).

Previous research experience in Costa Rica indicates that it takes exceptional climatic or tectonic events to produce massive removal of sediment. Figures 4.2 and 4.3 present two cases of the impact of recent climate variability, land use change, and earthquakes. Figure 4.2 shows how double mass curves are used to identify the increase of sediment transport as a result of deforestation and exceptional wet years (1975 and 1984) at the Upper Reventazon Basin in Costa Rica. The 1975 shift at the "La Troya" stream flow station was associated with deforestation in a specific area of the "La Troya" drainage basin. A more detailed analysis of the Upper Reventazon basin can be found on Sanchez-Azofeifa (1993) and Sanchez-Azofeifa and Harriss (1994).

Figure 4.3 presents normalized suspended sediment at the Pacuare River Basin. An anomaly is observed at the end of the record as a result of the April 22, 1991 earthquake (Sanchez-Azofeifa, 1995). The Pacuare river basin is considered partially undisturbed and with a forest cover of ~73% of its area. This basin is important because of its potential for hydropower generation, as well as because of its importance for the tourist industry (white water rafting). Increases in sediment transport due to the 1991 earthquake was also observed in other Caribbean drainage basins. The effect of the 1991 earthquake was especially strong

in the La Estrella, Blanco, Barbilla and Sixaola river basins, where sediment production increased more than 100% when compared to previous years (Figure 4.4).

Our analysis of total regional sediment production (for the Pacific and Caribbean regions) does not show a significant upward/downward trend for the Pacific (1980-91) or the Caribbean regions (1971-91) (Figure 4.5). The lack of sediment transport trends due to erosion contrasts with a net loss of 749,000 ha of forest during the same period (Sader & Joyce, 1988). Several factors can be related to this lack of temporal trend:

First, lack of trends can be related with data collection procedures used by Costa Rica's Electricity Institute (ICE, 1993). ICE's sampling scheme is selective rather than intensive. Monthly and annual sediment estimates are based on sediment rating curves. Curves are developed from sporadic samples of suspended sediment concentrations and from the discharge measured when the sample is taken. Suspended sediment samples are collected randomly, with twelve samples a year or sometimes less. Therefore, ICE's selective sampling procedures are not able to detect the drainage basin system's response to sediment transport. Efforts to implement a 24 hour automated sampling procedure, at the Reventazon River Basin, have not been successful (Jansson and Rodriguez, 1992).

Secondly, the lack of sediment trends can also be related to intra-basin storage. After erosional processes take place, sediment can be stored on stream-banks, gullies, forest roads, forest ditches and local slips (Painter et al., 1978). These geographic features act as sediment storage elements. Sediment storage elements in the landscape are defined as the medium through which the transport processes act. In low order channels, stream transport has little opportunity to communicate changes in sediment supply by land use change and hillslope

processes because of their high capacity storage. Meade and Trimble (1978) suggested that the lack of sediment trends (up or downward trends) is a function of the average resident time of sediment in storage elements. Dietrich et al (1991) indicated that sediment residence time in storage elements can average up to 100 years, even in low order drainage basins. Meade and Trimble (1978) also suggested that discrepancies between expected and observed changes in sediment loads due to LUCC in selected drainage basin in the Atlantic region of the United States, were related to sediment residence time in storage elements. The main reason for this discrepancy was the main rivers were still receiving sediment from their storage elements upstream. The authors concluded that this sediment was not from current erosional process due to LUCC process at that time, but due to accumulated sediment during the years of accelerated erosion following the deforestation and farming of the land. This evidence indicates that the increases (upward trends) in sediment transport associated with land use change are not identified immediately in the stream flow.

Third, climatic variability is also an important force driving sediment production in Costa Rica. The Influence of “El Niño” on regional sediment production was studied between 1971 and 1991. During the study period, the influence of “El Niño” was observed on the those basins draining into the Pacific Ocean. Sediment transport data for the Grande de Terraba and Abangares drainage basins during the 1972-73, 1976-77, 1979-1980 and 1986-97 “El Niño” periods are shown in figures 4.6 and 4.7. These drainage basin were selected because provide a sediment record long enough for the analysis. During “El Niño” periods, a net decrease on sediment loss is observed (Table 4.3). During the 1972-73, 1976-1977, and 1986-87 “El Niño” periods, precipitation decreased 6%, 28% and 12% respectively

at the Grande de Terraba watershed. The relative reduction in precipitation from the long term mean was reflected in 73%, 61% and 23% reductions respectively in sediment production during “El Niño” years given above. It can be hypothesized that: the relative reduction on sediment production is related, at the temporal scale, with a reduction of rainfall intensities rather than a reduction in the number extreme events with less intensity. The data available, unfortunately, does not provide insights to confirm this, but the drought periods associated with “El Niño” can produce an direct impact on reducing the frequency of extreme events and this phenomena can be partially responsible for this reduction on sediment production rather than the total annual precipitation.

The Abangares drainage basin shows similar results. Precipitation decreased 3%, 24% and 41% during the “El Niño” years given above. At the same time, sediment transport decreased 82%, 80% and 59% respectively. A reduction in sediment transport is not observed during the 1979-80 “El Niño” years. The 1979-80 “El Niño” period has been considered a weak event in contrast with the other years. The impact of an exceptional number of hurricanes, rather than a weak “El Niño”, is a possible cause for the net increase in sediment production during the 1979-80 period. During the 1979-80 season, an exceptional number of hurricanes, a total of six, passed through the Caribbean sea (Brenes & Saborio, 1994). Generally, Caribbean hurricanes have a greater impact on the Pacific watersheds than on the Caribbean basins (Sanchez-Azofeifa, 1991). Hurricane bands cross over the country and hit the Pacific high relief mountains producing intense precipitation along the Pacific coast. However, the quality and temporal resolution of the data set does not make it possible to analyze this effect at the event level.

Although there is an important decrease on sediment production during “El Niño” years, a Mann-Whitney test indicates that mean sediment production during “El Niño” years is not statistically significant when compared with the long term sediment production mean ($P < 0.05$). The main reason of this lack of significance is the variance associated with the current monitoring system. Because sediment sampling is done sporadically rather than during extreme events the data set variance can be buffering the effect of changes on climatic variability.

The Caribbean watershed's regional sediment production does not show any trends from the impact of hurricanes nor from the “El Niño” years. Sediment production in this region seems to follow a random pattern without direct response to climatic variability. Figure 4.5 shows that regional sediment production is not affected by the frequency of hurricanes in the Caribbean Sea. For example, sediment production was a minimum during the 1979-80 hurricane season, even though this year had a total of 6 hurricanes. Available data only suggests that sediment production for those basins draining into the Caribbean Sea are the result of a combination of several factors, such as land use change, regional climate and episodic earthquakes. Of these factors, only the impact from earthquakes can be singled out with the available data set.

Sediment transport in Costa Rica also shows some degree of correlation with the percentage of forest cover at the basin level. Figures 4.8 and 4.9 shows that sediment transport increases as percentage of forest cover decreases. This general relationship is not strong but suggestive of a general or regional trend. For example, the Grande de Terraba, Grande de Tarcoles and Parrita drainage basins (all Pacific Watersheds) have about the same

percentage of forest cover, but significantly different total sediment transport during 1984 and 1991. Differences are explained by: (1) the different land cover types in each basin, (2) topographic and geomorphologic characteristics, and (3) regional micro-climate. Land cover at the Grande de Tarcoles is dominated by the City of San Jose. The Parrita watershed is covered mostly by pasture land, and the Grande de Terraba is considered the watershed with the most forest fragmentation in the country (Table 4.2). Soil types and slopes are different in each basin (MAG/FAO/CIEDES, 1995), suggesting that erosional process on hillslopes can be of a different nature in each basin. Climate is also different in each drainage basin. The Grande de Terraba is affected by several different types of micro-climates and rainfall intensities as a result of the Caribbean Hurricanes and tropical storms. Sanchez-Azofeifa (1991) reported rainfall intensities exceeding 240 mm/hr for Hurricane Joan (1988) at the Grande de Terraba watershed. Regional precipitation patterns at the Grande de Tarcoles and Parrita are dominated by the movements of the Inter-tropical Convergence Zone (ITCZ) and northern trade winds (Mojica, 1972). The impact on mean annual precipitation distribution as a result of the ITCZ, has been documented by Chacon (1985) and Sanchez-Azofeifa (1993) at the Reventazon basin.

The impact of LUCC in the agricultural census, between 1950 and 1984, cannot be identified in the available sediment data sets (Pacific or Caribbean). This can be explained by the following. First, suspended sediment information is only available since 1971, for most drainage basins in the country. The lack of suspended sediment information prior to 1971 does not provide insights into the system's response during the time of fast LUCC in the country (1950-1973). Second, the agricultural census reports LUCC at the county level

without information on spatial distribution of forest and crops. Therefore, the lack of spatial distribution does not allow researchers to estimate with accuracy, rates of LUCC trends over time at the drainage basin level.

Discussion

A literature review indicates that forest fragmentation will affect a watershed's hydrologic cycle. Forest fragmentation has important impacts on water balances. Bierregaard et al. (1992) indicated that forest fragmentation influences insolation, wind penetration, temperature, and relative humidity. Kapos (1989) suggested that fragmentation produces changes in temperature, humidity, photosynthetically activity radiation (PAR), and soil moisture. This study also suggested that forest fragmentation produces depletion of soil water near the forest / non-forest boundary therefore increasing evapotranspiration. Salati et al. (1978) indicated that altered forest structure may influence regional evapotranspiration budgets and rainfall patterns. These impacts at the national and regional level must be addressed in the future, especially on those drainage basins such as The Grande de Terraba (PD= 1.3) and the Reventazon (PD= 0.48) which are important for the national hydropower generation system.

As deforestation and forest fragmentation increase in Costa Rica the implications for the national watershed systems are critical. It has been documented that most of the drainage basins in Costa Rica have less than 50% forest cover, and that most of this forest is at elevations above 1000 and 2000 masl. In addition, this study has found that forest

fragmentation is higher at the Terraba, Parrita, Naranjo and Reventazon river basins. Because of their geographic location and vulnerability to indirect effects of hurricanes passing by the Caribbean sea, the first three drainage basins are of concern due to their high potential for natural hazards. This has been proven true during hurricane “Caesar” (July 29-31, 1996) which produced serious infra structural damage, loss of agricultural crops and 40 deaths within those drainage basins (Cordero-Infante, 1996).

Researchers need to be aware that available sediment data sets are not accounting for extreme events, or for small temporal changes. The lack of more detailed information prevents scientists from understanding with greater detail, the different forces that are affecting sediment transport and the erosional process in the country. A new monitoring program, in selected drainage basins such as the Sixaola (Caribbean) and Grande de Terraba (Pacific) which showed high sediment transport, based on intensive sampling rather than selective sampling, will eventually help scientists to understand those processes and forces driving sediment production in Costa Rica.

In terms of sediment production, this study has failed to prove a definitive connection between LUCC and sediment production. The former does not mean that the current systems must be entirely eliminated, since results provided important insights on how to design future observational networks. Findings of this study will help to design a more comprehensive sediment monitoring system based on extreme events rather than monthly averages.

Several aspects are important to consider when analyzing sediment production in Costa Rica:

- (1) The monitoring program is designed to produce broad estimates of sediment

production, but is not designed to show regional or temporal sediment production trends. This process is more selective than intensive. Erosional processes in Costa Rica occur in very localized areas such as in high relief and other vulnerable areas, and their response to climatic or land use change process cannot be detected with selective sampling techniques currently in use.

(2) The monitoring systems is not truly nationwide. The current monitoring system implemented by Costa Rica's National Electricity Institute (ICE), only is in place on those drainage basins important for hydropower generation, so impacts on sediment transport due to LUCC and climatic variability on other areas under systematic LUCC cannot be detected.

(3) Climatic variability is an important issue to consider when sediment production is studied in Costa Rica. The analysis indicates that for the Pacific region, sediment transport over time is affected by "El Niño". This effect has been overlooked in the past, but its impact can be better understood with the implementation of a more intensive sediment monitoring program. Additionally, the analysis suggested that sediment production in the Caribbean region follows a random pattern, without any direct connection to climatic variability (e.g. Hurricanes and "El Niño"). Currently, available sediment and climatic information does not provide enough information to conclude which forces or combination of forces are driving sediment production in the Caribbean watersheds. The only detected direct influence is associated with the

role of episodic earthquakes.

(4) Current land use and land cover change information cannot be correlated with national or regional sediment data sets. The lack of spatial distribution of land cover and land use in the agricultural census does not make it possible to evaluate the impact of LUCC processes at the drainage basin level between 1973 and 1984.

(5) Because existing sediment transport data sets contain relatively recent data and only go back until 1979-71, the data set does not contain enough early data, for time periods before 1970, to detect the system response to LUCC. These data sets are therefore not capturing the signal of the LUCC process which occurred during the 1950's and 1960's.

The current sediment monitoring program is failing to detect important responses of the regional watershed system to LUCC. This is an issue of concern because other Central American countries have been following the same methodology designed by the World Meteorological Organization (WMO). Therefore, the lack of information can be present in other countries in the region. In order to solve this problem it is proposed to define a new set of criteria for suspended sediment sampling on key drainage basins. This new sediment monitoring program based on continuous sampling rather than partial sampling can be implemented on drainage basins such as the Reventazon (Caribbean) and Grande de Terraba (Pacific). These two drainage basins are / or will important sources of hydropower energy for

Costa Rica and the Central American region. The design and implementation of this program can be carried on by regional organizations such as the Central American Committee on Water Resources (CRRH).

A continuous monitoring program linked to current telemetric rainfall stations will make it possible to identify sediment transport for: (1) different ranges of rainfall intensity, duration, and frequency (2) systematic LUCC process (e.g. shifting cultivation, localized deforestation), and (3) climatic variability (e.g. movement of the ITCZ or “El Niño”). This new monitoring system can take advantage of state-of-the-art techniques and equipment for suspended sediment monitoring. Moreover, collected information at fine temporal scales, linked with forthcoming high resolution satellites (resolution < 1 m) will help to define more precise strategies for erosion and soil loss control, as well as to identify critical sediment source areas.

Conclusions

1. This study has documented degree of forest cover and forest fragmentation at the basin level in Costa Rica. Current forest cover and forest fragmentation indicates the sustainability of water resources in Costa Rica will depend on controlling those forces contributing to forest fragmentation on selected drainage basins. Conservation programs aimed to protect upper drainage basins in the Caribbean drainage system and to promote restoration on the Pacific drainage system are critical for sound management of water resources.

2. The monitoring of deforestation trends and forest fragmentation at the national level most be considered an important component of future water resource management programs. Institutions such as the Costa Rica's National Electricity Institute must focus efforts on monitoring the rate of forest loss on critical drainage basins for the present and future hydropower generation.
3. The analysis of 20 years of annual river and stream suspended sediment data for Costa Rica does not provide conclusive information on the impacts of LUCC over time. It also indicates that soil erosion and sediment transport in Costa Rica is the result of more complex interactions, such as climate variability, sediment deposition and erosion dynamics, localized land use patterns, and episodic earthquakes.
4. Soil erosion and subsequent sedimentation in hydropower reservoirs is an significant cost factor in electrical generation operations. Available data suggests that earthquakes and changes in land cover and land use can contribute to an enhancement of soil erosion in Costa Rica. However, current methods for the collection of sediment data are not adequate for studies of linkages between specific local sources of sediment generation and reservoir sedimentation rates.
5. If a significant fraction of total sediment erosion occurs in a relatively small area of a watershed, where land with steep slopes is unstable due to land cover change or landslides causes by earthquakes, higher resolution data on land cover and soil erosion

processes will be required to implement cost-effective methods of erosion control. The effect of the April's 1991 earthquake and its combination with a tropical storm in later June of the same year are clear indicators that the problem of sediment production in Costa Rica needs of high resolution spatial information.

Table 4.1 Hydropower potential, forest cover and suspended sediment production for selected drainage basins in Costa Rica

Watershed Name	Power (MW)	Energy (GWh)	Basin Area (ha)	1991 Sediment Production (Ton)	1991 Forest Area (ha)	1991 Forest Cover (%)	1991 Forest 1000 masl (ha)	1991 Forest 1000 masl (%)	1991 Forest 2000 masl (ha)	1991 Forest 2000 masl (%)
Chirripo	377	1900	147639	537014	63166	42.8	22815	56.4	1262	100.0
Sarapiquí	332	1711	229329	186488	95697	41.7	31631	82.6	4544	84.8
San Carlos †	283	1667	275388	730095	64123	23.3	27678	60.7	1571	65.7
Reventazón †	640	3534	303332	819748	147599	48.7	86227	60.5	38542	78.6
Pacuare † †	940	4859	83319	340217	61006	73.2	33967	93.0	0	-
Matina	528	2920	142000	120104	96147	68.0	54827	92.6	0	-
Barranca	84	318	91913	57447	9049	9.8	7029	27.9	151	15.4
Tarcoles †	372	1942	212824	944811	26687	12.5	23528	20.6	8389	71.4
Sixola	1273	8012	245762	2415916	209938	85.4	123866	95.4	0	-
Parrita	375	1618	129474	157338	29769	23.0	25747	34.6	7545	56.9
Naranjo	174	1017	37521	100923	16632	44.3	9952	59.7	3605	73.6
Savegre	487	2497	59230	144606	40132	67.8	29074	80.5	16549	83.6
Terraba	2607	10944	499186	1356547	162733	32.6	126050	67.4	1	14.1
Total	8472	42939								

Notes:

1. Sediment production corresponds to the 1990-91 hydrologic year (April to May).
2. † Watersheds with hydropower projects in operation or under construction.
3. † † Watershed with hydropower projects in the planning phase.

Table 4.2 Rank of drainage basins in Costa Rica as function of forest fragmentation.

Watershed Name	Watershed Area (ha)	1991 Forest Area (ha)	1991 Forest Cover (%)	1991 PD (# Patch/100 ha)	1991 MPS (ha)
Terraba*	499186	162733	33	1.30	25.1
Parrita*	129474	29769	23	0.79	29.2
Naranjo*	37521	16632	44	0.52	88.9
Reventazon	303302	147599	49	0.48	100.6
Barranca	91913	9049	10	0.44	22.3
Tarcoles	212824	26687	13	0.39	32.4
Sarapiqui	229329	95697	42	0.37	111.7
San Carlos	275388	64123	23	0.35	66.5
Pacuarc	83319	61006	73	0.33	224.3
Matina	142000	96147	68	0.26	264.9
Savegre	59230	40132	68	0.22	311.1
Chirripo	147639	63166	43	0.20	210.6
Sixaola	245762	209938	85	0.09	985.6

Note : Patch density used as a ranking criterion.

*Note: * Watersheds with more impacts from the Huracan Cesar, July 1996*

Table 4.3 Impact of "El Nino" at the Abangares and Grande de Terraba drainage basins

El Nino Year	EL Nino Intensity	Grande de Terraba Drainage Basin Streamflow station: El Brujo Pacific System			Abangares Drainage Basin Streamflow station: Limonal Viejo Pacific System		
		Precipitation Change (%)	Sediment Change (%)	Mann-Whitney Rank Sum	Precipitation Change (%)	Sediment Change (%)	Mann-Whitney Rank Sum
1972-1973	Strong	-5.7	-72.8	No Difference	-3.3	-81.8	No Difference
1976-1977	Moderate	-25.8	-61.2	No Difference	-24.0	-79.8	No Difference
1979-1980	Weak	9.1	67.7	No Difference	4.3	81.1	No Difference
1982-1983	Very Strong	-11.7	-23.0	No Difference	-40.8	-58.3	No Difference
1986-1987	Moderate	N.D.	-15.1	No Difference	N.D.	-64.7	No Difference

Note: The Mann-Whitney indicates that the differences in the median values (El Nino Years vs Long term record) are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference.

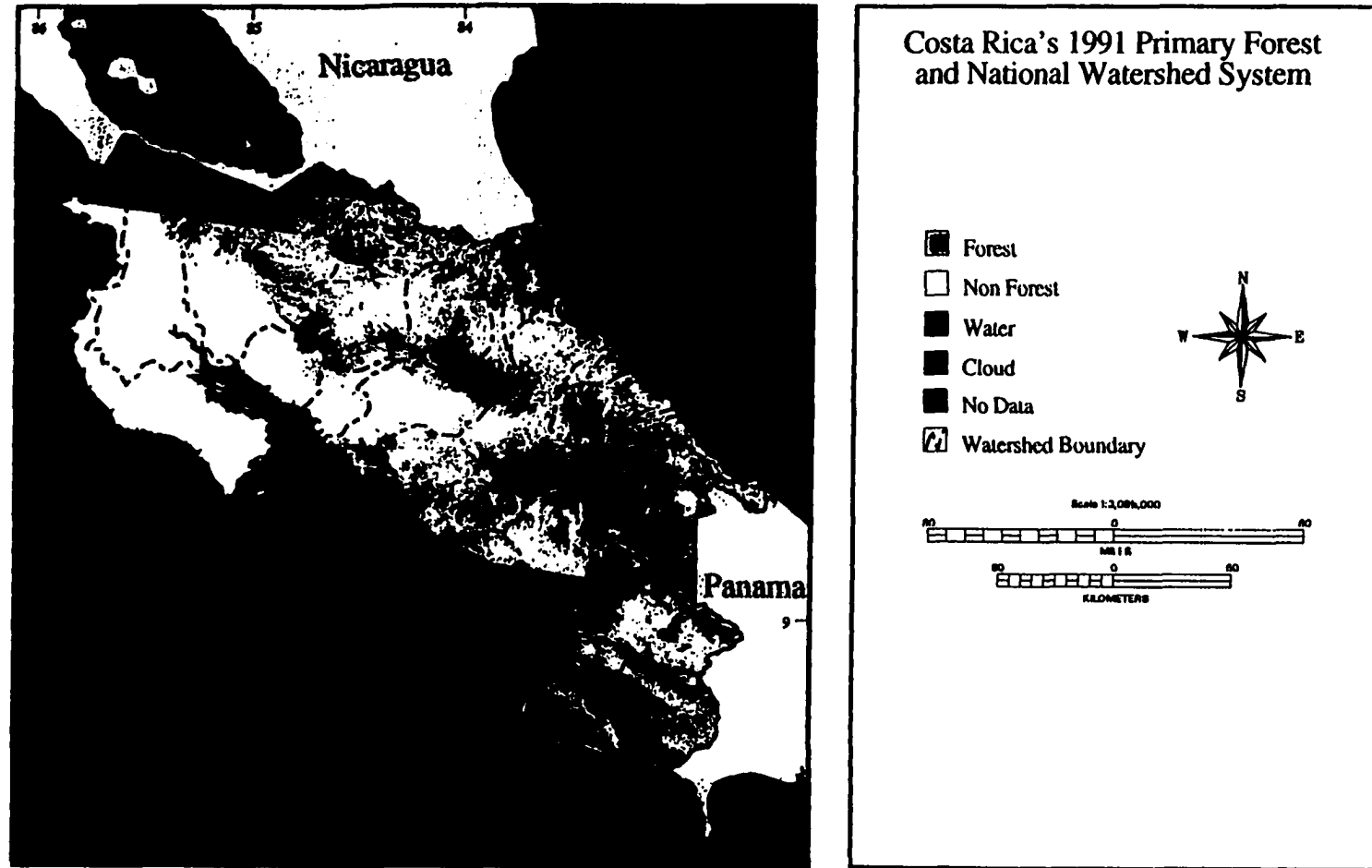


Figure 4.1. Costa Rica 1991 forest cover and national watershed system. Forest cover represents all units with 80% of higher canopy closure.

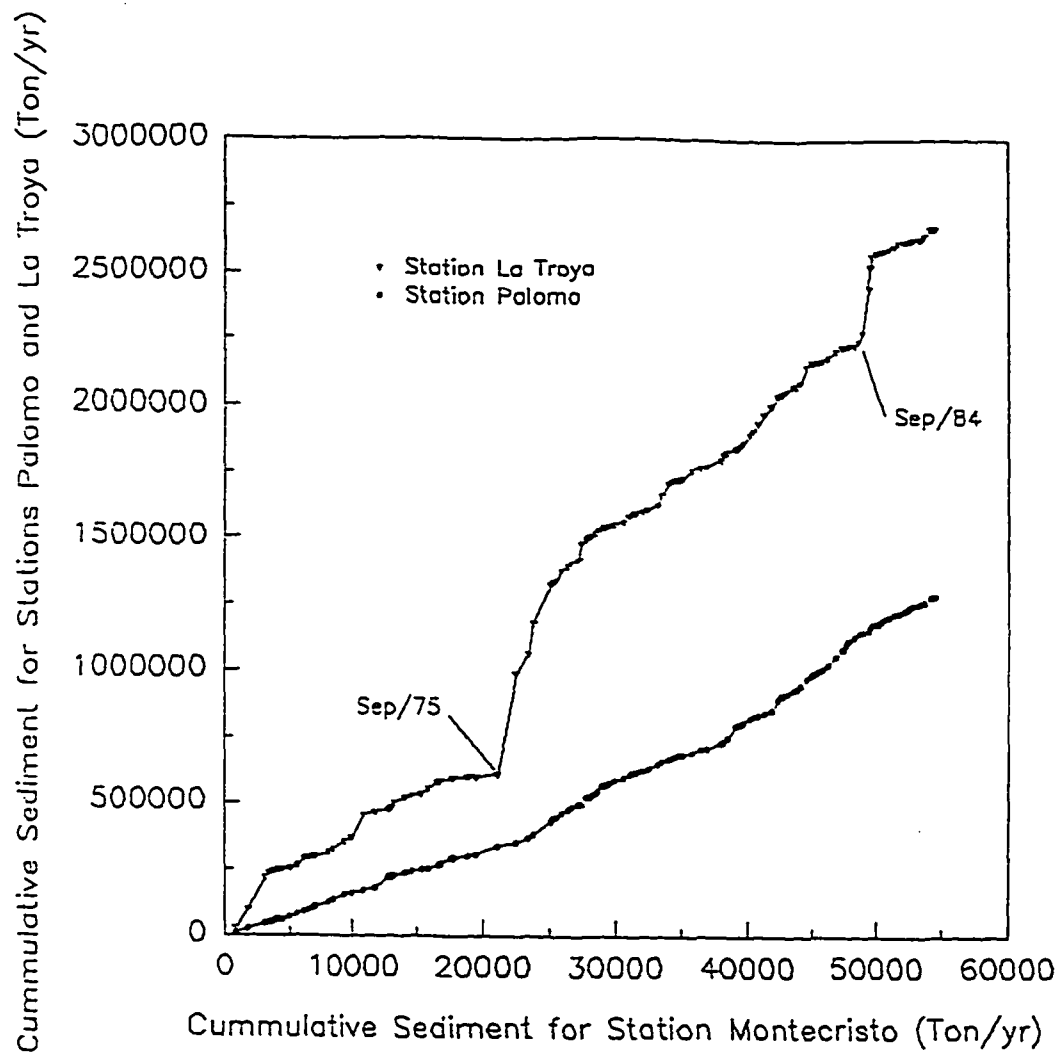


Figure 4.2. Monthly sediment double-mass curves for stations Palomo (monitoring primary forest) and La Troya (zone of shifting agriculture) compared with station pattern Montecristo (primary forest). La Troya presents more complex behavior as a result of LUCC process in this basin (After Sanchez & Harriss, 1994).

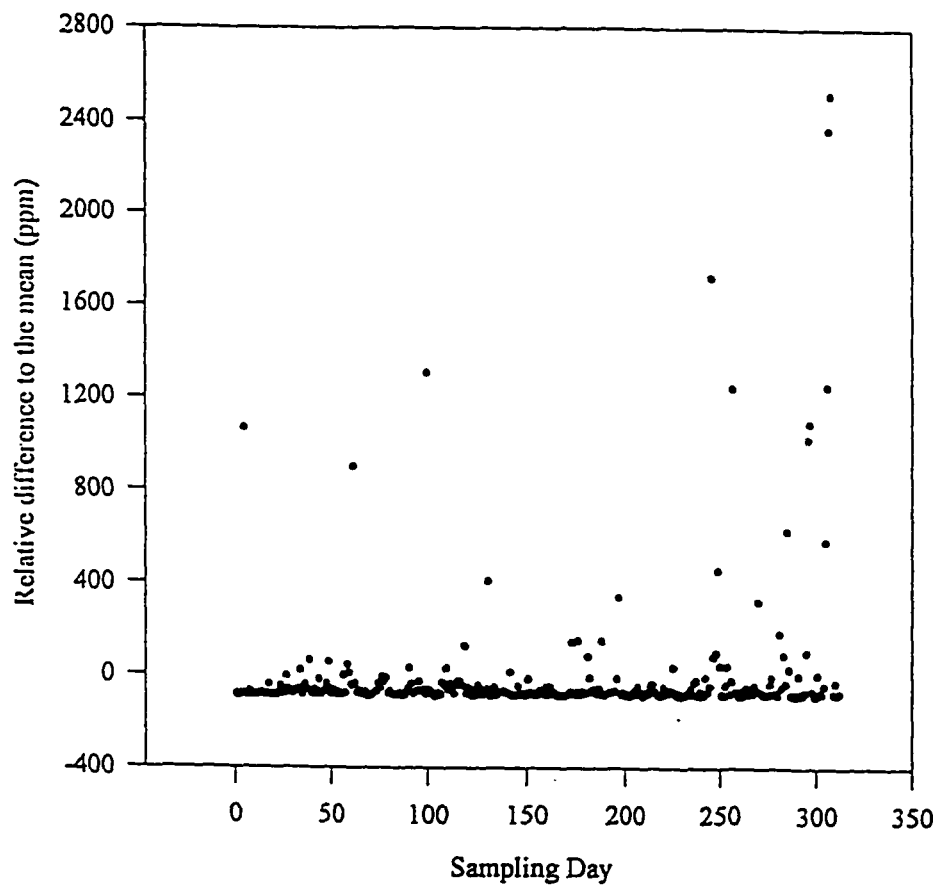


Figure 4.3. Relative differences to the long term mean of suspended sediment samples at the Pacuare River basin, Costa Rica. An departure from the mean it is observed at the end of the record as a result of the April 22, 1991 earthquake (7.5 Richter scale).

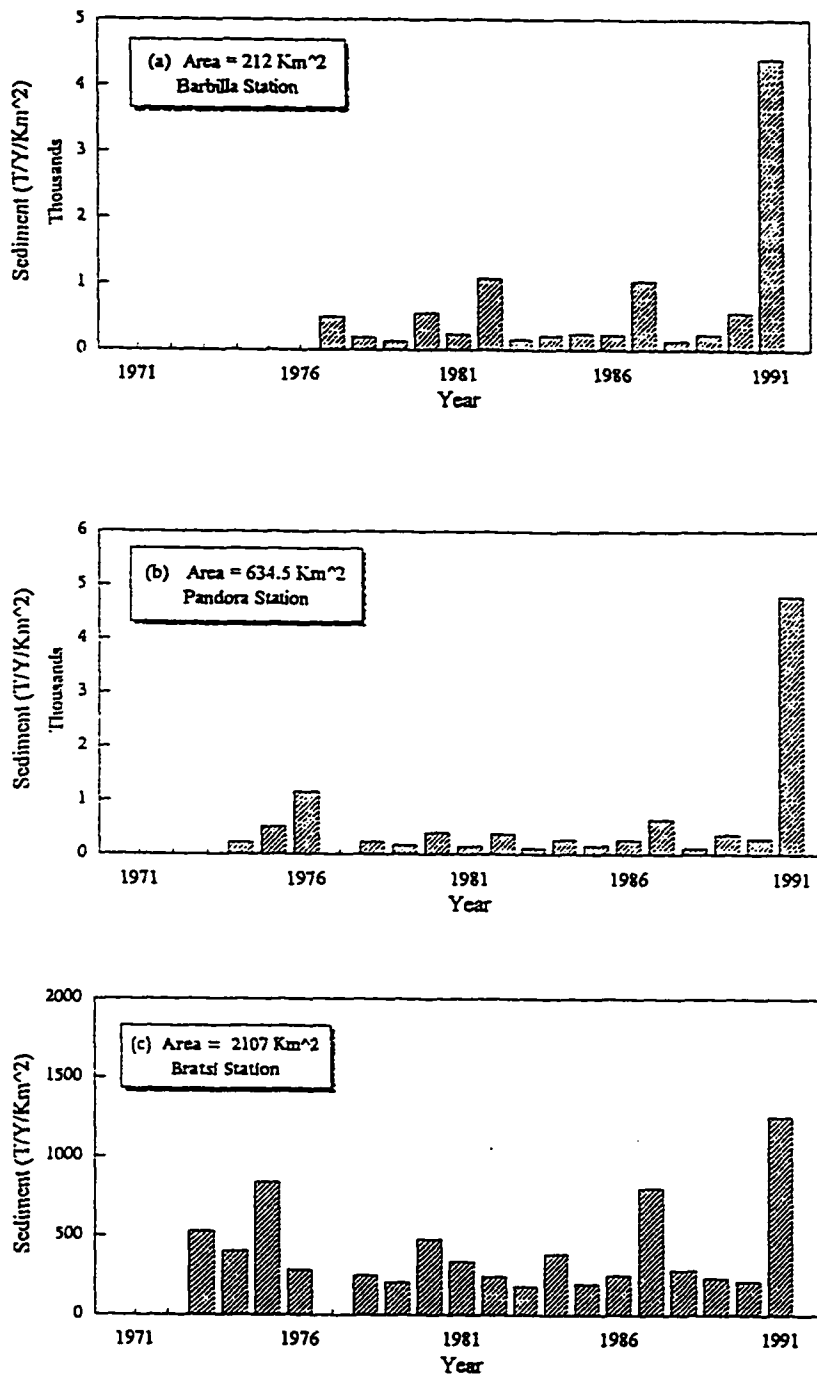


Figure 4.4. Annual suspended sediment production for selected drainage basins on the Caribbean coast of Costa Rica: (a) Barbilla watershed, (b) La Estrella watershed, and (c) Sixaola watershed. A significant increase on sediment production it is observed during 1991 as a result of the April 22, 1991 earthquake.

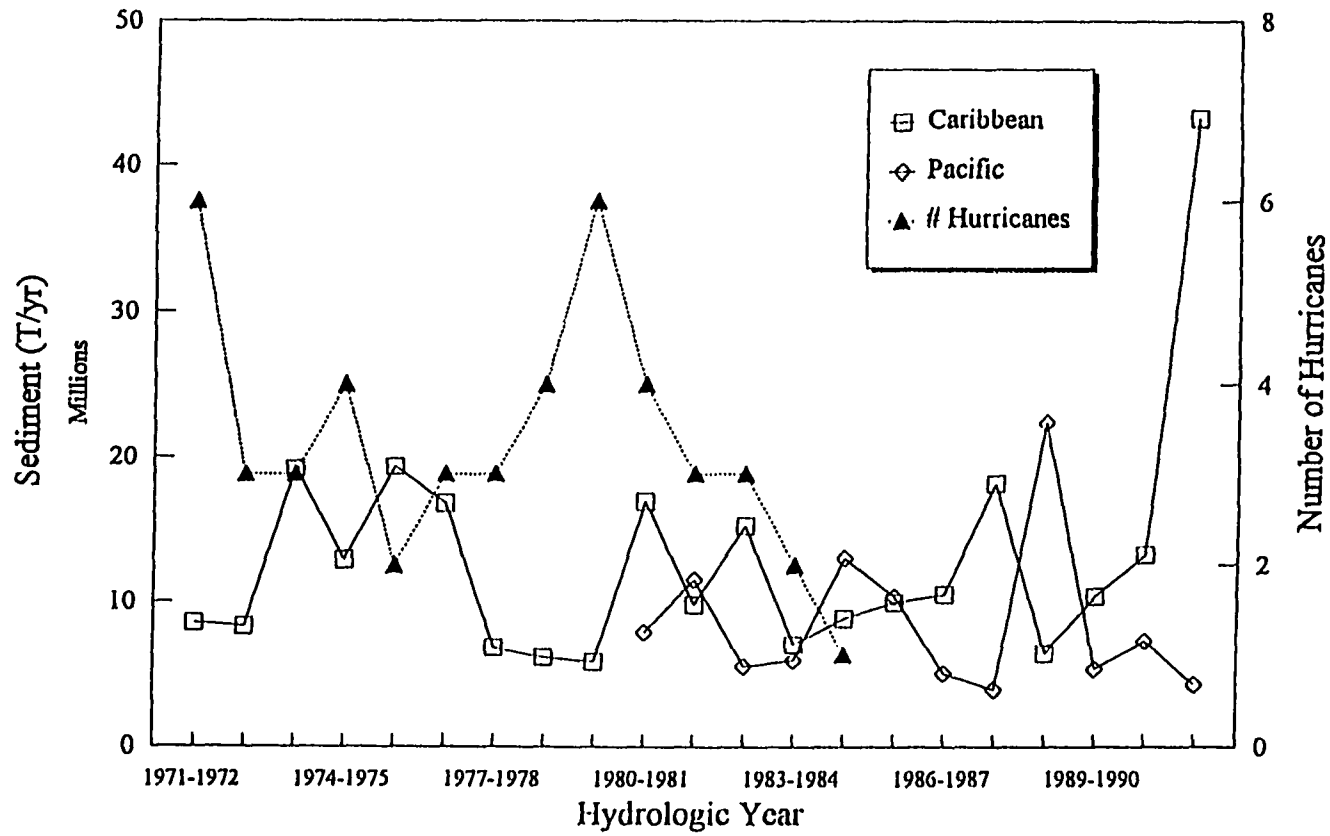


Figure 4.5. Total sediment production for the Pacific and Caribbean watersheds in Costa Rica. The number of hurricanes is also presented during the 1971-1984 period.

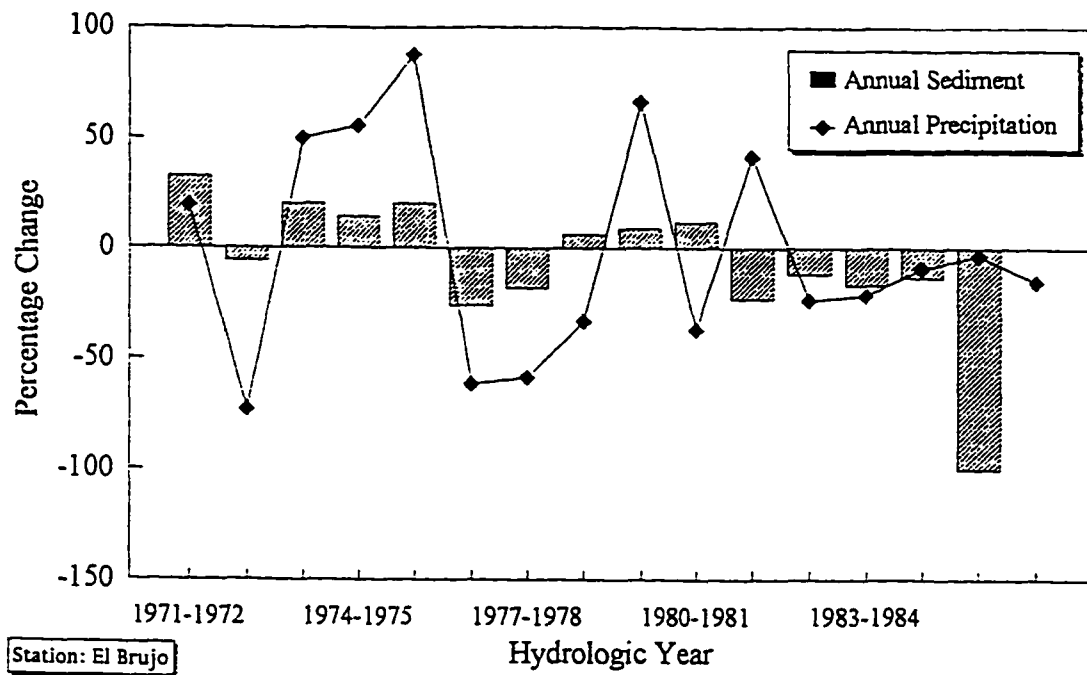


Figure 4.6. Grande de Terraba watershed annual suspended sediment production and mean annual precipitation. A reduction on sediment production is observed during “El Niño” years (1972-1973, 1976-1977, 1979-1980, and 1982-1983). Even though these reductions seems to be important, they are not significant different from the long-term mean.

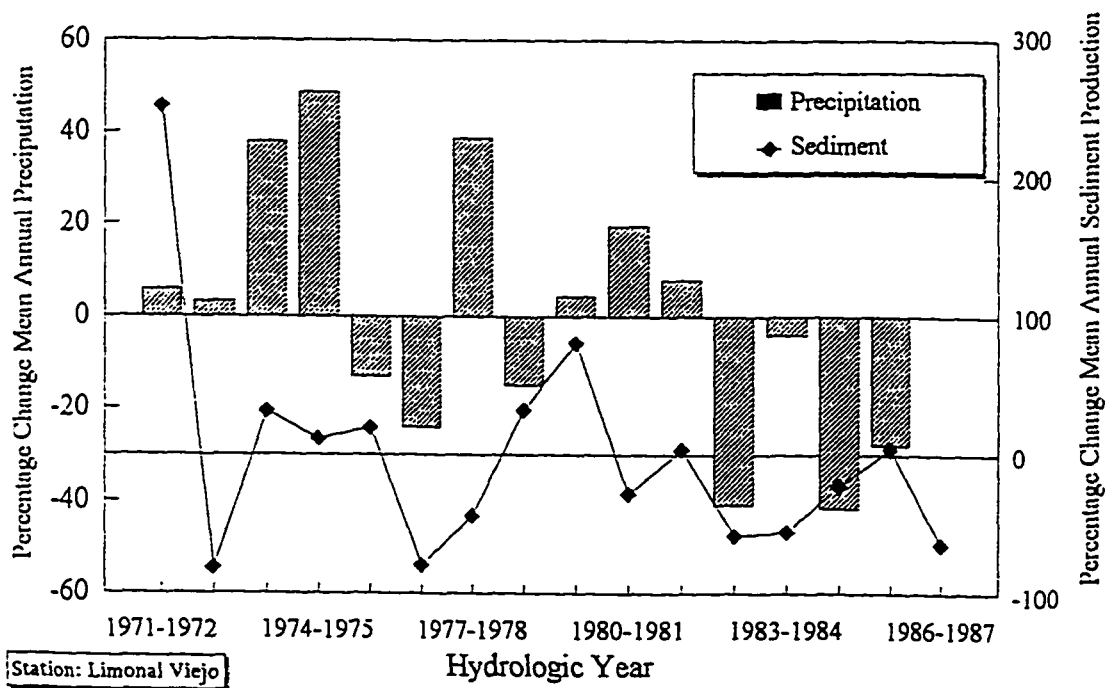


Figure 4.7. The Abangares watershed annual suspended sediment production and mean annual precipitation. A reduction on sediment production is observed during “El Niño” years (1972-1973, 1976-1977, 1979-1980, and 1982-1983). Even though these reductions seems to be important, they are not significant different from the long-term mean.

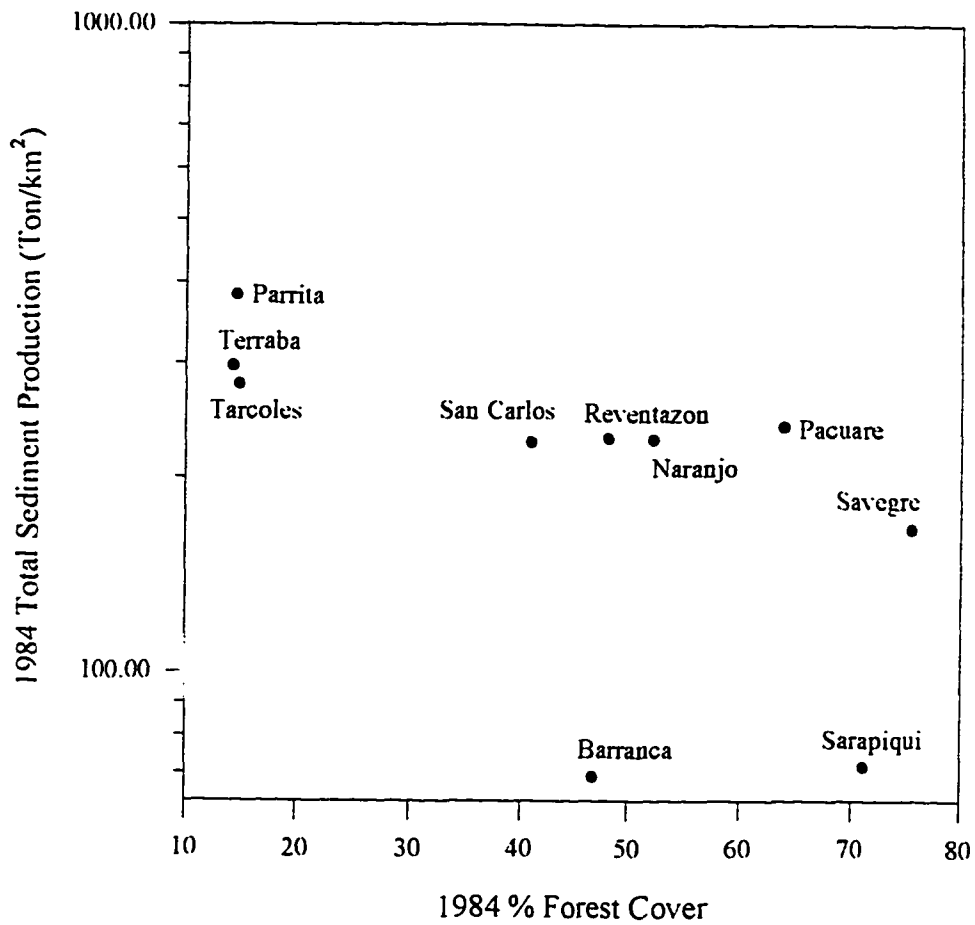


Figure 4.8. Total sediment production for selected watersheds in Costa Rica as function of their 1984 forest cover. Forest cover represents information extracted from the Costa Rica's National Geographic Institute land use map (IGN, 1984).

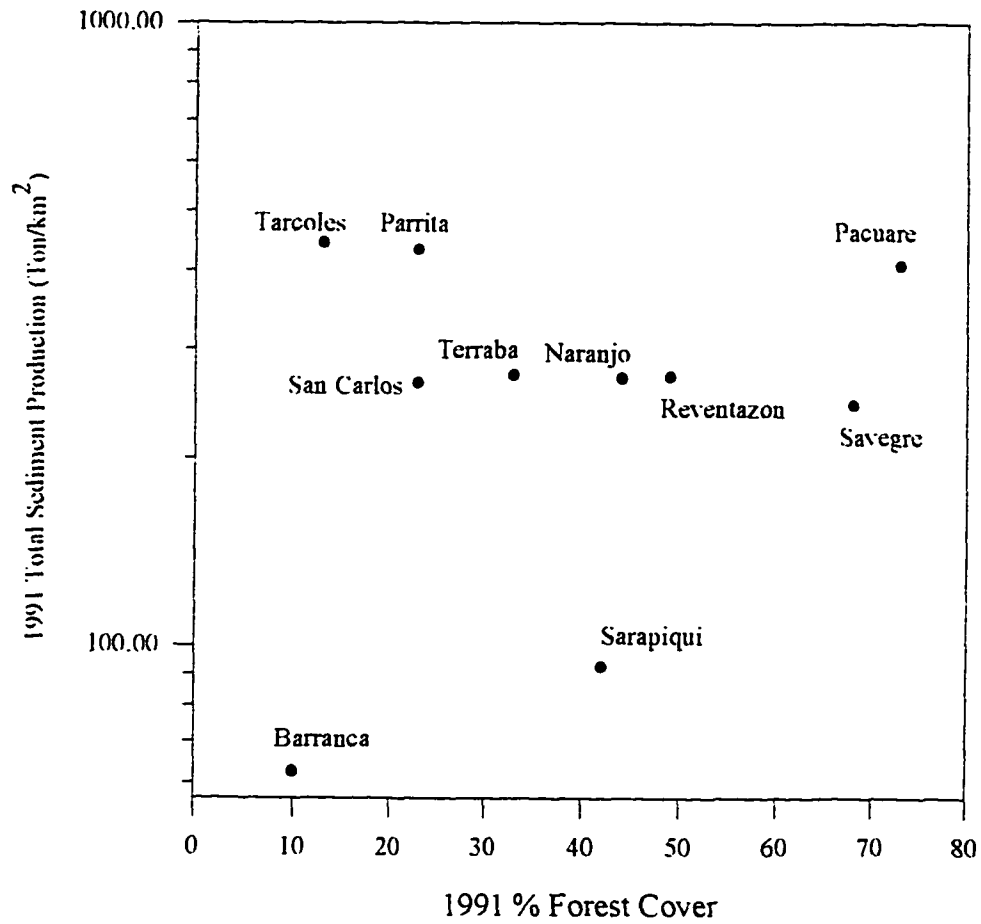


Figure 4.9. Total sediment production for selected watersheds in Costa Rica as function of their 1991 forest cover. Forest cover represents ~80% of higher forest canopy closure, forest cover was extracted using a December 31, 1990 Landsat TM (path 15 / row 53).

REFERENCES

- Aguilar, J. (1982). Cambios en el Uso de la Tierra en Costa Rica . San Jose, Costa Rica: CONICIT.
- Alfaro, R., Bouma, J., Fresco, L. O., Jansen, D. M., Kroonenberg, S. B., Leeuwen, A. C., Schipper, R. A., Sevenhuysen, R. L., Stoorvogel, J. J., & Watson, V. (1994). Sustainable Land Use Planning in Costa Rica: A Methodological Case Study on Farm and Regional Level. In L. O. Fresco, L. Stroosnijder, J. Bouma, & H. v. Keulen (Eds.), The Future of the Land: Mobilizing and Integrating Knowledge for Land Use Options (pp. 183-202): John Wiley and Sons, Ltd.
- Allen, J. C., & Barnes, D. F. (1985). The causes of deforestation in developing countries. Annals of the Association of American Geographers, 75(2), 163-184.
- Aselmann, I. (1989). Global-scale Extrapolation: A critical assessment. In M. Andreae & D. Schimel (Eds.), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere (pp. 119-133). Berlin: John Wiley & Sons Ltd.
- Askins, R. A. (1995, 31 march 1995). Hostile landscapes and the decline of migratory songbirds. Science, 267, 1956-1958.
- August, P., Michaud, J., Labash, C., & Smith, C. (1994). GPS for Environmental Applications: Accuracy and Precision of Locational Data. Photogrammetric Engineering and Remote Sensing, 60(1), 41-45.
- Baker, R. D. (1979). Land use/land cover mapping from aerial photographs. Photogrammetric Engineering and Remote Sensing, 45(5), 661-668.
- Berry, B. J., & Baker, A. M. (1968). Geographic sampling in spatial analysis - a reader in statistical geography. In B. Berry, J. Brian, & D. Marble (Eds.) (pp. 91-100). Englewood Cliffs, N.J.: Prentice-Hall.
- Bierregaard, R. O., Lovejoy, T. E., Kapos, V., Dos-Santos, A. A., & Hutchings, R. W. (1992). The biological dynamics of tropical rainforest fragments. Bioscience, 42(11), 859-866.
- BIRF. (1971). Economic Memorandum on Costa Rica . Washington, D.C.

Brenes, A., & Saborio, V. (1994). Changes in the general circulation and its influence on Precipitation trends in Central America: Costa Rica. AMBIO, 22(1), 87-90.

Bros, W.E. and Cowell, B.C. (1987). A Technique for optimizing sample size (replication). Journal of Experimental Marine Biology and Ecology, 114, 63-71.

Butterfield, R. (1994). The Regional Context: Land Colonization and Conservation in Sarapiquí. In L. McDade, K. Bawa, H. Hespenehede, & G. Hartshorn (Eds.), La Selva: Ecology and Natural History of a Neotropical Rain Forest (pp. 299-306). Chicago: The University of Chicago Press.

Campbell, R. W. J., Rodriguez, H., & Sader, S. A. (1979). Design of a nationwide natural resource inventory and information system for Costa Rica. Los Altos, California: Resource Development Associates.

Centro-Cientifico-Tropical. (1982). Costa Rica: Perfil Ambiental. Estudio de Campo: Centro Cientifico Tropical, San Jose: Costa Rica.

Chacon, R. E., & Fernandez, W. (1985). Temporal and Spatial Rainfall Variability in the Mountainous Region of the Reventazon River Basin, Costa Rica. J. of Climatology, 5, 175-188.

Chatfield, C. (1988). Problem Solving a Statistician's Guide: Chapman & Hall.

Chomentowsky, W., Salas, B., & Skole, D. L. (1994, April 1994). Landsat pathfinder project advances deforestation mapping. GIS World, 7, 34-38.

Cohen, J. (1960). A coefficient of agreement for nominal scales. Educ. Psychol. Measurement, 20(1), 37-46.

Congalton, R. G. (1988). A Comparison of Sampling Schemes Used in Generating Error Matrices for Assessing the Accuracy of Maps Generated from Remotely Sensed Data. Photogrammetric Engineering and Remote Sensing, 54(5), 593-600.

Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment, 37, 35-46.

Cordero-Infante, C. (1996, July 27). Tormenta Cesar golperaria al pais hoy. La Nacion, pp. 6A.

COSEFORMA. (1994). Inventario Forestal de la Region Huetar Norte: Resumen de Resultados. San Jose, Costa Rica: Proyecto de Cooperacion Tecnica entre la Republica de Alemania y La Republica de Costa Rica.

Costa-Rica. (1950). Censos Agrícolas . San Jose, Costa Rica: Direccion General de Estadisticas y Censos.

Costa-Rica. (1955). Censos Agrícolas . San Jose, Costa Rica: Direccion General de Estadisticas y Censos.

Costa-Rica. (1963). Censos Agrícolas . San Jose, Costa Rica: Direccion General de Estadisticas y Censos.

Costa-Rica. (1973). Censos Agrícolas . San Jose, Costa Rica: Direccion General de Estadisticas y Censos.

Costa-Rica. (1984). Censos Agrícolas . San Jose, Costa Rica: Direccion General de Estadisticas y Censos.

Costa-Rica. (1995a). Estadisticas de Desarrollo Economico.

Costa-Rica. (1995b). Plan Nacional de Energia 1995-2015 . San Jose, Costa Rica: Ministerio de Recursos Naturales, Energia y Minas.

Dietrich, W., Dunne, T., Humphrey, N., & Reid, L. (1991). Construction of sediment budgets for drainage basins. Unpublished manuscript.

Dunn, R., Harrison, A. R., & White, J. C. (1990). Positional accuracy and measurement error in digital databases of land use: an empirical study. International Journal of Geographical Information Systems, 4(4), 385-398.

Edwards, G., & Lowell, K. E. (1996). Modeling uncertainty in photo-interpreted boundaries. Photogrammetric Engineering and Remote Sensing, 62(4), 337-391.

Ehrlich, P. R., & Wilson, E. O. (1994) Biodiversity studies: Science and policy. Science, 253, 758-762.

Elizondo, C. (1995). Description of Costa Rica's 1984 Land Use Maps. Personal communication.

Erdas (1991). ERDAS: Field Guide, Version 7.5. (Second ed.). Atlanta, GA: ERDAS, Inc.

FAO. (1990). Forest Resources Assessment : FAO, Rome.

Fitzpatrick-Lins, K. (1981). Comparison of sampling procedures and data analysis for a land-use and land-cover Map. Photogrammetric Engineering and Remote Sensing, 47(3), 343-351.

Gaupp, P. (1992). Ecology and development in the tropics. Swiss Review of World Affairs, September, 14-19.

Gullison, R., & Losos, E. (1993). The role of foreign debt in deforestation in Latin America. Conservation Biology, 7(1), 140-147.

Harrison, S. (1991). Population growth, land use and deforestation in Costa Rica, 1950-1984. Interciencia, 16(2), 83-93.

Harriss, R. (1989). Experimental Design for Studying Atmosphere-Biosphere Interactions. In M. Andreae & D. Schimel (Eds.), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere (pp. 291-300). Berlin: Wiley-Interscience.

Hewitt, J., McBride, G., Pridmore, R., & Thrush, S. (1993). Patchy distributions: Optimizing sample size. Environmental Monitoring and Assessment, 27, 95-105.

Holdridge, L. R. (1994). Life Zone Ecology. San Jose, Costa Rica: Tropical Science Center.

ICE. (1993). Boletín de sedimentos en Suspensión No. 3 : Instituto Costarricense de Electricidad.

Instituto Geografico Nacional. (1984). 1:200,000 Mapa de Uso de la Tierra . San Jose, Costa Rica: Instituto Geografico Nacional.

Instituto Geografico Nacional (1994). 1:50,000 topographic maps . San Jose, Costa Rica: Instituto Geografico Nacional.

Jansson, M., & Rodriguez, A. (1992). Sedimentological studies in the Cachi reservoir, Costa Rica: Sediment inflow, reservoir sedimentation, and effects of flushing (UNGI report 81): Uppsala University: Department of Physical Geography.

Jensen, J. R. (1986). Introductory Digital Image Processing. Englewood Cliffs, New Jersey: Prentice-Hall.

Kapos, V. (1989). Effects of isolation on the water status of forest patches in the Brazilian Amazon. Journal of Tropical Ecology, 5, 173-185.

Keller, M., Jacob, D., Wofsy, S., & Harriss, R. (1991). Effects of tropical deforestation on global and regional atmospheric chemistry. Climatic Change, *19*, 139-158.

Keller, M., Veldkamp, E., Weitz, A. M., & Reiners, W. A. (1993, 16 September 1993). Effect of pasture age in soils trace-gas emissions from a deforested area of Costa Rica. Nature, *365*, 244-246.

Kruess, A., & Tschamtkke, T. (1994, 10 June 1994). Habitat Fragmentation, species loss, and biological control. Science, *264*, 1581-1584.

Leon, J., Barboza, C., & Aguilar, J. (1982). Desarrollo tecnologico en la ganaderia de carne. San Jose, Costa Rica: CONICIT.

Leonard, H. (1987). Natural Resources and Economic Development in Central America. New Brunswick, NJ: International Institute for Environment and Development.

Lutz, E., & Daly, H. (1990). Incentives, Regulations, and Sustainable Land Use in Costa Rica (Environmental Working Paper No. 34). Washington, D.C.: The World Bank.

Luvall, J., Lieberman, D., Lieberman, M., Hartshorn, G., & Peralta, R. (1990). Estimation of tropical forest canopy temperatures, thermal response numbers, and evapotranspiration using an aircraft-based thermal sensor. Photogrammetric Engineering and Remote Sensing, *56*(10), 1393-1401.

Ma, Z., & Redmond, R. (1995). Tau Coefficients for Accuracy Assessment of Classification of Remote Sensing Data. Photogrammetric Engineering and Remote Sensing, *61*(4), 435-439.

MAG/FAO/CIEDES. (1995). Mapa de principales unidades de suelos de Costa Rica . San Jose, Costa Rica: Centro para Investigaciones en Desarrollo Sostenible (CIEDES-UCR).

Matson, P., Vitousek, P., & Schimel, D. (1989). Regional extrapolation of trace gas flux based on soils and ecosystems. In M. Andreae & D. Schimel (Eds.), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere (pp. 97-108). Berlin: John Wiley & Sons Ltd.

McGarigal, K., & Marks, B. (1994). FRAGSTATS: Spatial pattern analysis program for quantifying landscape structure (Version 2.0). Corvallis, OR.

Meade, R. H., & Trimble, S. W. (1974). Changes in sediments loads in rivers of the Atlantic drainage of the United States since 1900, Effects of man on the interface of the hydrological cycle with the physical environment (Vol. 113, pp. 99-104). Surrey, U.K.: International Association of Hydrological Sciences.

Mojica, I. H. (1972). Effects of Changes in Land Use on the Streamflow of the Reventazon River, Costa Rica. Unpublished Ph.D., University of Washington.

Mora, S. (1989). Analisis de la Susceptibilidad Geologica Geomorfologica a la erosion de la Cuenca del Rio Reventazon, Costa Rica. , 107-123.

Mulders, M. A., De Bruin, S., & Schuiling, B. P. (1992). Structured approach to land cover mapping of the Atlantic zone of Costa Rica using single TM data. International Journal of Remote Sensing, 13(16), 3017-3033.

Painter, R. B., Blyth, K., Mosedale, J. C., & Kelly, M. (1974) The effect of afforestation on erosional processes and sediment yield. Effects of man on the interface of the hydrological cycle with the physical environment. (Vol. 113, pp. 62-67). Surrey, U.K.: International Association of Hydrological Sciences.

Pettinger, L. R. (1980). Environmental stratification: A method to improve Landsat digital analysis accuracy and land cover map utility. Paper presented at the Proceedings of the Fourteenth International Symposium on Remote Sensing of Environment, San Jose, Costa Rica.

Quesada-Mateo, C (1992). Deforestation and sediment transport in the Upper Reventazon Basin, Costa Rica. Personal communication.

Quesada-Mateo, C. (1990). Estrategia de Conservacion para el Desarrollo Sostenible de Costa Rica. (1st ed.). San Jose Costa Rica: Ministerio de Recursos Naturales Energia y Minas.

Ramirez, A., & Maldonado, T. (Eds.). (1988). Desarrollo Socioeconomico y el Ambiente Natural de Costa Rica: Situacion actual y perspectivas. San Jose, Costa Rica: Garcia Hermanos, S.A.

Rodriguez, A. (1992). Flushings in the Cachi Reservoir. Personnal communication.

Rodriguez, R. (1989). Impactos del Uso de la Tierra en la Alteracion del Regimen de Caudales, la Erosion y Sedimentacion de la Cuenca Superior del Rio Reventazon y los Efectos Economicos en el Proyecto Hidroelectrico de Cachi, Costa Rica. Unpublished M. Sc., Centro Agronomico de Investigacion y Ensenanza.

Rosenfield, G. (1982). Sample Design for Estimating Change in Land Use and Land Cover. Photogrammetric Engineering and Remote Sensing, 48(5), 793-801.

Sader, S. (1979). Renewable resource analysis and monitoring in Costa Rica. Los Altos, California: Resource Development Associates.

Sader, S. (1988,). Satellite Digital Image Classification of Forest Change Using Three Landsat Data Sets. Paper presented at the Proceedings of the Second Forest Service Remote Sensing Applications Conference - Remote Sensing for Resource Inventory, Planning, and Monitoring, Slidell, Louisiana.

Sader, S., & Joyce, A. (1988, March 1988). Deforestation Rates and Trends in Costa Rica, 1940 to 1983. BIOTROPICA, 20, 11-19.

Sader, S. A., Powell, G. V. N., & Rappole, J. H. (1991). Migratory bird habitat monitoring through remote sensing. International Journal of Remote Sensing, 12(3), 363-372.

Sanchez-Azofeifa, G.A.; Harriss, R.C. (1996). Sediment production in Costa Rica. In preparation.

Sanchez-Azofeifa, G.A.(1995). Hydrologic Characterization of the Pacuare River Basin (Hydrologic Report). San Jose, Costa Rica: Centro Cientifico Tropical.

Sanchez-Azofeifa, G. A. (1991). Calibration and simulation of the hurricane Joan in Costa Rica using the HEC-1 (Hydrological Paper No.1). San Jose, Costa Rica: Civil Engineering School, University of Costa Rica.

Sanchez-Azofeifa, G. A. (1993). Environmental Change in a Tropical Rain Forest Basin, A Case Study: The Upper Reventazon Basin, Costa Rica. Unpublished Master of Science, University of New Hampshire.

Sanchez-Azofeifa, G. A., & Harriss, R. (1994). Remote sensing of watershed characteristics in Costa Rica. International Journal of Water Resources Development, 10(2), 117,130.

Sanchez-Azofeifa, G. A., & Quesada-Mateo, C. A. (1995). Deforestation, Carbon Dynamics, and sustainable mitigation measures in Costa Rica: The Puerto Viejo de Sarapiquí Case Study. Interciencia, 20(6), 396-400.

Schelhas, J. W. (1991). Socio-economic and biological aspects of land use adjacent to Braulio Carrillo National Park, Costa Rica. Unpublished Doctoral Dissertation, The University of Arizona.

Schipper, R. A., Jansen, D. M., & Stoorvogel, J. J. (1995). Sub-regional lineal programming models in land use analysis: a case study of the Neguev settlement, Costa Rica. Netherlands Journal of Agricultural Science, 43, 83-109.

Seligdon, M. A. (1984). El Campesino y el Capitalismo Agrario en Costa Rica. San Jose, Costa Rica: Editorial Costa Rica.

Shafer, C. L. (1995). Values and shortcomings of small reserves. BioScience, 45(2), 80-88.

Short, N. (1982). The Landsat Tutorial Workbook: Basics of satellite remote sensing. Washington, D.C.: NASA - Scientific and Technical Information Branch.

Skole, D. (1991,). Data on Global Land Cover Change: Acquisition, Assessment, and Analysis. Paper presented at the 1991 Global Change Institute on Global Land-Use/Cover Change, Snowmass at Aspen, Colorado.

Skole, D. (1992). Measurement of Deforestation in the Brazilian Amazon Using Satellite Remote Sensing. Unpublished Doctor of Philosophy, University of New Hampshire.

Skole, D. L., & Tucker, C. (1993, 25 June 1993). Tropical Deforestation and habitat fragmentation in the Amazon: Satellite Data from 1978 to 1988. Science, 260, 1905-1910.

Solorzano, R., de Camino, R., Woodward, R., Tosi, J., Watson, V., Vasquez, A., Villalobos, C., Jimenez, J., Repetto, R., & Cruz, W. (1991). Accounts Overdue: Natural Resource Depreciation in Costa Rica. Washington, D.C.: World Resources Institute.

Stewart, J. (1989). Group Report: Extrapolation of flux measurements to regional and global scales. In M. Andreae & D. Schimel (Eds.), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere (pp. 155-173). Berlin: John Wiley & Sons Ltd.

Stoorvogel, J. J. (1995). Geographical Information Systems as a Tool to Explore Land Characteristics and Land Use with Reference to Costa Rica. Unpublished Ph.D. Dissertation, Wageningen Agricultural University, Wageningen.

Townshend, J. R. G., & Justice, C. O. (1988). Selecting the spatial resolution of satellite sensors required for global monitoring of land transformations. International Journal of Remote Sensing, 9(2), 187-236.

Umaña, A., & Brandon, K. (1992). Inventing institutions for conservation: lessons from Costa Rica. In S. Annis (Ed.), Poverty, natural resources and public policy in Central America (pp. 85-107): Transaction Publishers.

USGS. (1990). Land use and land cover digital data from 1:25,000 and 1:100,000 scale maps (Data Users Guide 4). Reston, VA: United States Geological Survey.

Vahrson, W. (1989). La erosividad pluvial en la cuenca del Rio Reventazon, Costa Rica. Paper presented at the III Congreso Nacional de Recursos Hidricos, San Jose, Costa Rica.

Veldkamp, A., & Fresco, L. O. (1994). Modeling land use changes and their temporal and spatial variability with CLUE (Final Project Report NRP 853128). Wageningen, The Netherlands: Wageningen Agricultural University.

Velkamp, A., & Fresco, L. O. (1995). Modeling land use dynamics by integrating biophysical and human dimensions (CLUE) Costa Rica 1973-1984. In S. Zwerver, R. A. v. Rompaey, M. T. Kok, & M. M. Berk (Eds.), Climate Change Research: Evaluation and Policy Implications (pp. 1413-1416): Elsevier Science.

Velkamp, E., Weitz, A. M., Starisky, I. G., & Huising, E. J. (1992). Deforestation Trends in the Atlantic Zone of Costa Rica: A case study. Land Degradation and Rehabilitation, 3, 71-84.

Wang, M., & Howard, P. J. (1993). Modeling errors in remote sensing image classification. Remote Sensing of the Environment, 45, 261-271.

Wilkie, D. S. (1989). Performance of a Backpack GPS in a Tropical Rain Forest. Photogrammetric Engineering and Remote Sensing, 55(12), 1747-1749.

APPENDIX A

Table A.1. Costa Rica 1991 forest cover assessment, thematic accuracy assessment

Classified Data	Reference Data			Row Total	Correct (%)	Commission (%)
	Forest	Non-Forest	Water			
Forest	28	4	0	32	88	13
Non-Forest	1	56	0	57	98	2
Water	0	0	0	0	N/A	N/A
Column Total	29	60	0	89		
Omission (%)	3	7	N/A			

Definitions:

Omission: Refers to the samples of a certain class of the reference data that were not classified as such.

Commission: Refers to the samples of certain class that were wrongly classified

User's Accuracy: The probability that a pixel classified on the image actually represents that category in ground, also known as reliability. Error of commission.

Producer's Accuracy: The probability of a reference pixel being correctly classified. Error of omission.

		95% confidence Limits	
		Lower	Upper
User's Accuracy (forest)=	88 %	73	100
Producer's Accuracy (forest)=	97 %	88	105
User's Accuracy (Defores)=	98 %	94	103
Producer's Accuracy (Defores)=	93 %	86	101
Sum of major diagonal=	84		
Overall Accuracy=	94 %		

Tau Coefficient Analysis (Ma & Redmond, 1995):

Interpretation:

1. T_e is an adjustment of percentage of agreement (P_o) by the number of groups and, as a measure of classification accuracy, it is independent of group size.
2. The Tau coefficient indicate that 89% more pixels were classified correctly than would be expected by random assignment. This means that based on the data collected we were correct 89% of the time.

$P_o=$	0.94	(Percentage agreement)
$P_c=$	0.62	
$K=$	0.85	(Kappa coefficient)
$P_r=$	0.5	
$T_e=$	89	

Kappa Hat coefficient analysis:

Sum $X_{ii}=$	84
Sum $X_{i+} * X_{+i}=$	4348
$N=$	89
$K(\text{Hat}) =$	88

Comparison:

Overall Accuracy:	94	%
Tau Accuracy:	89	%
KHAT Accuracy:	88	%

APPENDIX B

Geographic Information Data Generated During the 1991 Costa Rica's Forest Assessment

Coverage Type	Source	Year	Scale	Coverage	Digitized by
Forest Cover	Landsat TM	1991	1:250,000	National	N/A
1984 Land Use	Costa Rica's National Geographic Institute	1984	1:200,000	National	Clemson U.
Life Zone Division	Tropical Science Center	1995	1:200,000	National	CIEDES-UCR
National Roads	Costa Rica's National Geographic Institute	1983	1:50,000	National	CIEDES-UCR
Rural Roads	Costa Rica's National Geographic Institute	1983	1:50,000	National	CIEDES-UCR
Political Division	Costa Rica's National Geographic Institute	1983	1:50,000	National	CIEDES-UCR
Districts and Counties	Costa Rica's National Geographic Institute	1995	1:50,000	National	CIEDES-UCR
Elevation	Costa Rica's National Geographic Institute	1995	1:200,000	National	CIEDES-UCR
Watershed System	Costa Rica's Electricity Institute	1995	1:200,000	National	CIEDES-UCR
Dams and Reservoirs	Costa Rica's Electricity Institute	1995	1:200,000	National	CIEDES-UCR
Soil Classification	Costa Rica's Agriculture Ministry	1994	1:200,000	National	CIEDES-UCR
Agricultural Census	Costa Rica's Census Direction	1950, 1955 1963, 1973 1984	1:50,000	National	CIEDES-UCR