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Forest cover assessment, fragmentation analysis and secondary forest detection for the Chorotega Region, Costa Rica

by

©

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment for the degree of Master of Science

Department of Earth and Atmospheric Sciences

Edmonton, Alberta

Spring 2002

0-612-69680-4

University of Alberta

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Title of Thesis: Forest cover assessment, fragmentation analysis and secondary forest detection for the Chorotega Region, Costa Rica.

Degree: Master of Science

Year this Degree Granted: 2002

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Dedication

To Ariana

ABSTRACT

A forest cover assessment for the Chorotega region, Costa Rica (2000) was carried out at the regional and at the life zone levels using remote sensing and geographical information systems techniques. At the regional level, forest represents 45.1% of the study area (mainly secondary growth). At the life zone level, the tropical moist forest is the life zone with the largest forest area (58%). A forest fragmentation analysis was performed to determine the composition and configuration of forest patches. This analysis showed that fragmentation at the regional and life zone levels is the product of forest restoration rather than forest division. Finally, a novel methodology integrating ecology and remote sensing was used to map secondary growth within the Santa Rosa National Park, Costa Rica. By accurately mapping four successional stages within the Santa Rosa National Park this analysis showed the advantage of integrating both high and medium resolution satellite imagery.

ACKNOWLEDGMENTS

I would like to extend my sincere gratitude to my committee for their help and guidance. Special thanks to Dr. Arturo Sanchez-Azofeifa for his support and encouragement. As well, I would like to recognize Dr. Benoit Rivard for his overall contribution in this work, Dr. Colleen Cassady St. Clair and Dr. Peter Kershaw for their time and dedication in revisions in this thesis document.

I am sincerely grateful to Dr. Julio Calvo for his guidance, mentorship and inspiration to achieve my academic goals. As well, my sincere thanks to the following persons for their support and encouragement: Eugenio Gonzalez, Jorge Jiménez, Alfonso Mata, Quírico Jiménez and Ronnie de Camino.

I thank my wife Maritza Saborío for her constant patience, encouragement and love. I would like also to thank my mother for believing and praying for me everyday.

I would like to recognize the Regional Program of Graduate Fellowships in the Social Sciences funded by the John D. and Catherine T. MacArthur Foundation, The Ford Foundation, The William and Flora Hewlett Foundation for their financial support. As well, I thank the financial support of the Russell E. Train Education for Nature Program of the World Wildlife Fund (WWF) to achieve the research goals. Finally, a special recognition to The Tropical Science Center for the collaboration at many levels during my studies. As well, these Costa Rican organizations that collaborated in this study: Organization for Tropical Studies (OTS), Tropical Agricultural Research and Higher Education Center (CATIE), Guanacaste and Tempisque Conservation Areas and the Ministry of Environment (MINAE).

I owe special thanks to my Earth Observation Systems Laboratory colleagues for the support and friendship given to me and my family; Margaret Kalàcska, Tomas De Camino, Mark Kachmar, Robert Bechtel, Inian Moorthy, Steve Hamilton, Sheri Foley and Sanjay Shukla.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

Anthropogenic deforestation in tropical environments has had several ecological and biophysical impacts. Some of the most vulnerable tropical environments are the forest ecosystems located in the tropical dry and moist forests life zones. According to Ewel (1999), these two life zones have suffered the greatest amount of degradation due to their locations in areas favourable for agriculture and human settlement.

Life zones are bioclimatic units defined by mean annual biotemperature, rainfall and the potential evapotranspiration defined by the first two variables and a constant empirical value (Holdridge, 1967). Biotemperature is adjusted from the annual temperature to define a range where plants are able to grow (> 0 °C and < 30 °C). In the World Life Zones Classification by Holdridge, the tropical dry forest (*Td-f*) life zone is characterized climatically by six months per year that are effectively dry (Hartshorn, 1983). As well, it is characterized by an annual biotemperature greater than 24°C and a mean annual precipitation of 1,000 – 2,000mm (Holdridge, 1966). The vegetation of the *T-df* is shorter than in the rain forest, semideciduous and with two strata of trees (Hartshorn, 1983). In Costa Rica, the dry forest areas are mainly transitional zones to moist forest, but there exist some areas with pure dry forest (Bolaños and Watson, 1993). The tropical moist forest is characterized by an annual biotemperature of greater than 24°C and a mean annual precipitation of 2,000 – 4,000mm (Holdridge, 1966). The vegetation in mature moist forest stands is tall, multistratal, and semideciduous or evergreen (Hartshorn, 1983).

When the Spaniards first arrived to Mesoamerica, there were an estimated 550,000 km^2 of tropical dry forest formations on the Pacific side of lowland tropical Mesoamerica (Janzen, 1986). Within this vast extent, the tropical dry forest formations occupied much more of the Mesoamerican subcontinent than did rainforests. It is estimated that less than 2% of this tropical dry forest remains as relatively undisturbed wildlands, and only 0.08% of it lies within national parks or other kinds of protected areas (Janzen, 1986). As well, large extensions of tropical moist forest have been highly affected by deforestation processes in Costa Rica and, along with the tropical dry forest, were almost removed from the landscape (Sader and Joyce, 1988). During the period of 1966 to 1989, the tropical moist forest was the ecological life zone that lost the third largest area of forest (36.5%) after the dry (44.3%) and premontane wet forests (43.4%), respectively (Wendland and Bawa, 1996).

In Costa Rica, the tropical dry and moist forest life zones are located in the northwestern Guanacaste province (Chorotega region; Figure 1.1). Based on the 1998 Forest Cover Assessment and Cover Change derived from remote sensing analyses, the province of Guanacaste has 3,270 km^2 of forest cover, of which around 1,260 km^2 is tropical dry forest. The Guanacaste Conservation Area protects the largest remaining body of tropical dry forest remaining in Mesoamerica, but smaller and less defined areas of *Td-f* also exist in the Tempisque Conservation Area. Besides the protected areas, there are other extensions of dry and moist forest without any protection or conservation status. In addition, there is a lack of information about the state and management of these ecosystems, both in Costa Rica and Mesoamerica.

Uncertainty about the condition and dimensions of dry and moist forests in Costa Rica has hampered their management. The recent and burgeoning tools of remote sensing and geographical information systems have much potential to provide important information for managers (Sanchez-Azofeifa 1996). Several studies of deforestation, forest degradation, land cover and land use change using multitemporal satellite images have been done in the last five years in various ecosystems around the world (Tokola, 1999; Kuntz and Siegert, 1999, Michelson *et al.,* 2000). Costa Rica and other tropical areas (i.e. Brazil) have already been explored with Remote Sensing and Geographical Information Systems research (Sanchez-Azofeifa and Harris, 1994; Puig, 1996; Blanco and García, 1997; Bohlman *et al.*, 1998; Shimabukuro *et al.*, 1999), providing a solid foundation for subsequent and more detailed studies.

During the 1990's, various studies were conducted in Costa Rica combining these tools, mainly to monitor deforestation, habitat fragmentation and land use dynamics (Sanchez-Azofeifa, 1996). One common characteristic of these studies was the use of Landsat Multispectral Scanner (MSS) and Landsat Thematic Mapper (TM) images (Sanchez-Azofeifa and Harris, 1994; Kramer, 1996; Puig, 1996; Carlson and Sanchez-Azofeifa, 1999). Nevertheless, the tropical dry and moist forests have been studied much less frequently from the remote sensing and geographical information systems points of view. For example, only one study focusing on a dry forest ecosystem using remote sensing was carried out during the 1990's (Kramer, 1996).

Kramer (1996) indicated that some remote sensing and geographical information systems for the tropical dry forest are misclassification, and identified problems with geo-referencing, and both the phenological and physiological states of the vegetation. An additional limitation is that, atmospheric conditions at the time of image acquisition have affected the interpretations. For example, imagery acquired during drier months of the dry season increases the difficulty to discriminate between secondary forests and pasture lands. This is because the vegetation is deciduous in the dry season and there is much reflectance of ground and litter cover. In the wet season, satellite images show mainly cloud cover, so it is not feasible to use them (Figure 1.2). The effect of the phenology in the dry forest analyses was shown in 1998 when the most recent Forest Cover Assessment (FCA) of Costa Rica was carried out. Some issues could not be resolved using available remote sensing techniques (FONAFIFO-CCT-CIEDES 1998). One of the most significant limitations was the inability to identify different types of land cover in the tropical dry forest life zone (i.e. pasture lands, wood plantations, pristine forest, secondary forest, etc.). This is reflected in current maps that indicate the presence of pasture in areas that are in fact covered with tropical dry forest.

The following thesis presents a new FCA for the Chorotega region (Figure 1.1) in Costa Rica in which the following three questions are addressed:

1. What is the extent of the tropical dry and moist forests in the Chorotega region for the year 2000?
2. What is the level of fragmentation at the regional and at the life zone level in the study area?
3. Is it possible to detect different forest successional stages using remotely sensed data?

By answering these questions, this study will provide an improved approach for mapping tropical dry and moist forest ecosystems in Costa Rica. As well, this study will constitute the first fragmentation analysis for the Chorotega region. Finally this study presents a novel approach for the detection of secondary forests that may have application to other regions. This remainder of the thesis consists of three chapters. The following is a summary of the contents of each:

Chapter 1. Forest cover assessment and landscape structure analysis for the Chorotega region. This chapter presents an improved methodology to extract forest cover information by considering the acquisition date of the imagery based on the seasonality of the tropical dry and moist forests. As well, problems of misclassification are solved using a knowledge-based approach and a strong quality control process using colour aerial photography. A second section of this chapter analyzes the degree of fragmentation for the Chorotega region using not only basic fragmentation metrics such number of patches, mean patch size and patch size standard deviation, but also spatially explicit fragmentation metrics such as class division, percolation, entropy and homogeneity. Since the Chorotega region encompasses three different life zones with different ecological characteristics, the fragmentation analysis is also performed at the life zone level.

Chapter 2. Tropical dry secondary forest detection using IKONOS and Landsat ETM+ imagery. This chapter shows a novel methodology for detecting secondary forest in the tropical dry forest life zone. While most of the secondary forest studies using remote sensing techniques use chronological age to characterize the forest stand, I have employed an ecological approach to identify secondary forest. A definition of three successional stages is developed based on canopy closure, phenology and vertical and horizontal structure. Then, both medium and high spatial resolution imagery (IKONOS and Landsat ETM+, respectively) are used to extract the extent of the forest for each successional stage.

Chapter 3. Conclusions and recommendations. This chapter presents a general conclusion from chapter one and two about their contribution to conservation policies in Costa Rica. In addition, it integrates both methodologies to recommend the use of medium and high spatial resolution imagery, not only to extract the forest extent of a specific area, but also to produce more detailed information (i.e. secondary forest and deforestation fronts).

I expect that the information generated in this study on tropical dry and moist forest extent, fragmentation and secondary succession will provide to government agencies, Non-Governmental Organizations (NGOs) and other organizations, the necessary information to conduct better land cover change analyses aimed at prioritization of forested areas for conservation, research and management.

Chapter 1. Forest cover assessment and landscape structure analysis for the Chorotega region, year 2000.

1.1. Introduction

1.1.1. Land Use Land Cover Change in Costa Rica

Accurate forest cover assessments are important to define natural resource management strategies and policies for conservation in tropical regions (Sanchez-Azofeifa, 1996). It is through information about the location, the extent and the status of forest areas that threats to biodiversity ("hotspots") from deforestation fronts can be identified (Lambin and Ehrlich, 1997). The understanding of the effects of land cover changes through time is key to predict possible effects and then reduce environmental impacts over these areas. Remote sensing and geographic information systems are ideal techniques that can be used to determine deforestation trends (Sader and Joyce, 1988), identify terrestrial carbon sinks (Foody *et al.*, 1996) and forest fragmentation (Peralta and Mather, 2000).

Costa Rica is a tropical country with high biodiversity, but also with a history of severe environmental degradation. With its 51,000 km^2, Costa Rica encompasses approximately 6% of the world's biodiversity (Mendoza & Jiménez, 1995). However, this biodiversity has been threatened for decades. The country experienced severe landscape changes due to deforestation from the mid 1940's to the mid 1980's (Wendland and Bawa, 1996; Sanchez-Azofeifa *et al.*, 1997). This deforestation started where topography, weather conditions and good accessibility allowed for an easy transformation of forest to pasture and agricultural areas. These conditions are found in areas located in the tropical dry (*T-df*) and moist (*T-mf*) forest life zones (Ewel, 1999).

Starting in the mid 1940's a livestock subculture was established. The national and international meat prices increased and the government supported the conversion of forest to pasturelands through loans (Solorzano *et al.*, 1992). By the early 1960's most of the *T-df* and the *T-mf* areas located in the province of Guanacaste were almost removed (Sader & Joyce, 1988; Hartshorn, 1989). This degradation process extended to other regions of the country until the late 1970's and early 1980's, when a slowdown in the deforestation process began due to economical reasons and the development of conservation policies. Based on an extensive review and analysis of economic development policies and change in land cover use, Sanchez-Azofeifa (2000) outlined the main economic reasons driving the decrease in the deforestation process. Sanchez-Azofeifa (2000) noted that a decrease in the international price of meat resulted in the elimination of the government-supported loan programs for cattle grazing during the 1970's. As well, new policies were implemented between 1974-1978 aimed at transforming the national economy from agrarian to industrial. In the decade of the 1970's the result was a decline in the contribution of the agricultural sector to the country's gross national product (GNP) while the contribution of the industrial sector increased.

In addition, recommendations by national and international experts and organizations noting the chaotic situation of the nation's natural resources resulted in new conservation policies (Castro and Arias, 1998). Consequently, from 1974 to 1978 protected areas increased from 3% to 12%, an improved forestry law was implemented in 1979, and incentives for reforestation and forest protection were implemented (Castro and Arias, 1998). The effect of these changes during the 70's and 80's and a rapid growth in tourism in the early 90's allowed the regeneration of large forest areas (Damon & Vaughan, 1995). Currently, protected areas account for approximately 28% of the national territory (Mendoza & Jiménez, 1995).

1.1.2. Mapping efforts and current problems

Various efforts were carried out to quantify the forest cover of the country at different times. Initial studies used maps and aerial photography and were followed by the use of satellite imagery from sensors such as Landsat MSS and Landsat TM (Sader and Joyce, 1988; Sanchez-Azofeifa, 1996; TSC-CIEDES-CI/FONAFIFO, 1998). In addition, studies of habitat fragmentation (Kramer, E. 1996; Sanchez-Azofeifa *et al.*, 1999) and its effects on biodiversity were carried out for specific areas within the country.

Despite the number of studies on the forest cover in Costa Rica, problems remain in the use of remotely sensed data for mapping vegetation. One such problem is the detection of tropical dry (*T-df*), premontane moist (*Tp-mf*) and moist (*T-mf*) forests and their successional stages in the Chorotega region (Figure 1.1) (TSC-CIEDES-CI/FONAFIFO, 1998).

The inability to detect tropical dry and moist forest vegetation using remote sensing data may be the cause of the underestimation of a significant amount of forest, not only in the Chorotega region, but worldwide (Sanchez-Azofeifa *et al.*, 2001). Vegetation characteristics during the peak of the dry season in Costa Rica (February, March and April) when available satellite data is cloud free, causes confusion between early successional stages and pasturelands (Kramer, 1996; Pfaff *et al.*, 2000). The reason is that a high percent of the vegetation in the dry forest and somewhat less of a percentage in the moist forest is deciduous (Hartshorn, 1983). Early successional stages show a composition of trees and pasture that are similar in their spectral signatures, when observed by the Landsat MSS and TM sensors, to pasturelands with sparse trees and some agricultural fields (dry season). This problem is observable in the Costa Rica 1979 1992 land cover change assessment (Instituto Meteorologico Nacional *et al.*, 1996). The Instituto Meteorologico Nacional *et al.* (IMN) study based on Landsat MSS from 1979 (80 m. spatial resolution, 4 spectral bands) and Landsat TM from 1992 (28.5 m. spatial resolution, 7 spectral bands) satellite data led to the misleading interpretation of forest cover in 1979 and 1992 in areas of dry and moist forest located in the Chorotega region. Contrary to the IMN study results, the land use cover change for that region shows that by 1979 moist and dry forest present in these regions were almost removed (Sader & Joyce, 1988; Solorzano *et al.*, 1992; Sanchez-Azofeifa, 2000). Moreover, by 1992 a large area of modified moist and dry forest was growing back after changes in conservation policies; pasture abandonment and tourism growth (Damon & Vaughan, 1995, Wendland & Bawa, 1996, Sanchez-Azofeifa, 2000). Therefore, it is likely that in 1992, large areas of moist and dry forest (approximately 10 years old) were underestimated (Chorotega region) because imagery acquired during the dry season was employed for the analysis (Instituto Meteorologico Nacional *et al.*, 1996). Many areas were classified as secondary forest, natural forest and selective extraction forest in 1979, and classified as pastures in 1992. In addition, areas classified as pastures in 1979 were classified as forest in 1992 (not secondary forest, but mature forest).

A second problem related to the inability to map dry and moist forests in the Chorotega region is the lack of information about the current state of forest fragmentation. Information on the structure of the landscape (composition and configuration) obtained from forest patches is beneficial for assessing the loss of biodiversity and the connectivity of the landscape (McGarigal and Marks, 1994). The quantification of the number, size and variability in terms of forest patches size (McGarigal and Marks, 1994) and spatially explicit metrics such as percolation (Hori, 1989). Consequently, from 1974 to 1978 protected areas increased from 3% to 12%, an improved forestry law was implemented in 1979, and incentives for reforestation and forest protection were implemented (Castro and Arias, 1998).

The following paper has two objectives: (1) to determine accurately the forest cover for the year 2000 for the Chorotega region, Costa Rica using Landsat ETM+ (January, 2000), and (2) to perform a landscape structure analysis for the Chorotega region at the regional and at the life zone level (Appendix A), based on the information derived from the forest assessment.

1.2. Methods

1.2.1. Data acquisition and preprocessing

A forest cover assessment for a section of the Chorotega region was performed using a Landsat ETM+ (28.5 m resolution and 7 spectral bands plus one panchromatic) image for path 16 and row 53 (WRS-2) (Figure 1.1). As well, a forest fragmentation analysis was carried out for the entire study area at the life zone level. The analysis at the life zone level compares the landscape structure (composition and configuration) for the three major life zones in the study area; Tropical Dry Forest (*T-df*), Tropical Moist Forest (*T-mf*) and Tropical Premontane Moist Forest (*Tp-mf*) (Figure 1.3).

Due to the effect of the climate on the phenology of the forest ecosystems present in the study area (deciduousness), an image from January 2000 was used. Although some vegetation is deciduous at this time, a considerable amount of trees still have their leaves on, allowing the sensor to detect more green biomass than if an image from the drier months were used (Figure 1.3b-d).

To cast the raw data in a coordinate system, the Landsat image was orthorectified using a previously corrected Landsat image (P15R53/1997/TM5) and a digital elevation model (DEM). The DEM with a resolution of 30 x 30 meters was developed by the GIS laboratory of the Tropical Agricultural Research and Higher Education Centre (CATIE – Costa Rica). Fifty-control points were selected from the 1997 scene for the orthorectification process. A non-linear transformation - second order polynomial - was applied to rectify the image to Lambert Conformal Conic (Spheroid Clarke 1866). The mean root square error for the orthorectification process was 0.63 pixels (~20 meters).

Pixels occupied by clouds are localized in the northeast section of the image and were masked out through an unsupervised classification. An atmospheric correction was not applied since it was considered unnecessary for the classification of a single image (Song et al., 2001).

1.2.2. Image classification.

A supervised classification method was selected to extract the different land cover classes (forest, non forest, mangroves and water bodies) in order to integrate the resultant map into the Forest Cover Assessment for Costa Rica in 2001 However; only the forest data cover is used for further analysis in the present study.

Ground data was used to capture the spectral signatures for the supervised classification (ERDAS, 1999); whereby, groups of pixels, corresponding to areas that were visited on the ground were selected on the image to become "training sites". These "training sites" were contiguous pixels that could be used as inputs for the supervised classification. A total of 209 training areas were created, each of which represented one of the three classes in the field (forest, pastures and mangroves). These classes were defined by starting at the training sites and then adding neighboring pixels until the desired area was obtained based on the Euclidean distance (ERDAS, 1999). Those areas whose signatures did not have a Gaussian distribution for each spectral band were rejected. The spectral signature of every cluster was plotted and then the features with similar spectra were grouped into a specific land cover class. In order to determine class separability an analysis of variance (ANOVA) was applied (Steel *et al.*, 1997).

A parallelepiped decision rule was selected for the classification, applying parametric rules for unclassified and overlapping pixels. A maximum likelihood (Bayes criteria) method was chosen as the classifier system (ERDAS, 1999). This criterion assumes that there is an equal probability that a pixel belongs to a specific class, and each class represents a normal distribution (Tou and Gonzalez, 1974). Figure 1.7 shows the steps followed in order to classify the Landsat ETM+ image.

1.2.3. Training sites, misclassification problems and minimum mapping unit

The number (*N*) of training sites for the Landsat image classification was based on the binomial probability theory and the expected percent accuracy (Sanchez-Azofeifa, 1996; Fahsi *et al.*, 2000). Although it was determined that twenty-three points per class were enough to obtain an accuracy of 85%, a total of 209 ground sites were collected during

May and June 2000 to increase the sample reliability. Ground site information was collected in May and June, a time when green vegetation is present in the deciduous forest. The training sites were selected based on the road network, which covers most of the study area (Figure 1.4). Ground data was gathered in homogeneous sites at least 1-hectare in size (based on field observations), which is represented in the Landsat image by approximately a 9 x 9 window of pixels. The coordinates (datum NAD27 Central America) of every site were recorded using a Global Positioning System (Trimble III Geoexplorer). The GPS error was within 30 meters (~1 pixel in Landsat ETM+) after removal of the selective availability imposed by the U.S. government in June 2000. In addition, pictures were taken to document the training sites.

Although the objective of this study is a forest non-forest classification, training sites included forest areas of different successional stages, ranging from young secondary forest to old mature forest. This data is useful in providing a general qualitative idea of primary and secondary forest predominance in the region. Also, pastures with and without shade as well as pure stands (i.e. mangroves) were included in the sample of the training sites. The youngest successional stage considered as forest is represented by homogeneous areas where trees are taller than 6 meters (Pacheco, 1998; TSC-CIEDES-CI/FONAFIFO, 1998). The studies by Pacheco (1998) and TSC-CIEDES-CI/FONAFIFO (1998) indicate that a secondary forest with lower tree heights is less dense and includes considerable areas of pastures. For this study, forest is considered as those areas where the trees and shrubs are dense enough to eliminate patches of pasture.

In the mountainous region of the study area, some of the forest area was initially incorrectly classified as mangroves. The misclassification of forests and mangroves results from the spectral similarities of these forest cover types (Figure 1.5). However, by incorporating ancillary information, including altitudinal range information from the DEM, the misclassified areas were corrected. Mangrove classes located at elevations greater than 10 m were reclassified as forest. Once the image was reclassified, a visual quality control process was performed, comparing the classified image with the original satellite image and colour aerial photography from 1998.

In order to define the minimum mapping unit for this study, two approaches were chosen. The first approach considered the landscape structure analysis based on life zones. Therefore, two majority filters, 90% and 100%, were applied to the classified image. The function of these filters was to reclassify single pixels surrounded by 90% or 100% of pixels from a different class (Figure 1.6). This step allowed for the reclassification of single pixels into a more homogeneous area without causing large changes in the landscape configuration. The second approach considered the integration of this classification into the Costa Rica Forest Cover Assessment for the year 2000, which established a standard minimum mapping unit of three hectares.

1.2.4. Validation.

Validation points selected from two databases (statistically independent from the training data) were used for the accuracy assessment. The first database was provided by the Tropical Science Center (TSC) and was used for the classification and validation processes of the 1998 Costa Rica forest cover assessment. A description of this database can be found in TSC-CIEDES-CI/FONAFIFO (1998). A second database was provided by a research project located within the study area (Tempisque River basin), which was conducted by the Organization for Tropical Studies (OTS). The field information from the study carried out by the OTS was collected in the year 2000.

A total of 204 ground control points were used for validation (OTS and TSC databases) exceeding the minimum sample size needed (Sanchez-Azofeifa, 1996; Fahsi et al., 2000). Since a single pixel is not considered spatially representative of a class, a 3 x 3 pixel window was defined for validation purposes (Congalton and Green, 1998).

1.2.5. Accuracy assessment.

In order to calculate the accuracy of the classification, the verification data (validation points) was compared with the classification data using an error matrix or contingency table (Sanchez-Azofeifa, 1996). The robustness of accuracy estimators can vary (Fahsi *et al.*, 2000), thus six estimators were used including; class average (Congalton and Green, 1998), overall accuracy (Congalton and Green, 1998), Kappa (Congalton and Green, 1998), Tau (Ma and Redmond, 1995), and two new estimators *Juni*(X) and *Jpro*(X) developed by Nisshi and Tanaka (1999) (Appendix B).

1.2.6. Structure analysis of the landscape at the regional level and at the life zone level

Fragmentation for the *T-df*, *T-mf* and *Tp-mf* was analyzed according to a number of selected metrics that describe the landscape composition and configuration. Composition was measured based on class area (CA), while configuration was measured with the number of patches (NP) and the mean patch size (MPS). The variation in patch size was measured in absolute terms through the mean patch size standard deviation (MPSS). Because fragmentation metrics such as number of patches, patch size standard deviation are not spatially explicit (McGarigal and Marks, 1994), other fragmentation metrics were added to the analysis. In order to measure the heterogeneity of the landscape the homogeneity index was calculated (Hütt and Neff, 2001). Entropy was applied to compare the spatial organization among life zones regions (Wolfram, 1983), while percolation was applied in order to measure landscape connectivity (Hori, 1989). Class division (De Camino and Sanchez-Azofeifa, 2001) was used to give a spatial context to the results from number of patches. Table 1.1 shows the different metrics used for the fragmentation analysis.

1.3. Results

1.3.1. Forest cover assessment for the Chorotega region

The supervised classification of the Landsat ETM+ extracted 4,428 km^2 (45%) of forest and 5,179 km^2 (53.6%) of non-forest (Table 1.2). The forest area extracted in the present study exceeds by 1153 km^2 the area extracted in the last Costa Rican Forest Cover Assessment for the same region by TSC-CIEDES-CI/FONAFIFO (1998) which was 3,397 km^2. In this current study 75% of the ground control points used for classification and validation purposes were labeled as secondary forest. Therefore, most of what was classified as forest is not primary forest but secondary forest in various successional stages. This observation is supported by the land cover change history of the study area (Sader & Joyce, 1988). Most of the secondary forests are the results of pastures abandoned 20 to 25 years ago (Watson *et al.*, 1998).

The overall accuracy obtained for this classification is 89%. A similar value to overall accuracy is obtained when *Jpro*(X) is applied (88%). An advantage of *Jpro*(X) is that this estimator takes into account the proportion of points per class, therefore, it is considered a better estimator of accuracy. Contrarily, the lowest accuracy is obtained using *Juni*(X) (61%), which does not consider the proportion of validation points per class (Table 1.3).

The commonly used *KAPPA* and Tau estimators show a lower accuracy (≅ 80%) than the overall and *Jpro*(X) estimators.

The accuracy per class (Table 1.4) is very high for forest and non-forest, 90% and 93% respectively. In addition, results from the class separability analysis show that spectrally the classes are different ($p<0.001$) (Table 1.5).

1.3.2. Forest cover by life zone

The three life zones analyzed in this study, represent 95% of the study area. The premontane moist encompasses 42.6%; followed by the tropical moist (38.2%) and tropical dry (14.2%) forest life zones (Table 1.6).

The forest cover analysis per life zone (Figure 1.8) reveals that the tropical moist forest is the life zone with the highest forest area (58%) and the second largest non-forest area (42%). The tropical premontane moist forest encompasses the largest non-forest area (62%) due to its flat topography, where the current land use is agriculture (i.e. rice, sugar cane) and pastures. The forest area encompasses 54% of the tropical dry forest life zone, while 46% corresponds to non-forest. As in the premontane moist forest some areas of the dry forest are under agricultural and cattle grazing practices. However, areas in mid to steep slopes are under recover.

1.3.3. Fragmentation analysis for the study area

Since much of the forest cover in the study area is secondary growth, fragmentation processes are not the result of landscape division, but the results of landscape restoration. The summary of the results can be found in Table 1.7 and Table 1.8.

Although some landscape metrics reveal fragmentation values characteristic of highly fragmented landscapes (i.e. number of patches, class division), due to recuperation processes, large forest patches in the region affect other metrics revealing an organized and connected landscape (i.e. edge density, percolation, entropy).

The fragmentation statistics reveal a high number of patches in this region (47,535), along with a high patch size variability related to the patch size standard deviation (865 ha). Large forest fragments result from the establishment of protected areas in the 70's encompassing large forested areas (i.e. Santa Rosa National Park, Palo Verde National Park) and from the abandonment of pasture lands with medium and high slopes where cattle grazing was not economical feasible. Consequently, secondary growth formed large continuous forest patches. It is possible to find very small forest patches, but also large continuous masses of forest. Since no minimum mapping unit was applied, even the small patches (0.078 ha) are captured by the analysis. A frequency distribution of the number of patches (expressed as area) is shown in Figure 1.9.

An estimate of homogeneity shows that the landscape is very heterogeneous (0.87) (Table 1.8). In addition, a high-class division was obtained for forest areas (0.87) (Table 1.8). Heterogeneity and class division results can be related with the high number of patches and the high patch size standard deviation for both forest and non-forest classes.

The percolation results show a high percolation value (0.90) (Table 1.8), indicating the presence of large continuous forest areas.

1.3.4. Fragmentation analysis per life zone

The results for the landscape structure analysis for three life zones (95% of the study area) are presented in the following section. Since life zones represent ecosystems with different characteristics such as climate, land use and vegetation, fragmentation or restoration processes may differ. In addition, life zone subregions are distributed over the landscape in areas with different topography, land cover and land use history and accessibility. Therefore, results of fragmentation are shown for the different life zone subregions.

1.3.4.1. Premontane moist forest (Tp-mf)

Four *Tp- mf* subregions within the study area were analyzed (Figure 1.10). Results showed that more than 50% of the *TP-mf* is located at elevations below 100 meters. The maximum altitudinal range for this life zone is 300 meters (Figure 1.11a). However, forest areas are mainly (> 70%) located at altitudes less than 100 meters for three regions within the *Tp-mf*. An exception is the biggest subregion of this life zone (TPMF1), which represents 89.7 % of the total life zone area (Figure 1.10). The forest in this area is distributed along different altitudinal ranges (Figure 1.11b). TPMFI covers a variety of altitudinal areas, from mountainous regions close to the volcanoes to secondary growth and protected forest areas in lowlands.

Most of the *Tp- mf* is located on slope from 0 to 15 degrees (Figure 1.11c). The forested area is located mainly in this slope range as well. The exception is a small subregion

(TPMF3) that has irregular topography (Figure 1.11d). This small subregion is an example of flat areas under intensive or extensive land use with forest recuperation in more irregular terrains, due to abandonment 15 to 20 years ago.

Fragmentation results for *Tp- mf* indicate a relationship between the size of the subregion in the life zone and the number, size and variability metrics (number of patches, mean patch size and patch size standard deviation). As the area of the subregion increases the values for the aforementioned metrics also increase. For example, TPMF1 that covers most of the *Tp-mf* area (89.69%) (Table 1.9) shows the highest values for the number of patches (19, 248) and mean patch size (6.8 ha). However, regardless of the size of the *Tp-mf* subregion, deforestation and recuperation processes occurred simultaneously for every region within this life zone.

As was the case for the regional analysis, the *Tp- mf* shows a high variability in patch sizes. This is indicated by the high value for patch size standard deviation in the larger subregion of this life zone, TPMF1 and TPMF2 (252.1 ha and 51.7 ha, respectively) (Table 1.9).

The results from the spatially explicit metrics show a trend where the values of class division increase as the number of patches increases (Figure 1.12a). For this landscape the subregions with the greatest number of patches (TPMF1 & TPMF2) are showing significant class division values (close to 1). These two areas are under agriculture and pasture practices in flat and moderate slope areas. In addition, secondary growth is present in irregular terrain without a specific pattern (patchy).

A homogeneity value greater than 0.85 for all the *Tp-mf* subregions shows two characteristics of the landscape for this life zone. First, even the four subregions varies in size, the variation of homogeneity among them is very small (Figure 1.12b). Second, homogeneity values indicate that the life zone is very heterogeneous, which is explained by the high variation in patch size.

Percolation shows values close to 1 in areas with large fragments of continuous forest (Figure 1.12c). The lowest percolation value is in TPMF2 (0.73). The forest in this area is located along the coast, and presents forest remnants of various ages. The areas more to the interior are in an agricultural region where the forest is located along the river network and in sparse fragments with low connectivity.

The lowest value of entropy is in TPMF1 (0.16), while the maximum value is presented by TPMF2 (0.40) (Figure 1.12d). This means higher spatial organization in TPMF1 than in TPMF2, which is explained by the presence of larger patches in TPMF1 with a higher patch size standard deviation (mean patch size).

1.3.4.2. Tropical moist forest (T-mf)

The five regions that encompass the Tropical moist forest within the study area are presented in Figure 1.13. Areas located in the Guanacaste and Tilaran Cordilleras base, and the Nicoya Peninsula presents a wide elevation range: 0 to 1000 meters (Figure 1.14a). Only one subregion (TMF4) located in the northern margin of the Tempisque River shows a narrow elevation range (located at elevations lower than 300 meters). For the subregions located at the Guanacaste and Tilaran Cordillera base, forest is mainly located in the elevation range of 500 to 600 meters. The other elevation ranges in these subregions, with a significant amount of forest are 400 to 500 meters and 600 to 700 meters. In the subregion north of the Tempisque River the forest is located mainly in the 0 to 100 meter range (Figure 1.14b).

Slope results indicate that more than 70 % of the life zone is located in the range from 0 to 15 degrees slope for all the subregions (Figure 1.14c). As well, the forest area is also predominantly in this range of slope (Figure 1.14d). The subregion located on the Nicoya Peninsula (TMF5) shows forest in a wider range of slope. This could be explained by its significant extension, which represents 82 % of the total life zone area.

As it is found for the Premontane Moist Forest, the number of patches increases as the size of the subregion increases (Table 1.10). The results for mean patch size (from 5.6 ha to 16.0 ha) and patch size standard deviation (from 389.3 ha to 826.5 ha) indicate a high variability of patches. Large areas of secondary growth are common in this life zone. Additionally, small forest patches within agriculture and pasture areas are also present.

The region with highest number of patches (TMF5: 13,317) shows the highest class division value (0.96). Contrarily, the subregion located at the base of the Cordillera of Guanacaste (TMF1) shows the lowest class division value (0.30) (Figure 1.15a). This value is supported by the high patch size standard deviation in TMF5 (826.5 ha) and a lower patch size standard deviation in TMF1 (389.3 ha) (Table 1.10). In TMF1 there are continuous forest areas mainly located in high elevations with irregular terrain that were abandoned during the 1980's. In addition, it is also possible that some of the areas in this section were never deforested; resulting in well-defined forested areas. On the other hand, TPM5 has been greatly affected by deforestation processes. The restoration processes over the last 15 to 20 years have created an irregular pattern of forest patches.

Homogeneity results do not show great variability between the *T-mf* subregions (0.85-0.89) (Figure 1.15b). These homogeneity values show a landscape with a low level of heterogeneity. Percolation values (0.72-.94) reflect connectivity for the different subregions in this life zone (Figure 1.15c). As well, entropy values (0.30-0.36) do not vary between subregions. The predominance of large areas of forest in this life zone in the different regions explains the low variability of the values for these spatially explicit statistics.

1.3.4.3. Tropical dry forest (T-df)

Fragmentation results are presented for 7 subregions within the Tropical dry forest life zone (Figure 1.16). These subregions are located in an elevation range from 0 to 200 meters (Figure 1.17a) with the exception of TDF2 and TDF3. A similar pattern is seen in the forest cover within five subregions; more than 75% of the forest fragments is located at elevations lower than 100 meters (Figure 1.17b). For the other two subregions (TDF2 and TDF3), forest is present at elevations lower than 400 meters.

More than 75% of the *T-df* subregions are located in slope range of 0 – 10 degrees (Figure 1.17c). Most of the forest areas are also located in this range (Figure 1.17d). An exception is the forest located within the Santa Rosa National Park (TDF2). This area is characterized by very irregular topography, ranging from very flat with pastures to steep areas covered by forest. However, for all the regions it is possible to find irregular topography.

Fragmentation results show that in general the number of patches is related with forest area (Table 1.11). The subregion with the higher number of patches (3,096) encompasses Bagaces County (TDF3: 42.1% forest cover). Pastures, sugar cane and rice plantations are common in this subregion in flat terrains, while forested areas are located towards Tenorio and Miravalles Volcanoes in the mountainous regions. The subregion with the least number of patches is located on the Santa Elena cape (TDF1). Currently, that section is part of a protected area (Santa Rosa National Park).

The *T-df* life zone also presents high values for mean patch standard deviation (Table 1.11) that represents a landscape with great variations in patch size. Deforestation processes similar to the moist forest life zones occurred in the *T-df* (Sader & Joyce, 1988). Forest recuperation through secondary growth occurs in different ways in the *T-df*. Therefore, there is a variation in patch sizes for the different subregions (from 2.4 ha to 33.2 ha) (Table 1.11).

Class division presents the lowest value in the Santa Elena Cape (TDF1: 0.03), explained by a large continuous forest patch and a low number of patches in TDF1 (79) (Figure 1.18a and Table 1.11, respectively). This subregion is also less heterogeneous, showing a high homogeneity value (0.91) (Figure 1.18b). In contrast to TDF1, areas with agriculture and pastures show higher values for class division (TDF5: 0.93; TDF6: 0.92) (Figure 1.18a). As was the case for moist forest, homogeneity values do not show sensitivity between the *T-df* subregions (0.86-0.92) (Figure 1.18b). Percolation results indicate that most of the *T-df* subregions have high values (> 0.82), except for subregions TDF5 and TDF6 (0.57 and 0.21, respectively) (Figure 1.18c). These low percolation values are explained by the location of these two subregions: TDF5 is located in an agricultural area and TDF6 is in a mangrove area, both with isolated forest patches. Entropy results show no dramatic differences between life zone subregions (0.19-0.32) (Figure 1.18c). However, the higher entropy values are found in subregions with higher patch size standard deviations (i.e. TDF5 & TDF6).

1.4. Discussion

Sader & Joyce (1988) point out that deforestation occurred in the early 40's mainly in the tropical dry, premontane moist and moist forest life zones, which are located in the Chorotega region. Human activities such as forest to pasture lands conversion for cattle razing and agriculture were the main drivers of the natural resources depredation in these ecosystems. The anthropogenic effects have been continuously transforming the landscape through intensive processes of deforestation (Solorzano *et al*, 1992).

The forest area extracted in the present study for the Chorotega regions exceeds by 1,153 km^2 the area extracted in the last Costa Rican Forest Cover Assessment for the same region by TSC-CIEDES-CI/FONAFIFO (1998). The reasons for this difference in forest cover are:

- No filters were applied in the current classification in order to preserve a detailed representation of the landscape for the structure analysis. For the 1998 study, the classification results were filtered with a 3 x 3 window majority filter.
- The image used in this study is from January 2000; where there is a greater abundance of green biomass as compared to the March and May images used in the TSC-CIEDES-CI/FONAFIFO (1988) study.

There are, however, some problems regarding forest detection in the study area. The phenology of the different forest ecosystems is still a factor when satellite imagery is used to extract forest cover. It is likely that at the time of image acquisition (January) there is deciduous vegetation in the area that is leaf off in early successional stages (Janzen pers. comm.). At the time of image acquisition (January), there was still a considerable percentage of deciduous vegetation with leaves off, particularly in early forest successional stages (Janzen pers. comm.). A medium density of thin deciduous trees and the presence of shrubs characterize early successional stages (Pacheco, 1998). Therefore, the configuration of the landscape is such that the sensor detected areas of exposed soils (litter) and pastures within the forested areas. This leads to confusion between forested areas and pastures. Areas of low tree density with pastures and shrubs ("charrales") encompass a significant amount of recovering vegetation within the region that might not be counted by the present analysis.

The extent of forest cover at the life zone level shows that the tropical premontane moist (*Tp-mf*) forest has the largest forest area followed by the tropical moist forest (*T-mf*). The tropical dry forest also shows a substantial cover with a present forest area of 5,125 km^2. Most of the areas in these three ecosystems are secondary growth since they almost vanished from the landscape from the 1940's to the 1980's (Sader and Joyce, 1998), until some areas, which had been converted to pastures, were abandoned during the middle of the 1980's (Sanchez-Azofeifa, 2000). The abandonment process started in steep and medium slope areas where cattle grazing and agriculture practices were not profitable for the farmers (Berti, 2000). Therefore, the large continuous forest patches in these three life zones are shown by my results to be occurring in those areas.

Current threats to the secondary forest in the *T-df* life zone are natural and human induced forest fires (Janzen, 1988). In addition, current environmental problems such as deforestation of watersheds, water extraction by industry, irrigation, and human consumption (Echeverría *et al.*, 1998) in forest areas located in flat terrains (i.e.

Tempisque River basin), may severely affect these secondary regeneration in flat areas within the *T-mf* and the *Tp-mf.*

Forest fragmentation is generally analyzed as a process of division (Forman, 1997; Jagger, 2000). Fragmentation results in the study area show a high number of forest patches; which are highly variable in size and shape. This variability is the result of an unorganized natural restoration processes in the area. As a result, this restoration process is producing a fragmented landscape, which is itself the result of forest aggregation instead of forest division. For this reason, results of fragmentation can be misunderstood in the current study if the general context is analyzed. For example, only 7% of the total number of forest patches for the study area is smaller than 10 hectares and 14% is smaller than 100 hectares (Figure 1.9). The largest patches are found within protected areas. Those patches of continuous forest areas were protected as the last remnants of a specific life zone (i.e. Santa Rosa National Park-Tropical Dry Forest). Therefore, based on these results and the analysis of the data only from the fragmentation point of view, it can be thought that fragmentation is a current problem in the Chorotega region. In contrast, fragmentation in this context means that many of the forest areas are recovering, producing a fragmented forest landscape, when in the past there was no forest cover for most of the study area.

Spatially explicit statistics also confirm that the landscape is fragmented for the Chorotega region if a simple conception of fragmentation is used. For example, class division (0.8) is showing a divided landscape with high spatial organization as the consequence of a high number of small forest patches and large continuous forest in the same landscape. On the other hand, percolation (0.88) defines a high value of connectivity. Although there is a high percentage of small patches in the study area, the presence of large forest patches increase the percolation value. However, since different species of plants and animals require different spatial needs to survive, percolation can be interpreted as a measure of forest patch continuity in terms of area, rather than having an ecological meaning. In contrast to the idea that percolation gives about the landscape (i.e. low fragmentation), class division is still high. This is due to the presence of large continuous forest patches (high percolation value) and a high number of small patches (high class division – fragmented landscape).

Fragmentation at the life zone level also presents a process of forest aggregation and results cannot be interpreted as a forest division process. A general pattern is shown for the different life zones: the larger the life zone region is, the greater the number of patches and the standard deviation. The reason for this is that the lands use history is similar for these life zones: anthropogenic effects continuously affect areas in flat terrain, while areas in rough terrain are recovering. The results from the spatially explicit fragmentation metrics are not sensitive to differences between life zone regions and life zones in general. This is likely due to the presence of large forest patches that affect the values of percolation, homogeneity and entropy.

1.5. Conclusion and recommendations

1. The use of a Landsat ETM+ image of the transition from the rainy season to the dry season (January) in the Chorotega region is advantageous over images from the drier months for extracting forest areas. The interpretation of images form drier months can confuse the forest with pastures or crops. In addition, phenology is a

key factor that affects the perception of the sensor of the different forest ecosystems present in this region.

2. The fragmentation analysis for the study area shows a landscape where fragmentation is not caused by the degradation (division, shrinkage, perforation) of the forested areas. The Chorotega region has a considerable amount of area under natural restoration, producing a fragmented landscape in which fragmentation is a product of merging, growing and expansion processes. These restoration processes are linked to physiographic conditions such as slope, conservation policies (i.e. forest within national parks and other protected areas) and current land use. Moreover, areas with steep slopes are recovering faster due to pasture abandonment, while flat areas are still under pasture and agricultural practices (i.e. sugar cane, rice).
3. In terms of the life zones, the analyses show a similar pattern of restoration for the whole Chorotega region. Consequently, fragmentation metrics at the landscape level do not vary greatly for the different life zones. Metrics such as class division, percolation and entropy show a landscape that even though is fragmented (high class division), has a connectivity at a large scale (percolation). Due to the restoration process the landscape is also spatially organized (entropy).
4. The tropical premontane moist forest is the most affected ecosystem by the current land use, since most of this life zone is located in flat agricultural and pasture lands. The tropical moist forest, mainly located in the Peninsula of Nicoya and the tropical dry forest (*T-df*) located in different areas of Guanacaste are recovering mainly in protected areas and moderate to steep slope regions.

5. Secondary forest detection is still a challenge within the study area and mainly in the tropical dry forest life zone. However, it is proposed that with the use of ancillary information such as high-resolution data (i.e. aerial photography, IKONOS) it may be possible to distinguish different successional stages within the tropical dry forest. Moreover, since various studies in other tropical regions have found problems detecting secondary succession based on forest chronological age (Sader *et al.* 1989), the use and comprehension of the forest's structural characteristics could possibly aid the classification process. These structural characteristics should be based on the ecology of the forest and are related with vertical and horizontal canopy distribution, crown density and forest phenology.

Table 1.1. Formulas for the fragmentation metrics used for the analysis of the landscape structure at the regional level and at the life zone level.

Fragmentation metric	Formula	Source	Interpretation
Number of patches	NP = ni Units: none Range: > 1	McGarigal & Marks, 1994.	The minimum number of patches for a specific class must be greater than 1. Otherwise that class does not exist in the landscape
Mean patch size (ha)	$MPS = \frac{\sum_{j=1}^{n} a_{ij}}{ni}\left(\frac{1}{10,000}\right)$ Units: hectares Range: PD ≥ 0, without limit	McGarigal & Marks, 1994.	Sum of the area (m) of all patches of the corresponding class, divided by the total number of patches in that class.
Patch size standard deviation (ha)	$PSSD = \sqrt{\frac{\sum_{j=i}^{n}\left[a_{ij} - \left(\frac{\sum_{j=1}^{n} a_{ij}}{ni}\right)\right]^2}{ni}}\left(\frac{1}{10,000}\right)$ Units: hectares Range: PSSD ≥ 0, without limit	McGarigal & Marks, 1994.	Corresponds to the population standard deviation, high standard deviation values indicate high variability in patch size.
Homogeneity	$a_{ij} \rightarrow = \frac{1}{\lvert N_{ij} \rvert} \sum_{b \in N_{ij}} \Theta(a_{ij}, b)$	Hütt & Neff, 2001	High homogeneity values correspond to low heterogeneity
			Continued...

Spatial Entropy	$$H^b = \frac{1}{b}\sum_i p_i \log p_i$$ p_i is the probability of configuration i in a 3 x 3 window in the landscape, and b is the block size.	Wolfram, 1983	Higher values of H^b mean a higher degree of randomness in the landscape (low organization)
Percolation (0.001%)	$$p_s = \frac{p_2}{p_1}$$ p_2 and p_1 are the density of sites in state 2 (percolated) and 1 (occupied), respectively.	Hori, 1989	High percolation values can be related with high connectivity
Class division	$$D = 1 - \sum (p_i)^2 \text{ with } p_i = \frac{A_i}{\lvert L \rvert}$$ p_i is the probability that a random site belongs to a patch. A_i is the area of a patch and $\lvert L \rvert$ is total class area.	De Camino and Sanchez-Azofeifa, 2001	As class division approaches to 1, the class becomes more divided

Table 1.2. Land cover distribution for the study area, year 2000.

Type of cover	**Area (km^2)**	**% Area**
Non forest	5,179	52.7
Forest	4,428	45.1
Mangrove	1,309	1.3
Water	831	0.9

Table 1.3. Accuracy estimator results for the classification

Accuracy estimator	Accuracy (%)
Overall Accuracies A(X)	89
Kappa K(X)	78
Tau T(X)	80
Nisshi Estimator uniform priors Juni(X)	61
Nisshi Estimator proportional priors Jpro(X)	88

Table 1.4. Accuracy for the forest and non-forest classes

		Classification			
		Non-Forest	Forest	Total	Accuracy (%)
Validation	Non-Forest	106	12	118	90
	Forest	6	75	81	93
		112	87	204	

Table 1.5. ANOVA per Landsat spectral band based on twenty-three windows of 9 x 9 pixels.

ANOVA Band 3

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value <*	*F crit*
Between Groups	20,315.3	2	10,157.7	74.7	0.001	3.0
Within Groups	89,893.0	661	136.0			
Total	110,208.3	663				

ANOVA Band 4

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value <*	*F crit*
Between Groups	12,977.6	2	6,488.8	45.6	0.001	3.0
Within Groups	94,075.4	661	142.3			
Total	107,053.0	663				

ANOVA Band 5

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value <*	*F crit*
Between Groups	228,392.1	2	114,196.1	268.9	0.001	3.0
Within Groups	280,738.0	661	424.7			
Total	509,130.2	663				

ANOVA Band 7

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value <*	*F crit*
Between Groups	69,276.0	2	34,638.0	197.8	0.001	3.0
Within Groups	115,777.0	661	175.2			
Total	185,053.0	663				

Table 1.6. Life zone coverage within the study area

Life Zone	**Area (km2)**	**Area (%)**
Lower montane rain forest (*TLM-rf*)	5	0.1
Tropical wet forest (*T-wf*)	5	0.1
Premontane rain forest (*Tp-rf*)	20	0.2
Premontane wet forest (*Tp-wf*)	438	4.7
Tropical dry forest (***T-df***)*	1,332	14.2
Tropical moist forest (***T-mf***)*	3,582	38.2
Premontane moist forest (***Tp- mf***)*	3,995	42.6
Total	**9,377**	**100**

* Life zones analyzed.

Table 1.7. Fragmentation metrics for the regional analysis

Cover type	Class area (ha)	Number of patches	Mean patch size (ha)	Patch size standard deviation (ha)
Non-Forest	4,972.9	50 753	9.8	11.4
Forest	4,249.9	47 535	8.9	8.7

Table 1.8. Fragmentation statistics for the regional analysis (Forest class)

Homogeneity	0.87
Entropy	0.32
Percolation (0.001%)	0.90
Class division	0.80

Table 1.9. Forest fragmentation statistics for the four regions of *Tp-mf* in the province of Guanacaste and the Peninsula of Nicoya

Area	CA (ha)	NumP	MPS (ha)	PSSD (ha)	% of TA
TPMF1	131,513.4	19,248	6.8	252.1	89.69
TPMF2	9,646.3	1,989	4.8	51.7	6.58
TPMF3	252.1	7	0.0	0.0	0.17
TPMF4	5,189.2	847	0.0	0.0	3.54

CA	Class Area
NumP	Number of patches
MPS	Mean patch size
PSSD	Patch size standard deviation
% of TLA	Percentage of total area

Table 1.10. Forest fragmentation statistics for the four regions of *T-mf* in the province of Guanacaste and the Peninsula of Nicoya

Area	CA (ha)	NumP	MPS (ha)	PSSD (ha)	% of TA
TMF1	13,480.5	840	16.0	389.3	6.80
TMF2	1,697.2	304	5.6	31.4	0.86
TMF3	15,969.3	2,255	7.1	105.0	8.06
TMF4	4,662.8	733	6.4	102.5	2.35
TMF5	162,322.4	13,317	12.2	826.5	81.93

CA	Class Area
NumP	Number of patches
MPS	Mean patch size
PSSD	Patch size standard deviation
% of TLA	Percentage of total area

Table 1.11. Forest fragmentation statistics for the four regions of *T-df* in the province of Guanacaste and the Peninsula of Nicoya

Area	CA(ha)	NumP	MPS (ha)	PSSD (ha)	% of TLA
TDF1	2,624.2	79	33.2	287.6	5.1
TDF2	12,732.3	1,940	6.6	136.4	24.8
TDF3	21,608.3	3,096	7.0	157.1	42.1
TDF4	10,751.0	1,556	6.9	88.0	20.9
TDF5	1,311.2	367	3.6	16.4	2.6
TDF6	537.4	227	2.4	9.8	1.0
TDF7	1,799.8	204	8.8	85.2	3.5

CA Class Area
NumP Number of patches
MPS Mean patch size
PSSD Patch size standard deviation
% of TLA Percentage of total area

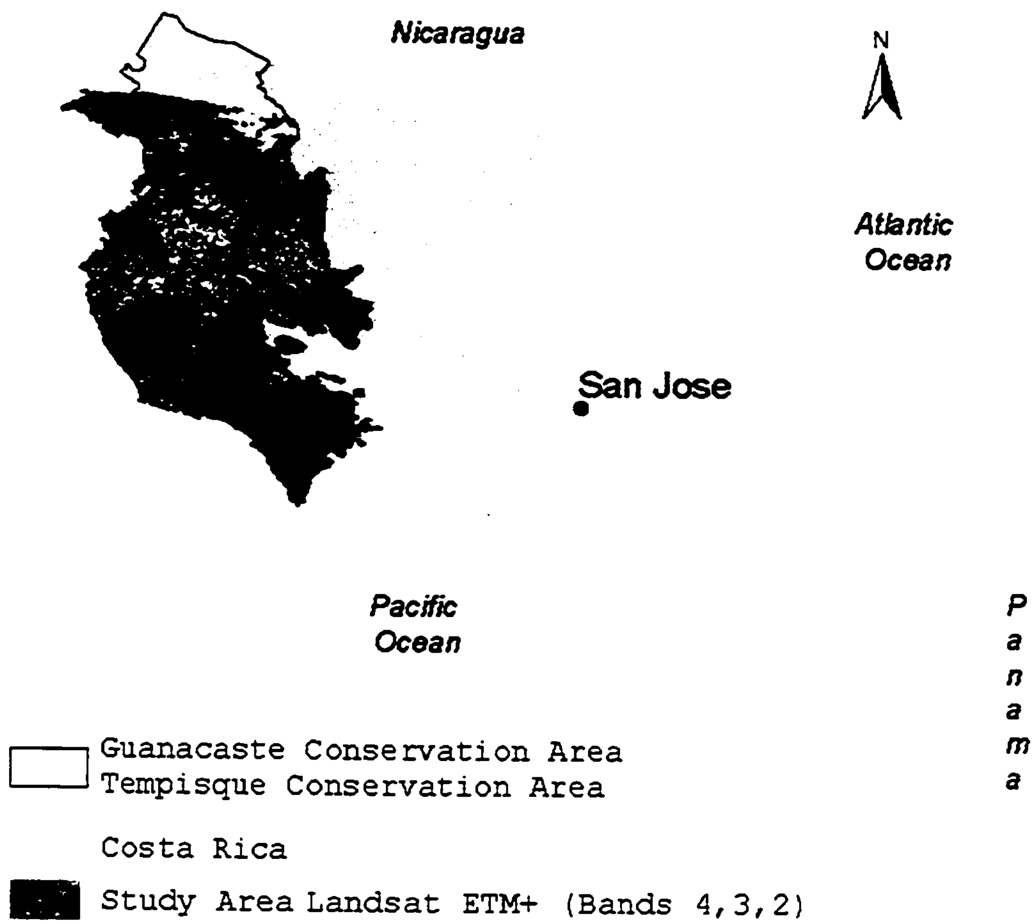


Figure 1.1. Study area for forest/non-forest detection using a Landsat ETM+ image (January 27, 2000)

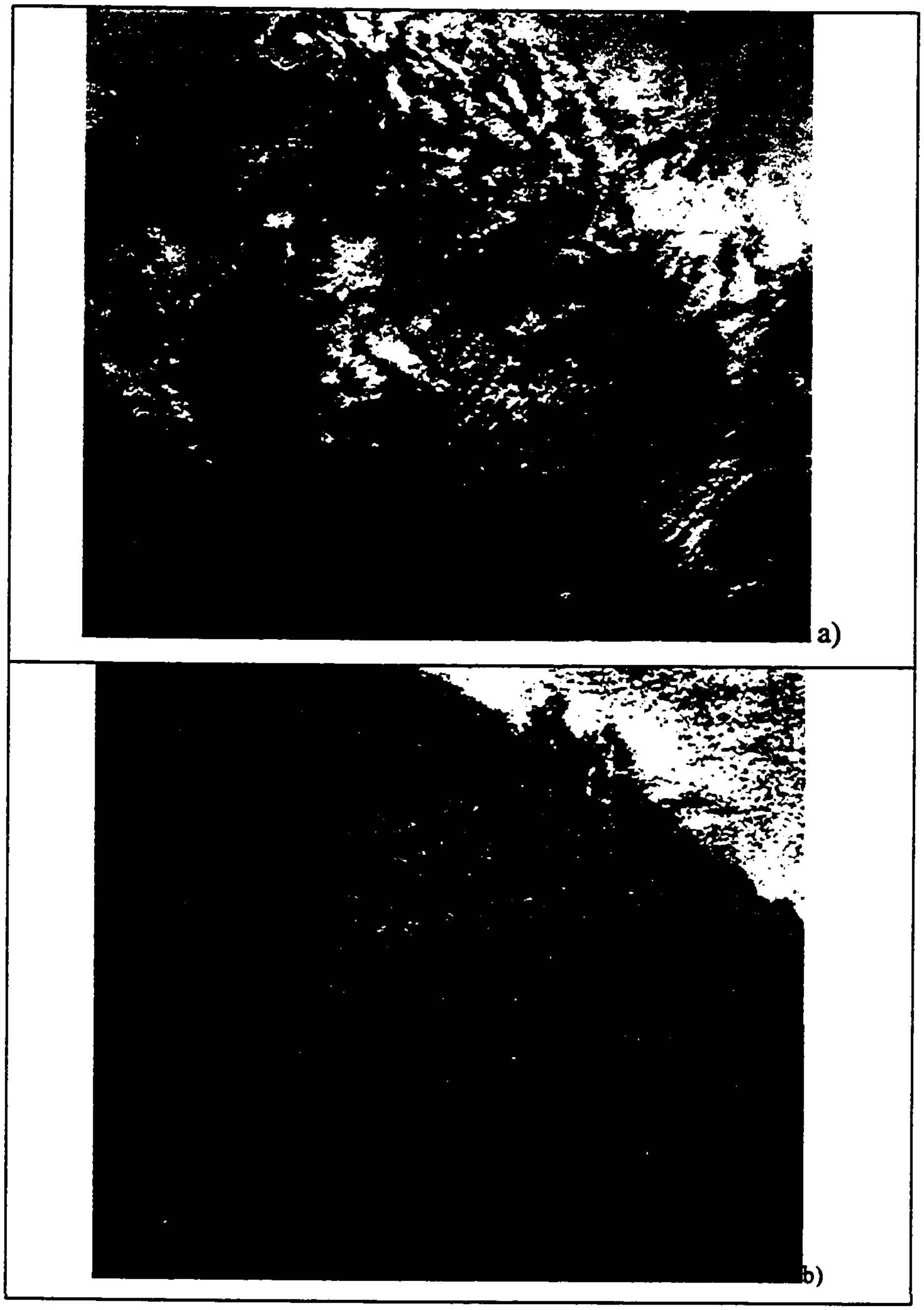


Figure 1.2. Landsat ETM+ images from a) Wet season (December, 2000) and b) Dry season (April, 2000).

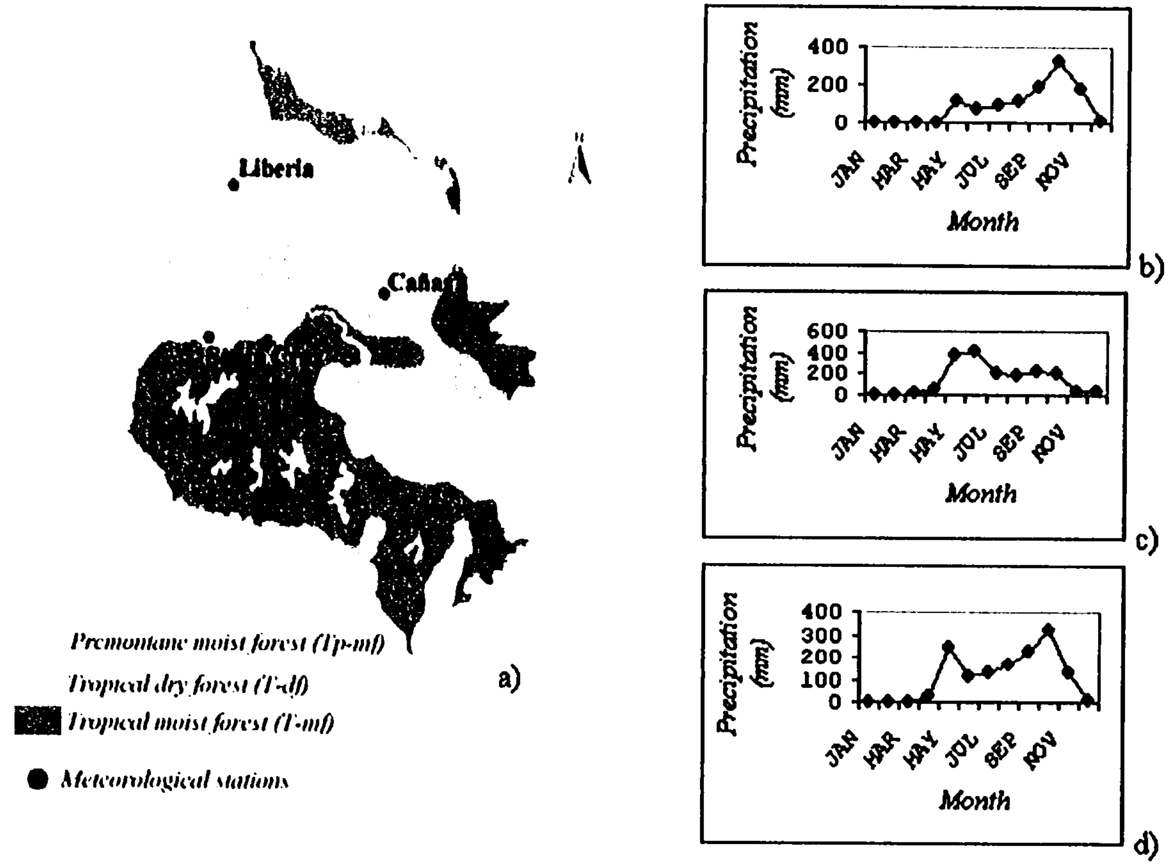


Figure 1.3. Study area: a) Life Zone map and location of meteorological stations. b) Precipitation data forLlano Grande Station - Liberia (19C7-1990). c) Precipitation data for the Santa Cruz Station (1937-1991) d) Precipitation data for the Ingenio Taboga Station in Cañas (1968-1990).

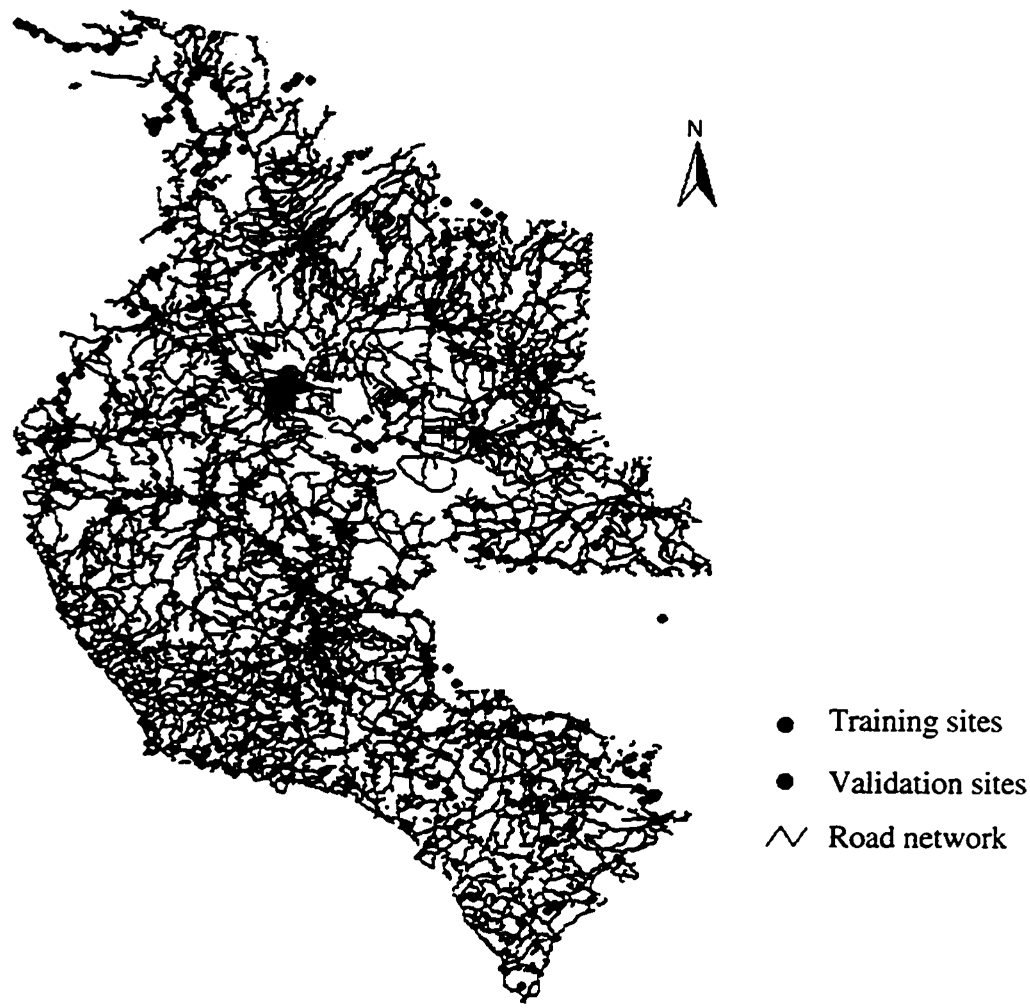


Figure 1.4. Study area: road network, location of training sites and validation sites.

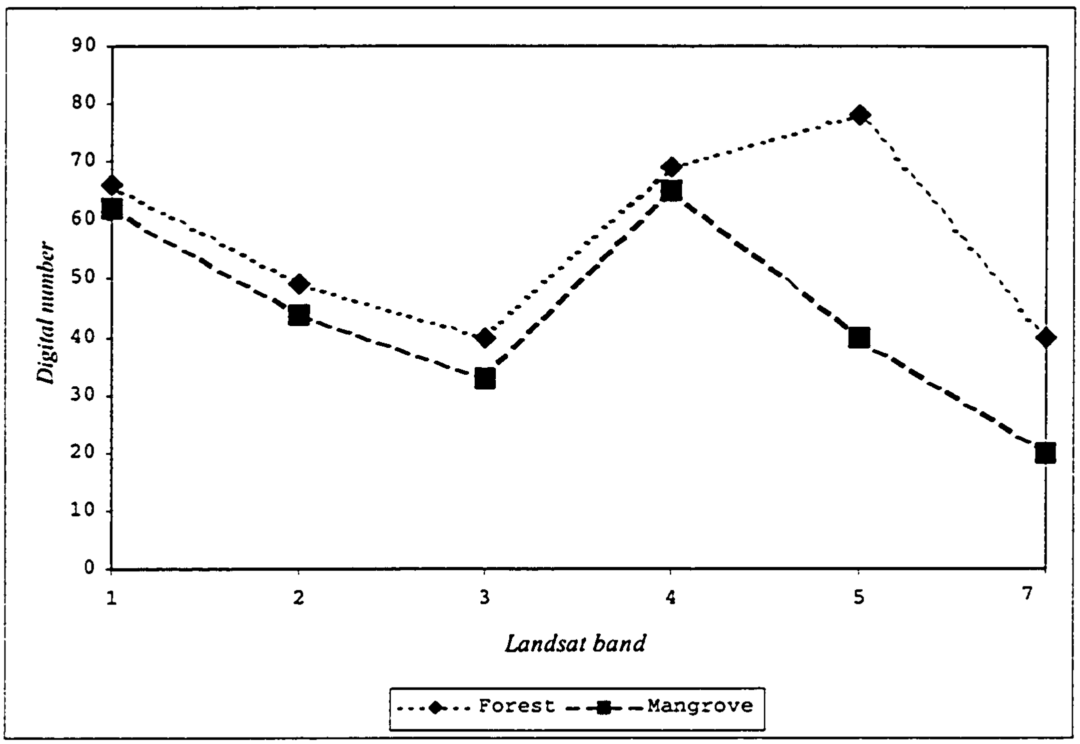


Figure 1.5. Spectral plot of mean digital number (DN) values for forest and mangroves

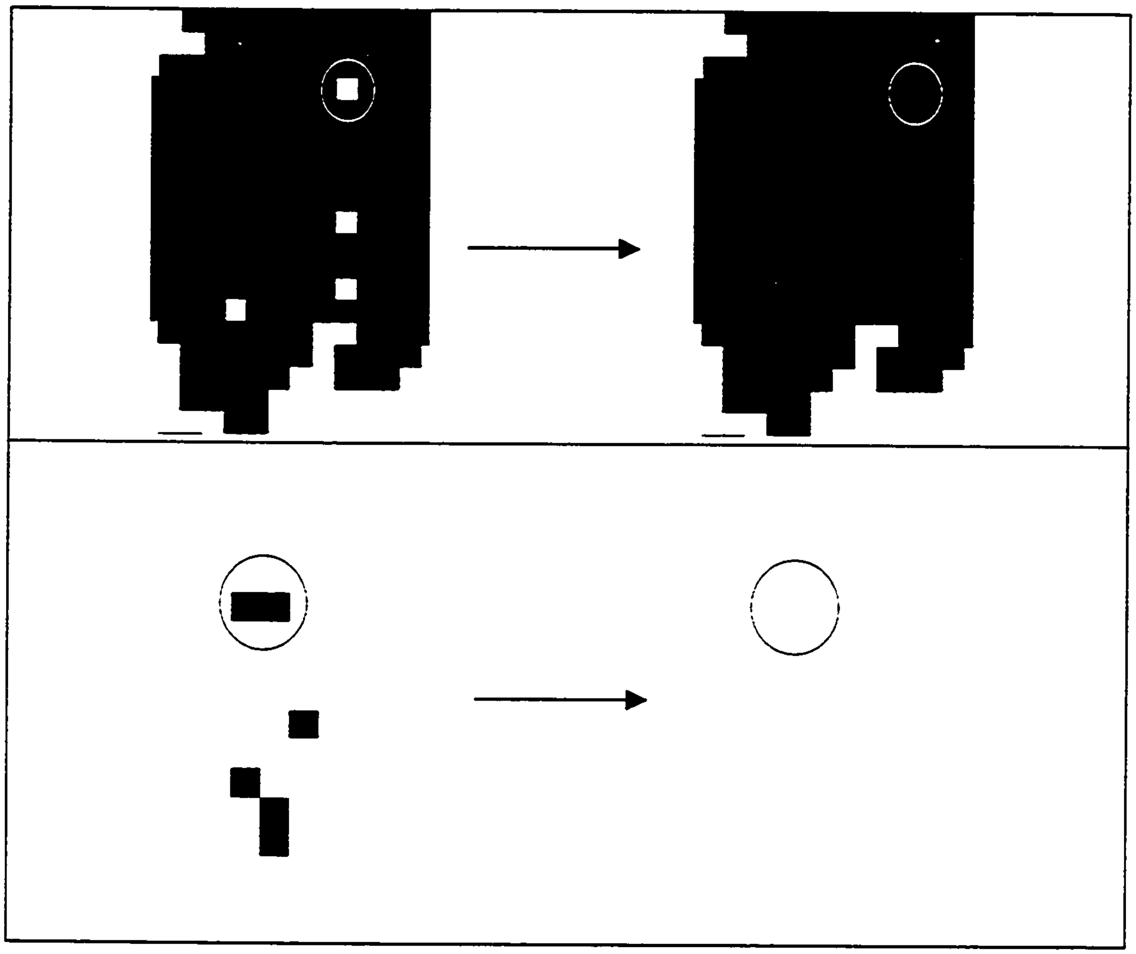


Figure 1.6. Filters used for the removal of single pixels from the classification.
a) 100 % filter. b) 90 % filter

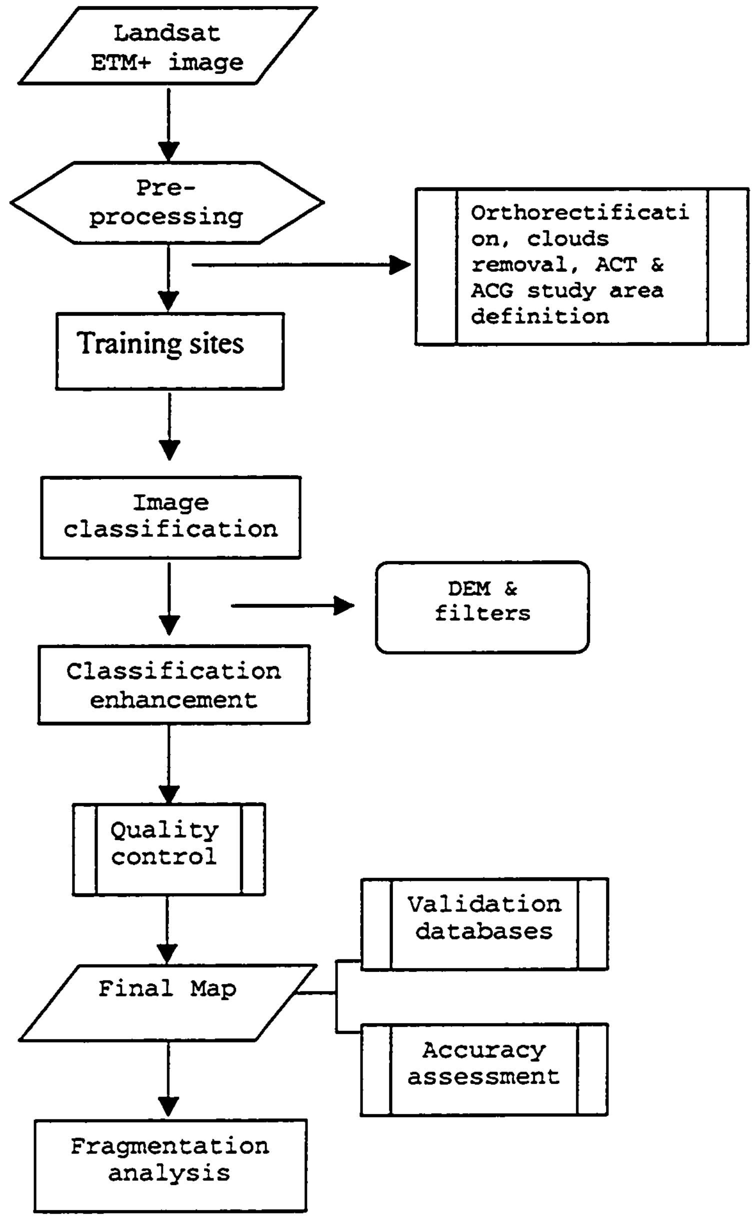


Figure 1.7. Procedures for image classification and fragmentation analysis.

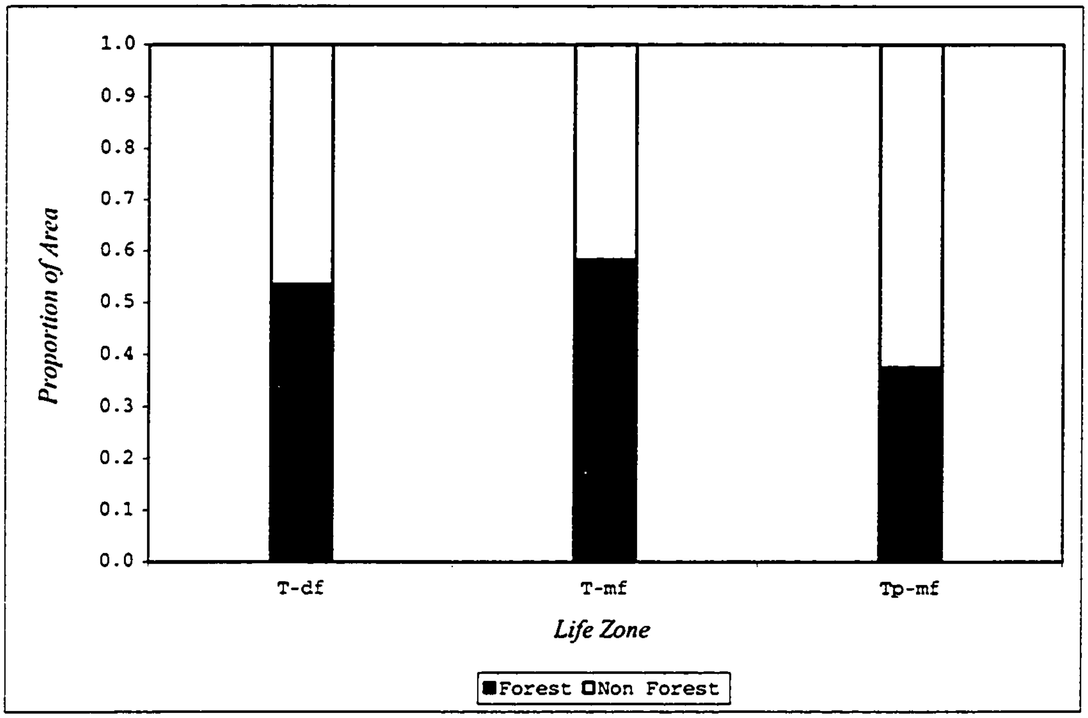


Figure 1.8. Proportion of forest and non-forest area per life zone

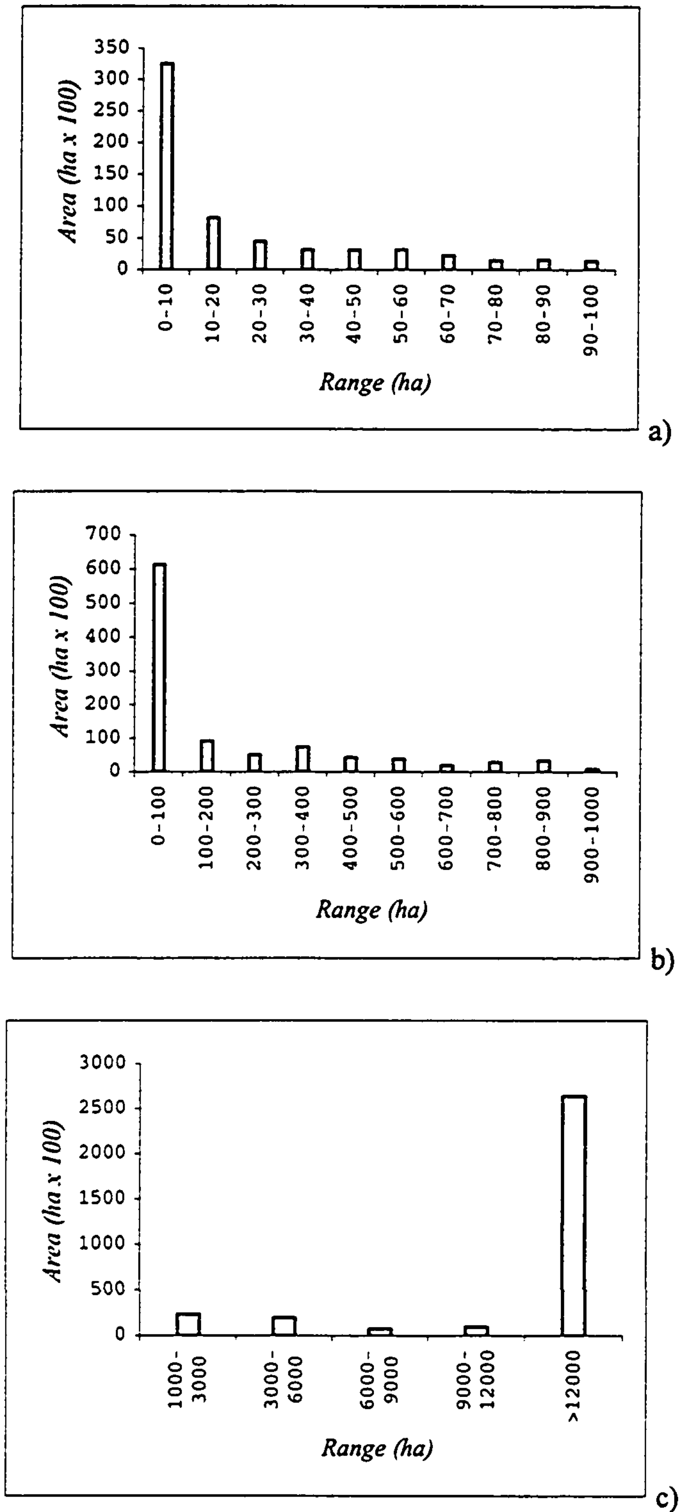


Figure 1.9. Forest patch size distribution. a) Patch size range from 0 to 100 ha. b) Patch size range from 100 to 1000 ha. c) Patch size range from 1000 to greater than 12 000 ha.

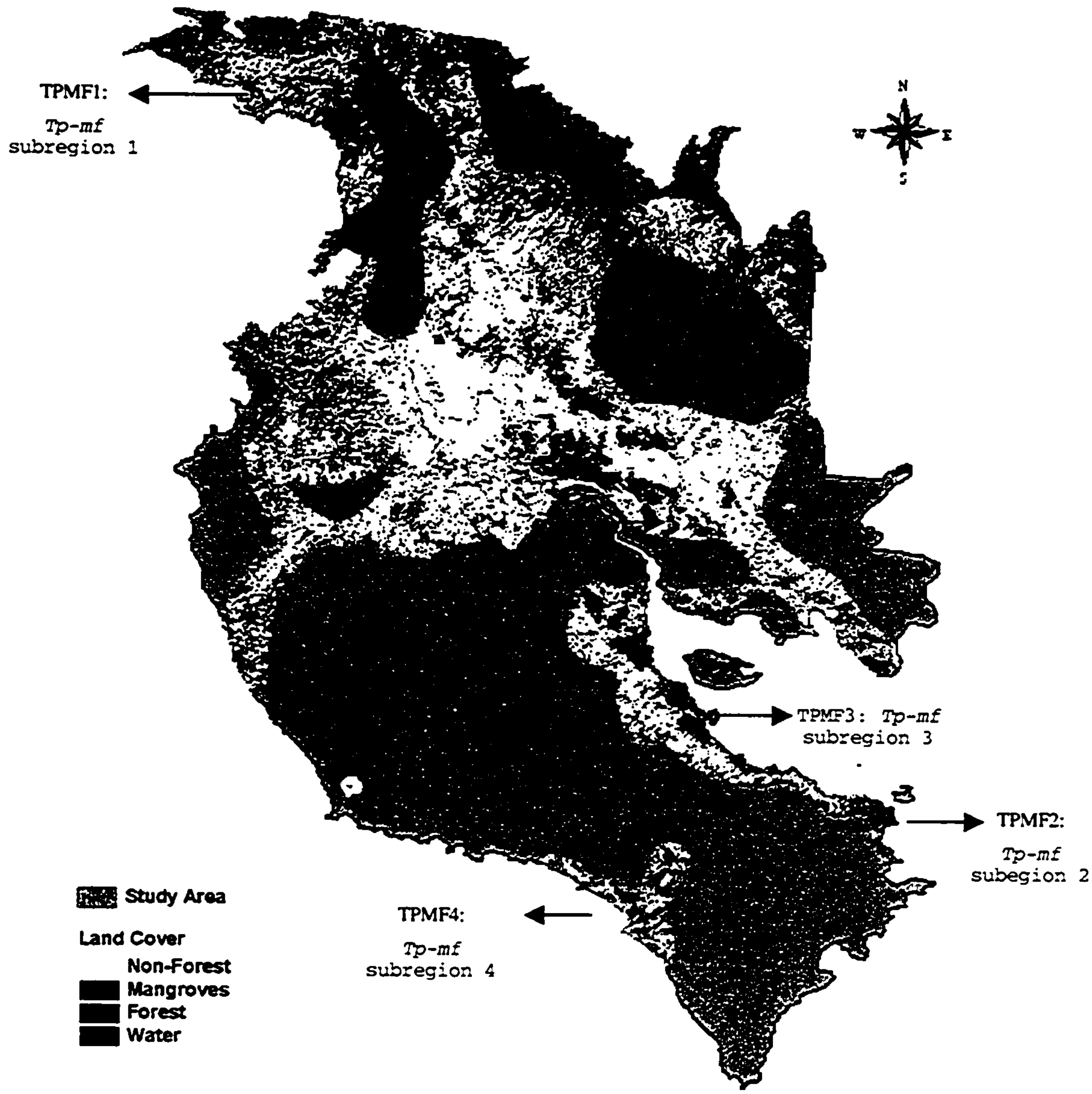


Figure 1.10. Location of the tropical premontane moist forest subregions within the study area

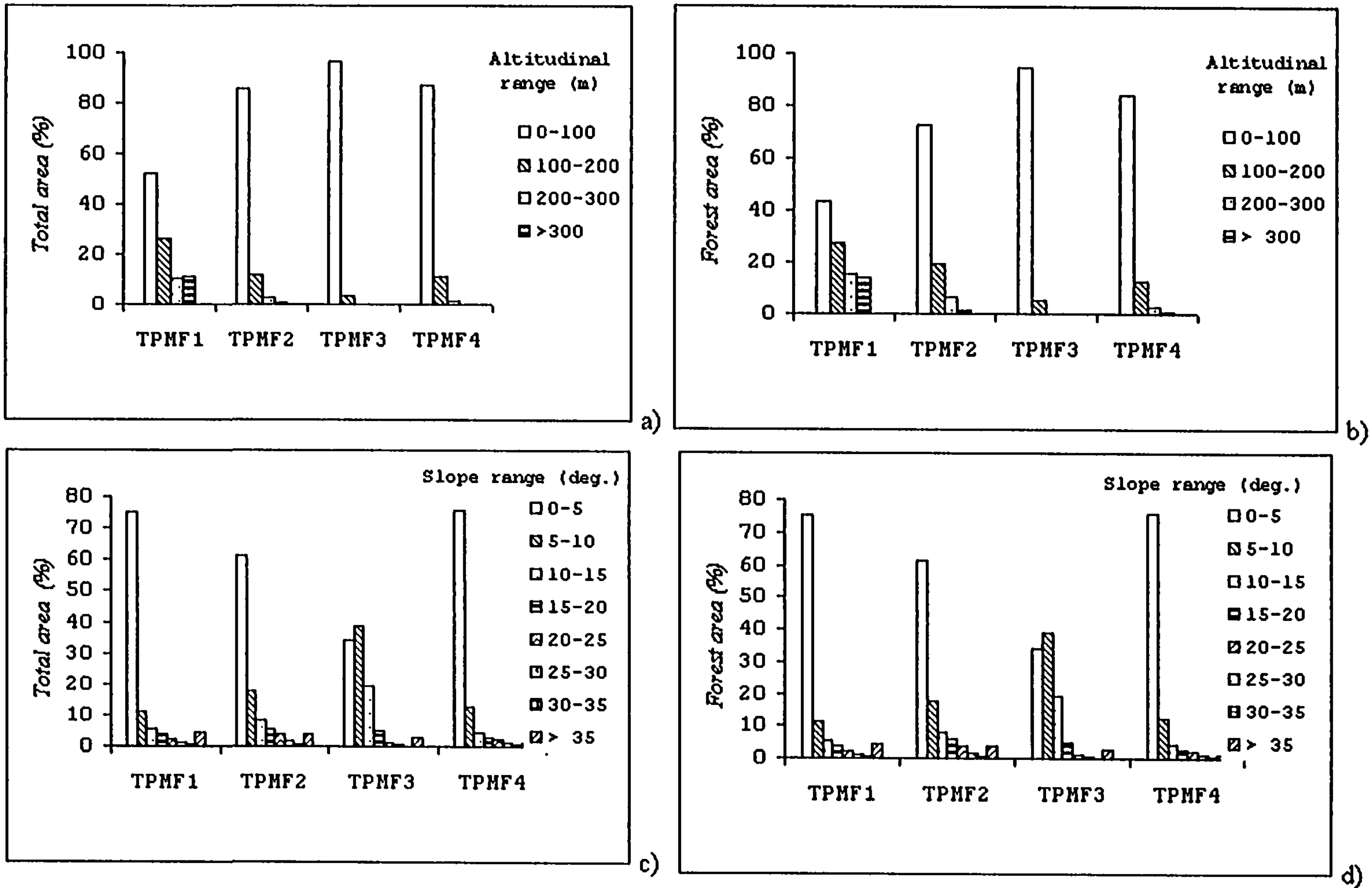


Figure 1.11. a) Total area (%) per altitudinal range for each *Tp-mf* subregion b) Forest area (%) per altitudinal range for each *Tp-mf* subregion c) Total area (%) per slope range for each *Tp-mf* subregion d) Forest area (%) per slope range for each *Tp-mf* subregion.

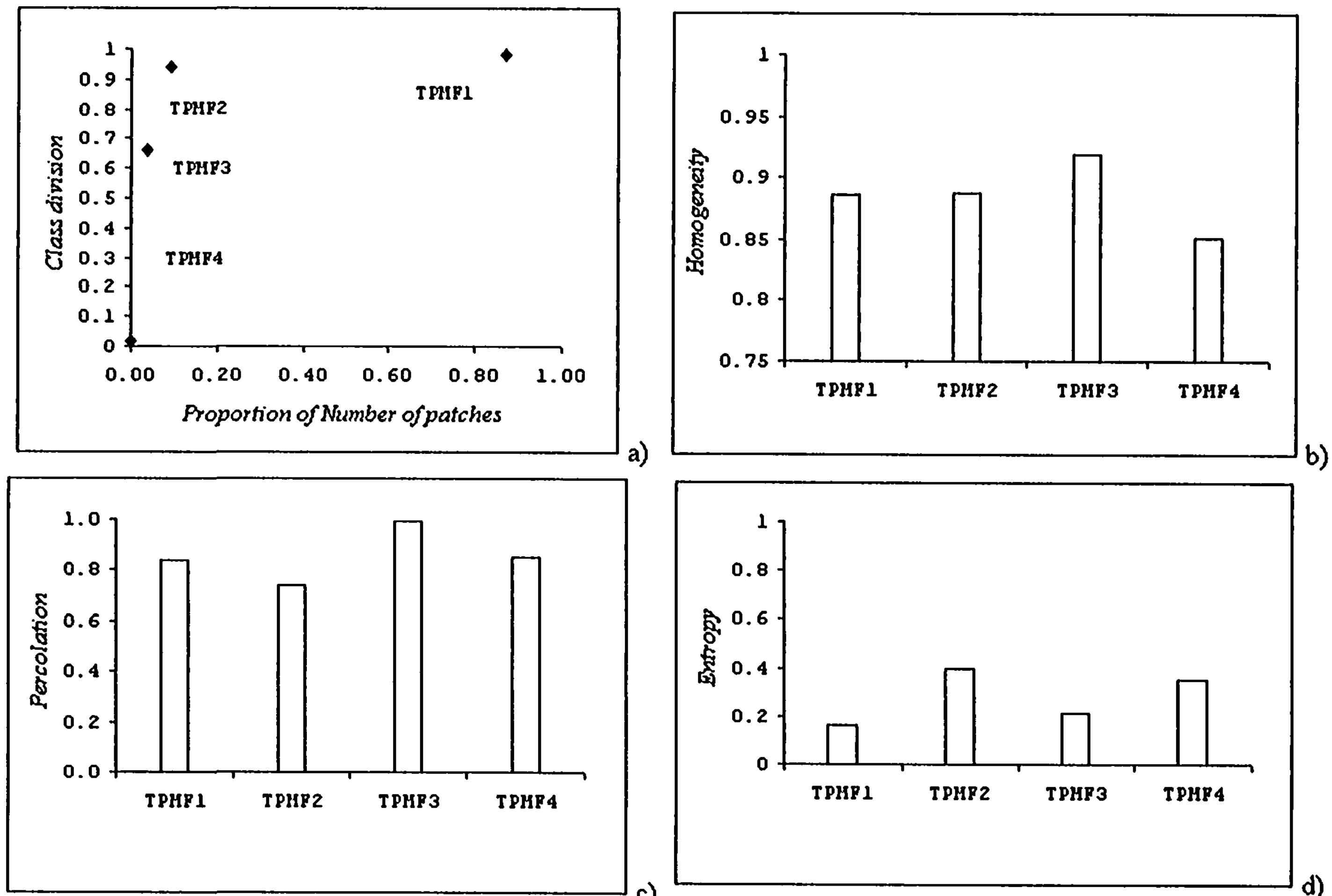


Figure 1.12. a) Class division b) Class Homogeneity c) Percolation d) Entropy, for the four subregions of *Tp-mf* in the province of Guanacaste and the Peninsula of Nicoya.

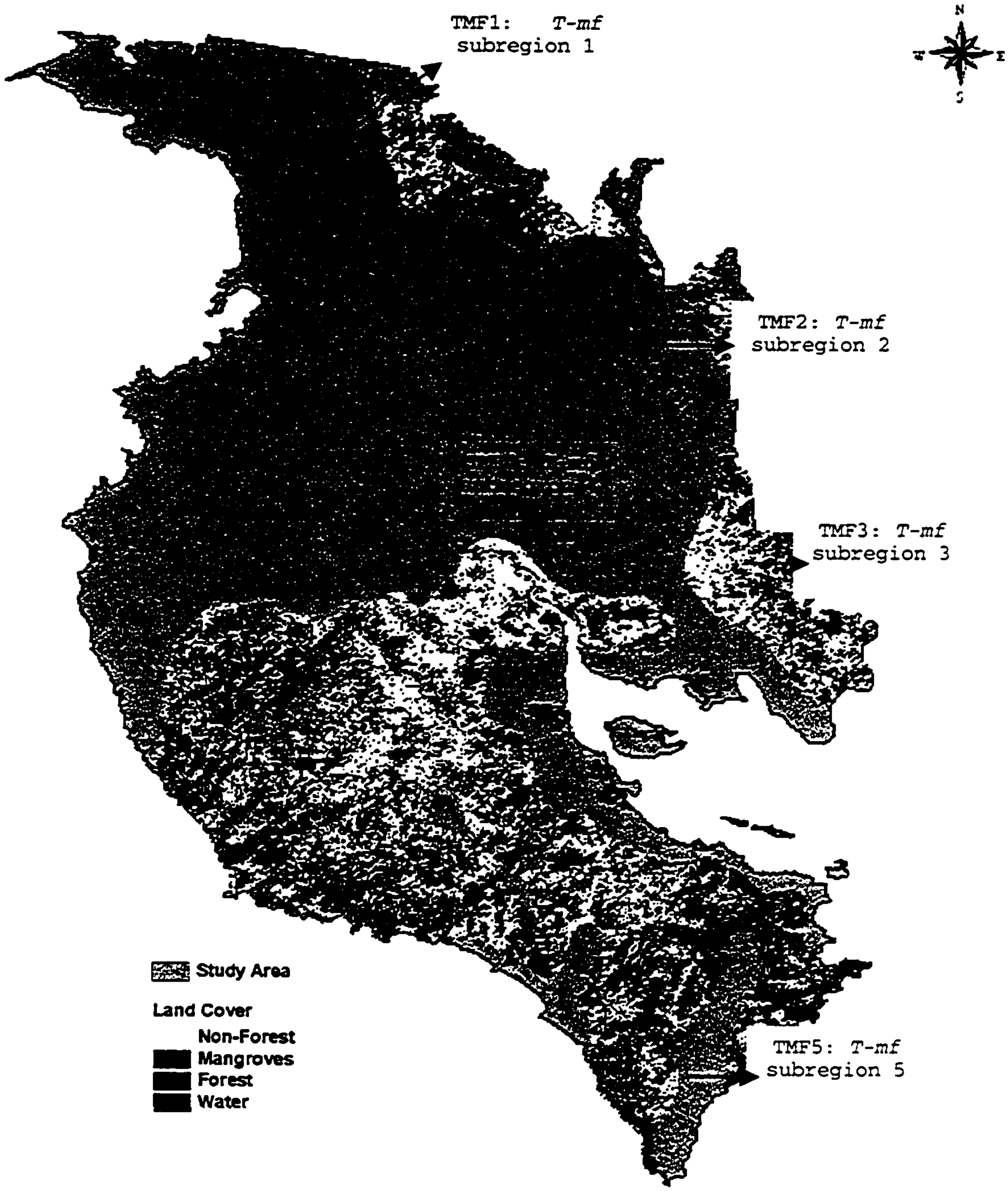


Figure 1.13. Location of the tropical moist forest subregions within the study area.

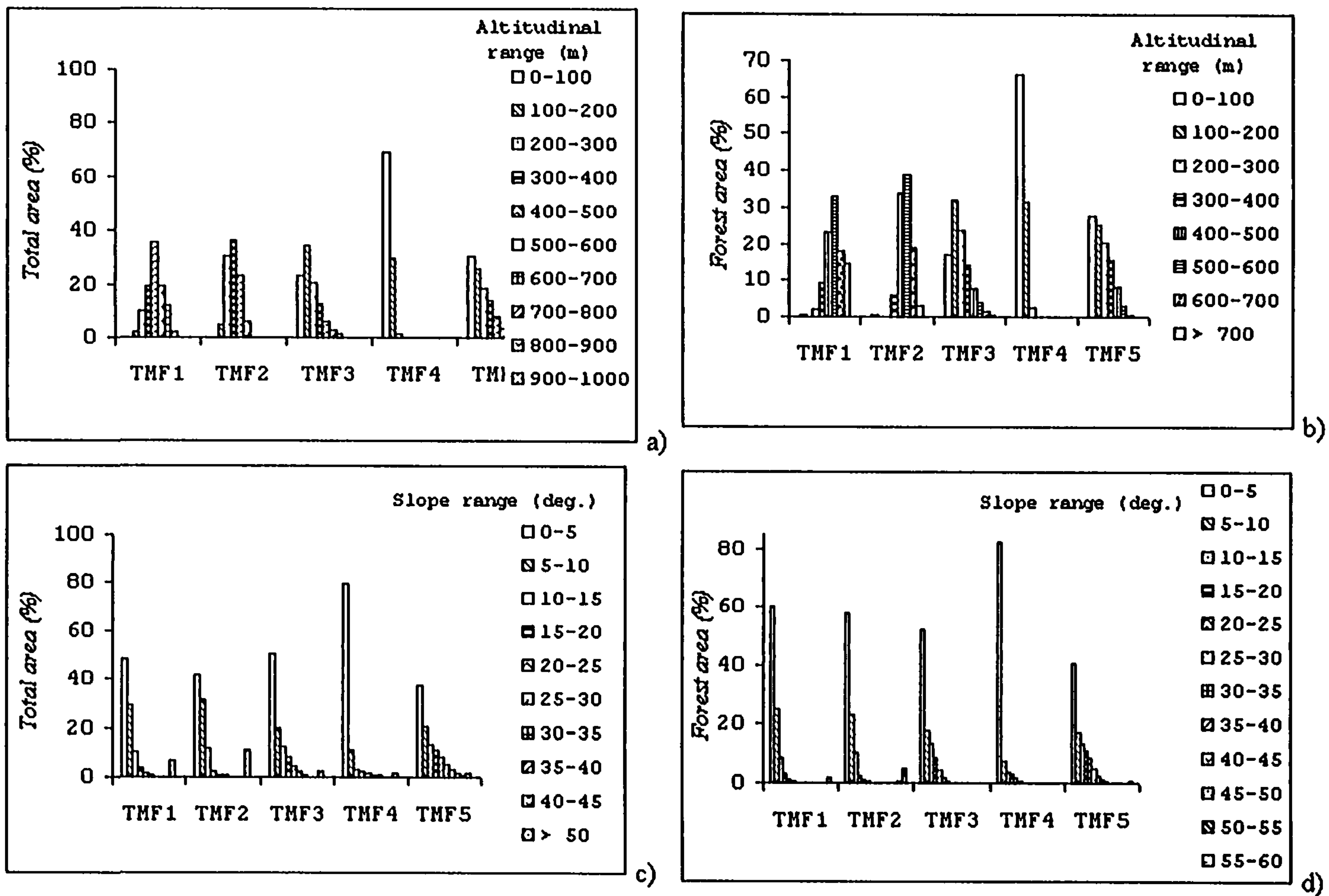


Figure 1.14. a) Total area (%) per altitudinal range for each *T-mf* subregion b) Forest area (%) per altitudinal range for each *T-mf* subregion c) Total area (%) per slope range for each *T-mf* subregion d) Forest area (%) per slope range for each *T-mf* subregion.

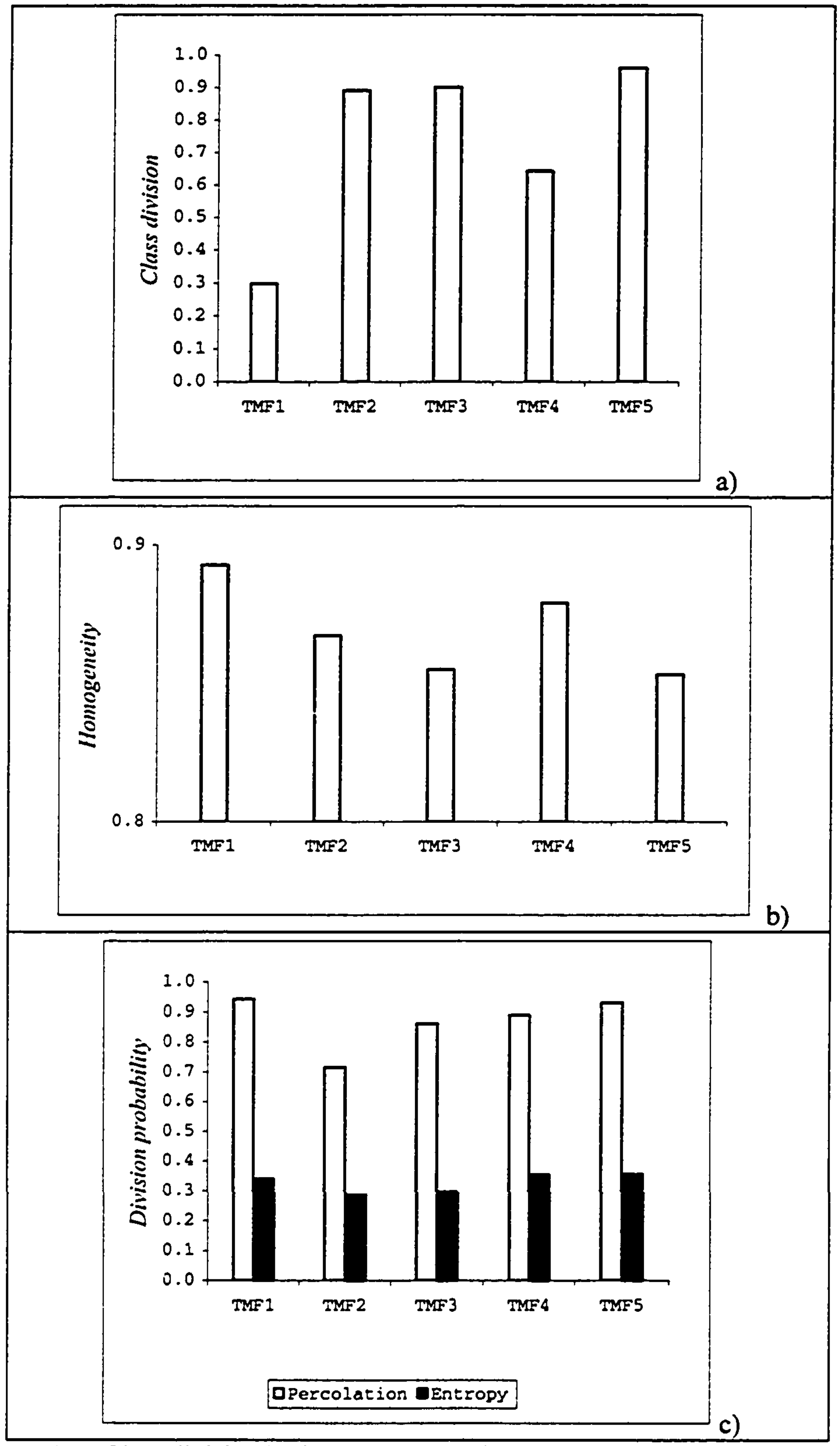


Figure 1.15. a) Class division b) Class Homogeneity c) Percolation and Entropy, for the four subregions of *T-mf* in the province of Guanacaste and the Peninsula of Nicoya

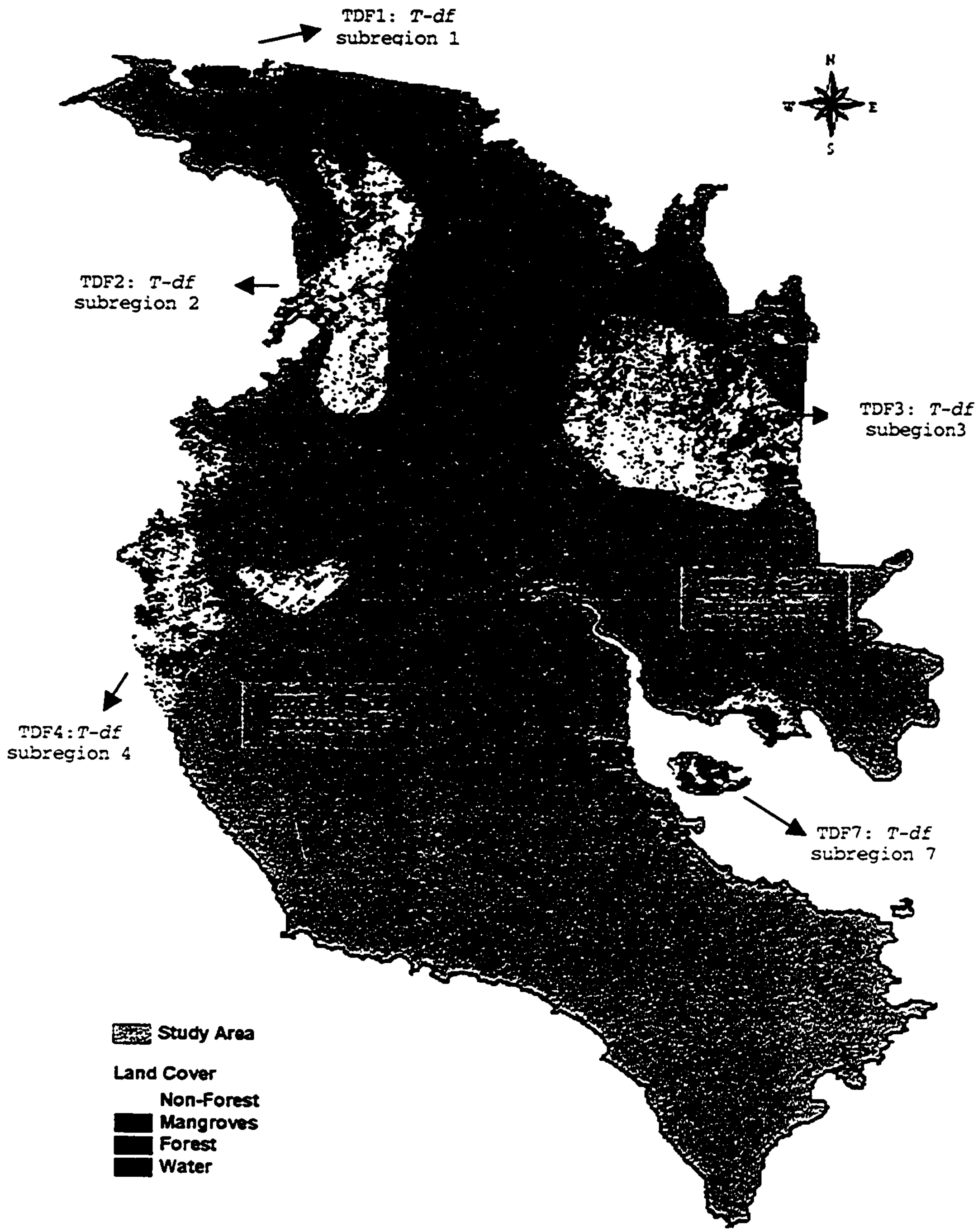


Figure 1.16. Location of the tropical dry forest subregions within the study area.

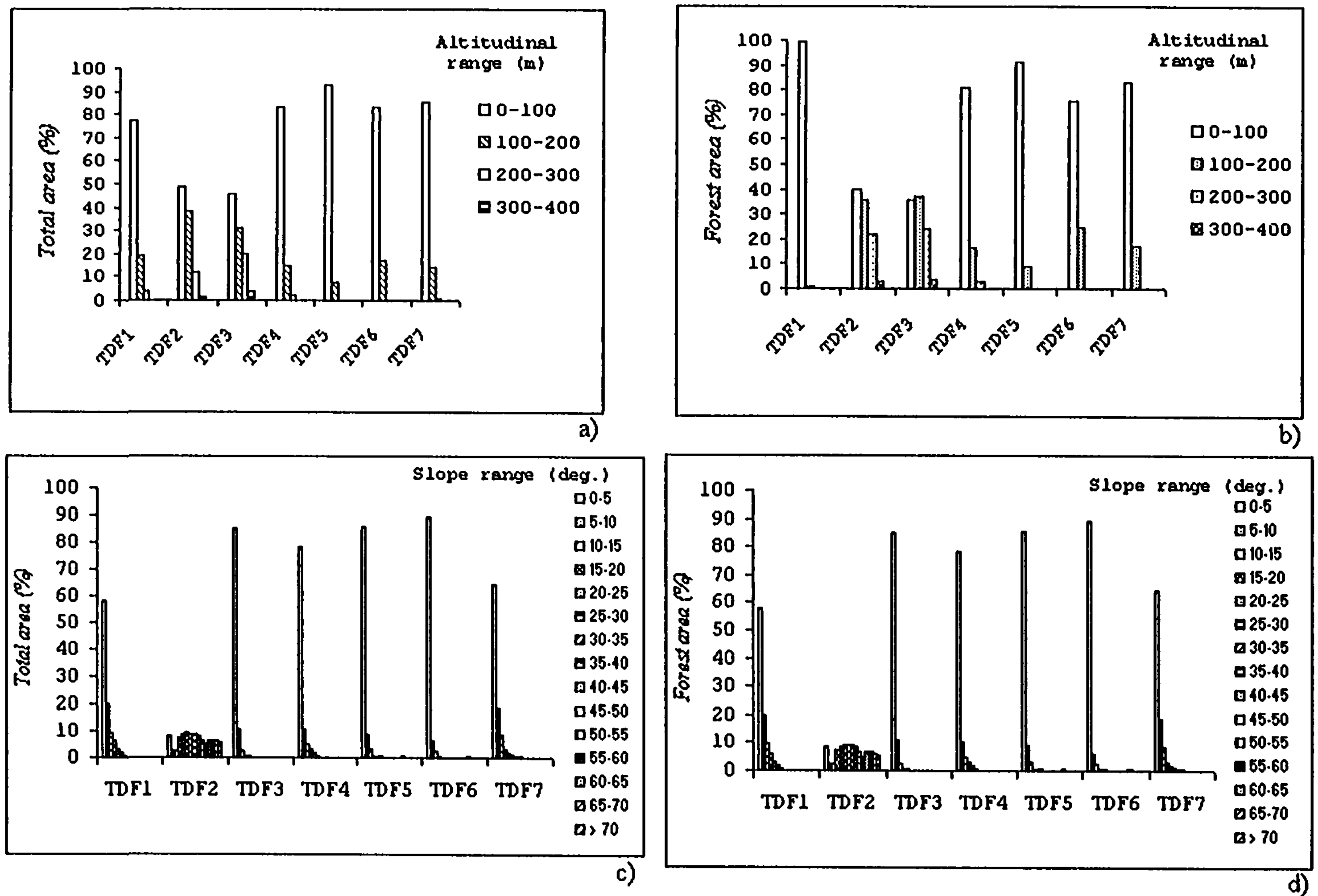
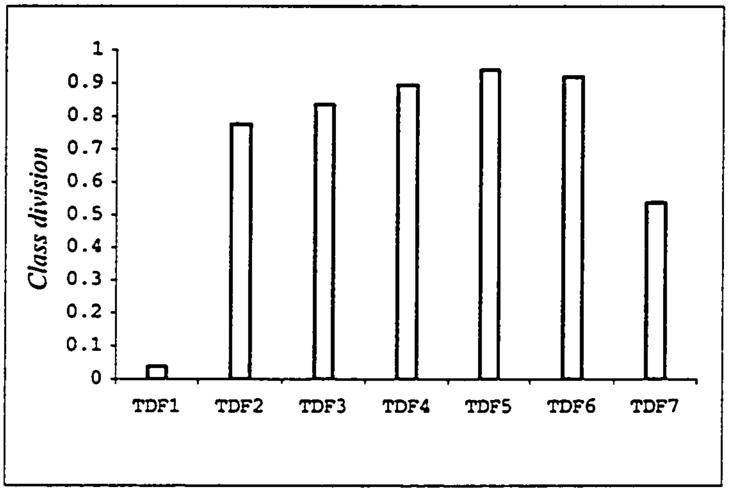
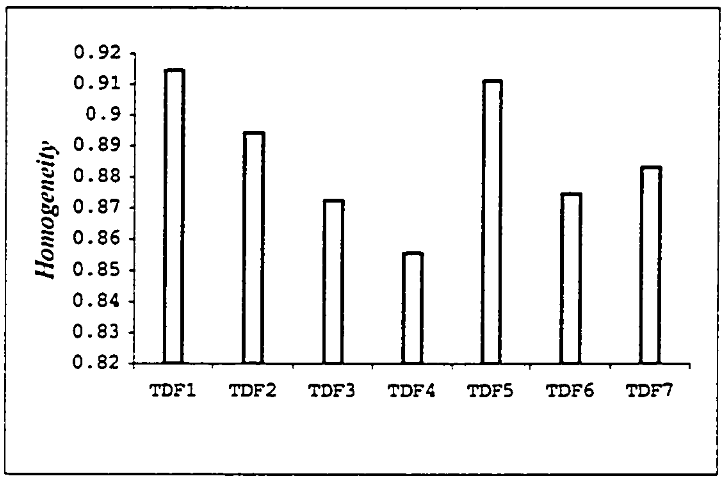


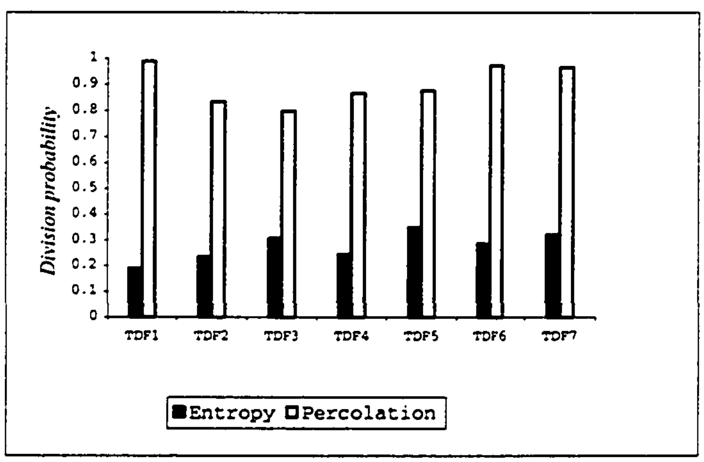
Figure 1.17. a) Total area (%) per altitudinal range for each *T-df* subregion b) Forest area (%) per altitudinal range for each *T-df* subregion c) Total area (%) per slope range for each *T-df* subregion d) Forest area (%) per slope range for each *T-df* subregion.



a)



b)



c)

Figure 1.18. a) Class division b) Homogeneity c) Entropy and Percolation, for the seven subregions of *T-df* in the province of Guanacaste and the Peninsula of Nicoya

Chapter 2. Tropical dry secondary forest detection using IKONOS and Landsat ETM+ imagery

2.1 Introduction

Secondary forest detection and mapping has been considered a critical issue for carbon budget assessments in tropical regions (Foody and Curran, 1994; Kimes *et al.* 1999). The possibility to detect this type of ecosystem using remotely sensed data presents difficulties not yet resolved. A first problem in secondary forest detection through remote sensing is the detection of green biomass in seasonal forests (Kramer, 1996; Paff. *et al.*, 2001). Seasonal forests are located in the tropical dry and moist forest life zones. The variations in phenology of these ecosystems are highly dependant on water availability (Bullock and Solí-Magallanes, 1990). During the dry season these ecosystems are deciduous, meaning that in general a considerable percentage of the trees lose their leaves. Consequently, remotely sensed data from the dry period tends to results in a confusion of young forest areas with pastures and low-density forest stands. In addition, imagery from the rainy season commonly presents increased cloud coverage over forest areas.

A second problem is the difficulties that are encountered at the basic level of forest stand age definition in remote sensing studies (Sader *et al.* 1989). Several forest stands in tropical regions have been growing for years without any recording of data that would allow a precise determination of age. Therefore, when the forest stand information is related to remote sensing data, it is not possible to define exact ages (Sader *et al.* 1989). Ecologically speaking, it is important to consider that age does not necessarily represent the forest stand characteristics, which means that chronological age cannot be related to unique stand characteristics (UNESCO-UNEP-FAO, 1978). Depending on the type of disturbance, two forest stands of the same age can present totally different structures (i.e. species composition, canopy closure, horizontal and vertical structure). For this reason the stand data may not be comparable from one study area to another based only on age. Rather than age, in remote sensing studies of vegetation the understanding of horizontal and vertical structure of the forest play a more important role. The horizontal structure will determine the patchiness of the forest based on crown distribution, while vertical structure defines the leaf area over a given point (Ewel, 1977). For example, Kellman (1970) shows the variability in the number of species and biomass (kg/ha x 10^{-3}) between plots of the same age in a study in Mindanao, Philippines, suggesting that age is not a good indicator of stand characteristics. Moreover, even within regions the structure and development of these forest stands can vary with respect to age. These variations will depend on site characteristics (i.e. soils, topography), land use history, and propagule availability (Corlett, 1994; Denslow, 1996).

Despite the disadvantage that it presents, age has been used in order to relate successional forest stand characteristics to remotely sensed data, since it is a simple parameter to determine; even if it is not exact or representative of the forest structure. Sader *et al.* (1989) in a study in the Luquillo Experimental Forest could not exactly determine age for different secondary forests using remotely sensed data. For this reason, age was determined base on aerial photos, using the midpoint of a known range in regeneration age for the successional forest stage. Sader *et al.* (1989) found in this study that the normalized difference vegetation index (NDVI) does not detect successional forest biomass changes in forest stands older than 15 to 20 years. These results however cannot be comparable with that of other regions, since the forest structure can be very different for a stand with the same age. Nonetheless, forest age can be accepted as a parameter to relate with remote sensing information (i.e. reflectance) when the land use history is well known or is under controlled experiments. Steininger (2000) applied this approach where age and land use history were well known for the study area (Brazil and Bolivia). In this study, Steininger found significant relationships between middle infrared canopy-reflectance and stand age and biomass (among other variables). In the same study, no significant relationship was found between canopy spectral reflectance and biomass (age related) for forest areas located in Bolivia. Lucas *et al.* (2000) were able to detect 4 forest age categories in the Brazilian Amazon using Advanced Very High Resolution Radiometer (AVHRR) imagery (1 Km spatial resolution). In order to define the age of regenerating forests, a times-series of Landsat (30 m spatial resolution) data was used. However, the accuracy was low due to uncertainties in age estimation, lack of field data and natural variability of regeneration throughout the region (Lucas *et al.*, 2000). As well, Kimes *et al.* (1999) used multitemporal SPOT HRV imagery (High Resolution Visible) to discriminate primary forest from secondary forest in Rondonia, Brazil. Although this study obtained a high accuracy, only two forest classes were separable: primary and secondary (1 to > 9 years). Since other successional stages (i.e. 10-20, 20-30 years) with a very different stand composition (horizontal and vertical forest structure) were considered primary forest, the amount of carbon for the Amazon basin based on this classification might be wrong.

Not only for the reasons mentioned above, but also because of the importance given in the last 20 years to the tropical rain forest (i.e. Amazon), most of the remote sensing studies (including secondary forest detection) have been carried out in this ecosystem (Sanchez-Azofeifa *et al.*, 2001b). However, 42% of the vegetation of Mesoamerica and the Caribbean, along with 42% of all intra-tropical worldwide vegetation is considered dry forest (Murphy and Lugo, 1995). The *T-dfs* cover more area than the tropical rain forest and unlike the tropical rain forest the *T-dfs* are deciduous (Ewusie, 1980).

Climatic characteristics have made the *T-df* one of the most suitable areas for agricultural activities (Mass, 1995; Ewel, 1999). As a consequence, the *T-dfs* are among the most heavily utilized and perturbed ecosystems due to human activities; a far greater proportion of *T-dfs* have been degraded or converted than wet forest (Mooney *et al.*, 1995; Murphy and Lugo 1986). In Costa Rica for example, the *T-df* has been one of the most deforested life zones within the country (Sader & Joyce, 1988; Watson *et al.*, 1998; Solorzano *et al.*, 1992). Currently, only 0.08% of the *T-dfs* located in Mesoamerica (Southern Mexico and Central America) are under conservation status and only 2% of their original extension remains in relatively undisturbed areas (Janzen, 1986). For these reasons, the *T-df* is considered to be one of the most threatened ecosystems in the tropics (Janzen, 1988). In addition, the *T-df* remains among the least studied of tropical ecosystems (Mooney *et al.*, 1995). However, the recovery processes due to pasture abandonment in some areas of *T-df* in the North Pacific region of Costa Rica (Watson *et al.*, 1998) are creating a mosaic of successional stages suitable for remote sensing studies related to ecological variables.

To date, no specific attempt has been made to use remotely sensed data to map secondary succession in *T-df* region based on forest structure rather than age.

The main objective of this study is the detection and mapping of different successional stages in a *T-df* ecosystem within the Santa Rosa National Park, Costa Rica using remotely sensed data (IKONOS and Landsat ETM+). A supervised classification and vegetation indices applied in the detection of tropical rain and wet forests (Richardson, 1977; Stone *et al.* 1994; Sader. *et al.* 1989; Steininger, 2000; McMorrow, 2001) are used to identify these successional stages. The specific indices examined are the single ratio (SR), the normalized difference vegetation index (NDVI), the infrared index (IRI) and, the middle infrared index (MIRI). In addition, the forest canopy and stand structure as previously explained are used to develop a clear understanding of what is detected by the sensor in these successional stages.

2.2 Methods

2.2.1. Study area and ecological definition of successional stages

The study area corresponds to the Santa Rosa National Park located in the northwestern province of Guanacaste, Costa Rica (Figure 2.1). The park covers a large area of *T-df* that has been under protection since 1971 (Janzen, 1983). The forest cover in Santa Rosa is a mosaic of various ages of secondary succession that ranges from abandoned grass pastures to 400-year-old forests. It is also possible to find remnants of forest almost intact where only a few individual trees have been removed (Janzen, 1988). The vegetation within the *T-df* located in the Santa Rosa National Park ranges from forest stands almost completely deciduous found in young successions (2 m tall) to semi-evergreen forests in old successions (nearly 30-meter tall) (Janzen, 1988).

Based on the vertical structure of the forest, the phenology and the canopy distribution and density, four successional stages were defined within the study area: pastures, early, intermediate and late or mature. Forest vertical structure is defined as the number of tree layers in a successional stage (Pacheco, 1998). Based on these parameters, pastures represent the simplest configuration namely open areas with very low tree density (< 5 trees per hectare) or without trees. The early successional stage presents one layer of vegetation with a maximum height of approximately 6 meters (Figure 2.2a). The vegetation composition of this successional stage consists of shrubs and small trees (Hubbell, 1979; Pacheco, 1998). Figure 2.2b shows a schematic representation of the low density of shrubs and small trees in an early successional stage. Pastures and bare soil cover open areas (Figure 2.2c). In addition, a high percentage of the vegetation is deciduous in the dry period (Janzen, 2000 pers. comm.), allowing light to reach the forest floor (Figure 2.2d).

Two vegetation layers characterize the intermediate successional stage. The first layer encompasses fast growing deciduous tree species reaching a maximum height of approximately 10 meters (Figure 2.3a). Lianas and vines represent a second vegetation layer together with shade tolerant species that begin to populate the forest stand (Figure 2.3b). A downlooking schematic representation of the forest canopy based on tree density and distribution is shown in Figure 2.3c. During the dry season or climatically transitional periods (i.e. January or June) a percentage of species in both layers are caducifolious. In the intermediate successional stage the forest is therefore characterized by a combination of green canopy, woody material and areas where incoming light can reach the forest floor (Figure 2.3d).

Two layers of trees represent the late or mature successional stage of the *T-df* (Hartshorn, 1993). A first layer of dominant trees forms the upper forest canopy (30 meters in height), while a second layer encompasses the regeneration of shade tolerant species (Figure 2.4a). Due to the high canopy density, a very small fraction of the incoming light reaches the forest floor (Figure 2.4b). In addition, evergreen species characteristic of this successional stage display very short periods of deciduousness (Janzen, 2000 pers. comm.). A schematic representation of the canopy in a late or mature successional stage is illustrated in Figure 2.4c. This representation is congruent with the canopy picture taken from the ground. During this stage overlapping tree crowns in the upper canopy form a continuous vegetation layer.

2.2.2. IKONOS and Landsat ETM+ imagery description and pre processing

Information from an IKONOS image was used to extract the location of training areas (4 successional stage classes) to perform a supervised classification of a Landsat ETM+ image. Data description and preprocessing for both images are presented as follows:

Data description: An IKONOS scene (4 x 4 meters resolution) was acquired during the middle of the dry season (March 2000) and a subset (7 x 7 km) was defined for a *T-df* segment within the Santa Rosa National Park. In Santa Rosa, the dry season extends approximately from December to May (Janzen, 1988). The average annual rainfall in the area is 1,500 to 2,000 mm (Tosi, 1969). Phenological changes determine the amount of both deciduous and green forest areas within the *T-df* at the time the image was acquired. The proportion of deciduous species in the early successional stages is greater than in the later ones. The Landsat ETM+ image (30 x 30 meters resolution) was acquired during the transition from the rainy to the dry season (January 2000). Proper justification for the use of Landsat ETM+ imagery from January can be found in section 1.2.1 of Chapter 1 (methods).

Imagery preprocessing: Training areas were determined from the IKONOS image to guide the classification of the Landsat ETM+ image. Therefore, it was necessary to establish common geographical coordinates for both images (Lambert Conformal Conic Costa Rica North projection, spheroid Clarke 1866). The Landsat image from January 2000 was georeferenced to a previously corrected Landsat image (P15R53/1997/TM5). A second order polynomial and nearest neighbor method were chosen for the rectification and resampling processes, respectively. Fifty well-distributed ground control points were acquired from the reference image, resulting in an RMSE of 0.6 pixels (≅ 18 meters). Since vegetation indices using bands 3 and 4 of the Landsat ETM+ image were calculated (Conghe *et al.*, 2001) the image was atmospherically corrected. The first step in the atmospheric correction process was to convert digital numbers to at sensor radiance values using the gain and offset values for the Landsat image. Then, the radiance values were converted to surface reflectance using the ACORN module in ENVI 3.4.

Fifty points were obtained from the Landsat ETM+ image for the geometric correction of the IKONOS image. The IKONOS image was georectified by means of a rubber sheet geometric model and resampled using a nearest neighbor method (ERDAS 1999). The RMES error for the geometric correction was 5 meters. Since the IKONOS image was used to guide the classification process (location of 4 classes) no atmospheric correction was required (Song *et al.*, 2001).

2.2.3. Definition of successional stages in IKONOS

To determine the various successional stages in the IKONOS image an unsupervised classification with four classes was performed (pastures, early, intermediate and late or mature) (Figure 2.5). In order to verify the correspondence of these four classes with the proposed successional stages, the density of the canopy and the theoretically expected deciduousness and horizontal structure were considered (Methods, section 2.2.1).

These ecological parameters are evaluated in a grid of 25 by 25 pixels (3 x 3 pixel window in Landsat ETM+) overlain on the IKONOS image (colour composite bands 4,3, and 2). The number of pixels representing green canopy (full foliage) and indicated by a red colour in the IKONOS colour composite were counted in the grid. Then, the percentage of pixels representing the canopy was calculated. Percentages of canopy cover greater than 60% were considered late or mature (Figure 2.6). Based on my interpretation of successional schemes, granulated dark blue and dark green areas correspond to leaf off canopies (upper canopy) with some green understory with a percentage of red pixels (full and medium foliage trees) less than 60% were considered intermediate (Figure 2.6). Granulated light blue areas (litter and woody component) with groups of brown dots (woody component with some foliage) were considered early succession. Finally, pastures show very low or no-canopy presence in the IKONOS image. Further validation of this interpretation is going to be completed with data field.

2.2.4. Landsat ETM+ supervised classification and validation

For image classification purposes a minimum number of points is required in order to calculate the spectral variability of the data (Jensen, 1996). The number of sample sites (3 x 3 pixel window) per successional stage for the Landsat image classification was based on the expected percent accuracy (Sanchez, 1996; Fahsi *et al.*, 2000). A minimum of twenty-five sites per successional stage is required to reach the expected accuracy of 85%.

The supervised classification was based on the site information generated from the IKONOS image analysis. Twenty-five sites per successional stage were used to classify the Landsat ETM+ image into early, intermediate and late or mature successional stages. For each of the twenty-five sites the spectral information from a 3 x 3 pixel window was extracted and averaged into a single spectral signature for the class. This single spectral signature per successional stage was used to run the supervised classification. To test the class separability a visual interpretation of scatter plots of two or three bands (4,3; 5,4; 3,5; 3,4,5) was performed. In addition, another class separability test was performed through an ANOVA for bands 2,3,4,5 and 7. The result of the supervised classification was a successional stage map for the Santa Rosa National Park. With the same methodology used to obtain the classification points from IKONOS, validation points for each class were obtained based on the proportion of the total area covered by each successional class (Stratified sampling). An accuracy assessment was performed to verify the correctness of the classification. The accuracy assessment estimators used were: overall accuracy, Kappa and Tau. In addition, two new estimators developed by Nisshi and Tanaka (1999), were applied (Chapter 1). The general process of image classification using Landsat ETM+ is illustrated in Figure 2.7.

2.2.5. Vegetation indices

Vegetation indices have been commonly used for change detection (Sader et al., 2001), forest age detection (Lucas et al., 2000) and general forest mapping (Purevdorj et al., 1998). The advantage of vegetation indices (spectral ratios) is that they enhance compositional information, while topographic and illumination effects are diminished (Vincent, 1997). As an alternative test to a supervised classification in the present study, various vegetation indices were evaluated for the separation of different successional stages in a T-df ecosystem. The vegetation indices tested were: (1) Simple ratio, (2) Normalized Difference Vegetation Index, (3) Infrared Index, and (4) Mid-Infrared Index (MIRI). A description of these indices can be found in Table 2.1

In order to define the thresholds to apply to the vegetation indices and define successional stages from Landsat ETM+ data, the same training sites extracted from IKONOS (during the supervised classification) were used to create plots of band combinations (4,3; 4,5; 5,7). These plots were overlain by a graphical representation of the vegetation indices. The resulting plots were examined to determine if threshold values of the vegetation indices could be defined to differentiate the successional stages. In the original scatter plot, an ellipse was defined for every data cluster (representing a successional stage) representing the mean and one standard deviation for the cluster. With this method it was possible to determine the threshold values for every successional stage. Moreover, an ANOVA was run to test significant differences between classes of successional stages for every vegetation index.

2.3 Results

Although IKONOS has a low spectral resolution, its high spatial resolution (4 meters) can be used to complement the analysis of multi-spectral data offering broader regional coverage (i.e. Landsat TM, SPOT). Results presented below show that it is possible to obtain accurate information from IKONOS about forest successional stages for the *T-df* located in the Santa Rosa National Park. These results are the combination of visual interpretation of canopy texture from IKONOS, supported by a general analysis of the radiation values (expressed as digital numbers - DN) for every successional stage (Figure 2.8).

It is important to mention that the IKONOS image was acquired during the dry season (March), so the radiation values represent specific conditions of the vegetation during this time of the year. Pastures and late or mature forest were readily extracted based on the results of the unsupervised classification. The digital number values for pasture are over 120 in all of the IKONOS bands. The presence of high green biomass in late or mature stages is confirmed by a low mean radiation value in the red portion of the spectra (Band 3 with DN = 30) and a high mean value in the near infrared portion (Band 4 with DN = 120); characteristic of healthy green vegetation (Tucker, 1979). In intermediate stages, field observations suggest that a mixture of woody vegetation, litter and green biomass can explain the mean spectral value in band 3 (DN = 65) greater than that for forest areas with a continuous evergreen canopy (DN = 30). In addition, the mean digital numbers for the infrared portion of the spectra (Band 4 with DN = 85) is lower than that of late or mature forest consistent with lesser amounts of green biomass (Figure 2.8). Early successional stages show similar changes in radiation from band to band to pastures. However, the mean radiation value is lower in early successional stages by approximately 20% in bands 1, 2, and 3, and 12% in band 4. I speculate that these differences are attributable to the presence of shrubs and sparse trees with small canopies and different proportions of woody material in the early successional stages. The aforementioned results illustrate the differences in visible near-infrared surface reflectance between successional stages using IKONOS.

As explained in section 2.2, 25-ground control points per successional stage were randomly generated in the IKONOS image. These twenty-five points per successional stage were used to sample the Landsat image using 3 x 3 pixel windows. The resulting 225 pixel values per class are displayed on Figure 2.9 as an aid to determine the differences in surface reflectance among classes. As well, Figure 2.9 shows ellipses that represent the mean and standard deviation value per class computed from the 225 reflectance values available for each successional stage.

These results from the graphical interpretation (Figure 2.9) show an overlap of the intermediate and late or mature successional stages for different bands combinations. Despite the overlap, the ANOVA analysis shows significant differences in surface reflectance for the Landsat ETM+ image between successional stages ($p<0.01$) (Table 2.2). In general, continuous canopies located in evergreen forest areas (late or mature forest) show low reflectance values in the red portion of the spectra ($\bar{x}=0.05$, $\sigma=0.005$) and high reflectance values in the infrared portion ($\bar{x}=0.31$, $\sigma=0.03$). In contrast, early successional stages in January display high reflectance values in the red portion of the spectrum ($\bar{x}=0.09$, $\sigma=0.02$), and low values in the infrared ($\bar{x}=0.25$, $\sigma=0.02$), consistent with forest areas that are characterized by less green vegetation and more woody material and litter.

The result of the supervised classification of the Landsat ETM+ image using the sites selected from IKONOS for each successional stage is shown on Figure 2.10. The intermediate successional stage occupies the highest proportion of the study area (0.4) followed by the late or mature forests (0.27), and the early successional stage and pastures (0.19 and 0.12 respectively). The validation results for this map show an overall accuracy of 83% when non-positional errors are considered (Table 2.3). The intermediate successional stage shows the lowest overall accuracy (65%) being mostly confused with the later or mature successional stage. This confusion is likely attributable to the coarse spatial resolution of the Landsat ETM+ sensor. Kappa and Tau error estimators show similar accuracy values (74% and 76%, respectively). In addition, two estimators developed by Nishi and Tanaka (1999) shows evidence of a good accuracy for the classification (83% and 80% respectively). The accuracy results stated above are based on a per pixel validation (Congalton and Green, 1999). Because a buffer (3 x 3 window) was used for the classification, a 3 x 3 pixel window was also used as a buffer to validate the classification results, increasing the overall accuracy to 95%, while Kappa and Tau increased to 91%. Using the buffer, the accuracy for pastures, early and late or mature successional a stage is 100% and that of the intermediate succession is 81% (Table 2.4).

Despite the high accuracy results obtained with the supervised classification using the full spectrum, commonly used vegetation indices were analyzed (Vincent, 1997).

Figure 2.11 and Figure 2.12 show the results using SR and NDVI indices, respectively. The late or mature successional stage is found in the NDVI range of 0.70 to 0.83, and in the range of 5.6 to 10.7 for SR. The intermediate successional stage is found in the NDVI range 0.58 to 0.7 and 3.76 to 5.6 for SR. At an NDVI value of 0.70 there is an overlap of these two successional stages, which is explained by the inability of Landsat to separate the physical canopy boundaries between them due to its limited spatial resolution. A similar overlap occurs between the early successional stages and pasture areas at an

NDVI value of 0.43. Because the overlap is small (Figure 2.9) the different successional stages are largely separable. This conclusion is supported by the ANOVA results that show significant differences ($p<0.01$) between successional stages in bands 4 and 3 (Table 2.2).

A third band ratio (IRI) using near and mid infrared portions of the spectra (Landsat bands 4 and 5, respectively) was also analyzed. The use of these bands for the detection of stand canopy phenology was studied in Brazil (Bohlman *et al.* 1998). The rational behind this index was to combine the ability of band 4 for biomass detection (Tucker, 1979) with the ability of band 5 to detect vegetation moisture (Knipling, 1970). The results show that this vegetation index does not separate the different successional stages (Figure 2.13) as well as NDVI. Using IRI, it is possible to define only three succession stages: later or mature (0.24 to 0.48), intermediate (0.08 to 0.24), and a single class for pastures and early successional stage (-0.13 to 0.08). The fourth vegetation index (MIRI) studied, did not allow the definition of thresholds for the different successional stages (Figure 2.14). The portion of the spectra used by MIRI is not sensitive to biomass (Gates *et al.*, 1965). Moreover, MIRI shows a linear behavior (Figure 2.14), explained by the explained by the inverse relationship of Band 5 with total leaf area index and the inverse relationship of Band 7 to total stand biomass (McMorrow, 2001). Pastures with large areas of soil exposure show no different MIRI values than late or mature successional stages (0.14 to 0.45).

2.4 Discussion

In a *T-df* ecosystem the horizontal structure and canopy density (number of tree crowns per unit area) is related with the successional stage and defines the patchiness of the canopy. In early successional stages, trees are more dispersed and separated by bare ground areas (Ewel 1977; Murphy and Lugo 1986). As the forest grows, canopy closure increases and areas of visible ground are less common. In late or mature stages the light reaching the forest floor is minimal due to the increase in canopy closure (Bazzaz and Pickett, 1980). This study has shown that the IKONOS and/or Landsat ETM+ sensors are capturing the energy variability (reflected and absorbed) among successional stages in relation to the changes in canopy distribution. Such changes are captured by the low values of reflectance in the red portion of the spectra for early successional stages and high reflectance values in the infrared portion, while late or mature successional stages present the opposite pattern (Figure 2.9).

Since the *T-df* is highly seasonal, another variable that facilitates the separability of the successional stages in IKONOS and Landsat ETM+ is the amount of green biomass by successional stage as a function of the dynamics of forest flushing. In *T-df*, the dynamics of flushing are highly correlated with the availability of water (Reich and Borchert, 1984). Generally the dry season is characterized by a high percentage of deciduous canopies (leaf off – low green biomass), while in the rainy season most of the canopy is in full foliage (Frankie et al., 1974; Bullock and Solí-Magallanes, 1990). In addition, flushing dynamics vary between successional stages, due to a higher percentage of deciduous species in early successional stages than in late or mature forests. As the forest ages, semi-evergreen species tend to populate the forest stand (Janzen, 2000 pers.

comm.). These species present short uneven periods of deciduousness (Reich and Borchert, 1984), a phenomenon that will not affect the amount of biomass perceived by the sensor in late or mature stages.

The high classification accuracy can be attributed to the facility with which the ecological variables were extracted from the IKONOS image. The use of very high spatial resolution data (IKONOS image) allowed the spatial and spectral identification of the different successional stages (Figure 2.6). In the case of Landsat the spatial resolution (28.5 m x 28.5 m) results in mixed pixels along boundaries between classes and negatively impacts the classification. This problem is relevant for the separation of the intermediate and late or mature successional stages. As shown in Figure 2.9, an overlap occurs for the ellipses of these two successional stages in different band combinations. From an ecological point of view, this overlap may represent areas where the forest composition is evolving and the structure starts to change from a medium to a high-density canopy. In these cases, more semi-evergreen species are present and a second layer of vegetation is being integrated into the vegetation community. Two indices (NDVI and SR) commonly used for mapping green biomass extent (Stone *et al.*, 1994; Lobo *et al.*, 1997; Steininger, 2000) also provide a discrimination of the four successional stages. A study carried out in California relating NDVI with canopy structure and photosynthesis in different vegetation types (Gamon *et al.*, 1995) shows that SR and NDVI are good indicators of green biomass in canopies with varying structure and seasonality. The study also revealed that NDVI is highly sensitive to differences in canopy cover in sparse canopy areas.

One of the ecological variables considered in this study is the amount of light reaching the forest floor, which is related to the canopy density and forest horizontal structure theoretical schemes (Figures 2.2-2.4). An increase in biomass and thus, a decrease in the influence of background reflectance as the forest grows is shown by a decrease in NDVI. Similar results were obtained in a controlled experiment by Huete *et al.* (1985) where the spectral behavior of cotton canopies was tested at various levels of vegetation density with different types of soils as background material. Vegetation indices based on band ratios between red and near infrared light (Bands 3 and 4) are optimal to map successional stages in the *T-df.*

2.5 Conclusions and recommendations

1. A description of the ecological characteristics of the tropical dry forest ecosystem (horizontal and vertical forest structure) provides a framework for the interpretation of three different successional stages within the Santa Rosa National Park using remotely sensed data. The use of high spatial resolution data (IKONOS) was key to the accurate definition of successional stages as of training data for the classification of medium spatial resolution data (Landsat ETM+). It may be possible to apply a similar methodology to other areas within the province of Guanacaste and the Peninsula of Nicoya.

2. The methodology presented in this study is based on the relationships between characteristics of the forest (horizontal and vertical structure, canopy density and deciduousness) rather than chronological age. Schematic representations of the forest

classes based on field observations were used to guide the interpretation of IKONOS imagery. Future work could target the direct estimations of some ecological parameters in a automated in an attempt to reduce the amount of subjectivity in the decision process and could improve the extraction of other features within the different successional stages (i.e. crown architecture).

3. The use of vegetation indices that consider the red and near infrared portion of the spectra has provided a means to extract secondary successional stages within the tropical dry forest ecosystem. In addition, these indices (i.e. NDVI) provide a means to minimize class confusion, which could be attributed to changes in illumination angle and topography. As well, the method presented here for creating the contour plots of the indices is advantageous to define the thresholds for the successional stages.

4. Since the forests in the Guanacaste province and the Peninsula of Nicoya are seasonal (tropical dry and tropical moist forest), imagery (Landsat and IKONOS) from other months may add information to improve the detection of successional stages.

Table 2.1. Vegetation indices used in the forest successional stages detection in a *T-df* ecosystem. Santa Rosa, Costa Rica.

Index name	**Formula**	**Source**
Simple ratio	$SR = \frac{\rho_n}{\rho_r}$	Rouse et al., 1974
Normalized difference vegetation index	$NDVI = \frac{(\rho_n - \rho_r)}{(\rho_n + \rho_r)}$	Jordan, 1969
Infrared index	$IRI = \frac{(\rho_n - \rho_m)}{(\rho_n + \rho_m)}$	McMorrow, J. 2001
Mid-Infrared index	$MIRI = \frac{(\rho_{m5} - \rho_{m7})}{(\rho_{m5} + \rho_{m7})}$	McMorrow, J. 2001

Note:

ρ_r = red reflectance (Landsat ETM+ Band 3)

ρ_n = infrared reflectance (Landsat ETM+ Band 4)

ρ_{m5} = mid infrared reflectance (Landsat ETM+ Band 5)

ρ_{m7} = mid infrared reflectance (Landsat ETM+ Band 7)

Table 2.2. ANOVA for different Landsat ETM+ bands

ANOVA Band 3

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value <*	*F crit*
Between Groups	2.07	3	0.6903	4666.49	0.001	2.610
Within Groups	0.28	1867	0.0001			
Total	2.35	1870				

ANOVA Band 4

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value <*	*F crit*
Between Groups	0.958	3	0.3193	460.10	0.001	2.61
Within Groups	1.296	1867	0.0007			
Total	2.253	1870				

ANOVA Band 5

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value <*	*F crit*
Between Groups	6.90	3	2.301	3616.31	0.001	2.61
Within Groups	1.19	1867	0.001			
Total	8.09	1870				

ANOVA Band 7

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value <*	*F crit*
Between Groups	4.13	3	1.3780	3520.30	0.001	2.61
Within Groups	0.73	1867	0.0004			
Total	4.86	1870				

Table 2.3. Classification accuracy assessment of successional stages for the Santa Rosa National Park without considering positional errors.

No Buffer

	Classification					
Validation	Pasture	Early	Intermediate	Mature	**Total**	**Class accuracy**
Pasture	20	2			22	**0.91**
Early		20	4		24	**0.83**
Intermediate		2	28	13	43	**0.65**
Mature			2	29	31	**0.94**
Total	20	24	34	42	120	

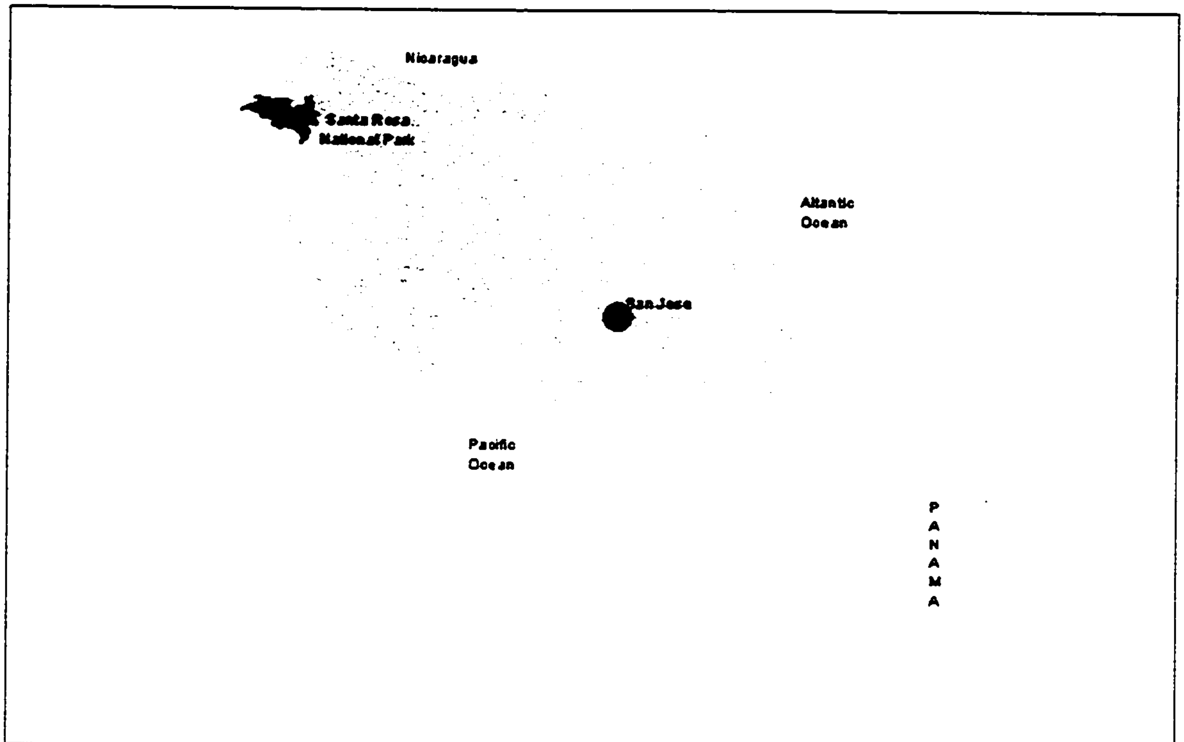
Class Average C(X) = 0.83
Overall Acuracies A(X) = 0.80
Kappa k(X) = 0.74
Tau t(X) = 0.76
Nisshi Estimator uniform priors Juni(X) = 0.837
Nisshi Estimator proportional priors Jpro(X) = 0.80

Table 2.4. Classification accuracy assessment of successional stages for the Santa Rosa National Park considering positional errors (1 Landsat pixel or 28.5 meters).

Buffer 1 pixel

	Classification					
Validation	Pasture	Early	Intermediate	Mature	**Total**	**Class accuracy**
Pasture	22				22	**1**
Early		24			24	**1**
Intermediate			35	8	43	**0.81**
Mature				31	31	**1**
Total	22	24	35	39	120	

Class Average C(X) – 0.95
Overall Accuracies A(X) = 0.93
Kappa k(X) = 0.91
Tau t(X) = 0.91
Nisshi Estimator uniform priors Juni(X) = 0.95
Nisshi Estimator proportional priors Jpro(X) = 0.93



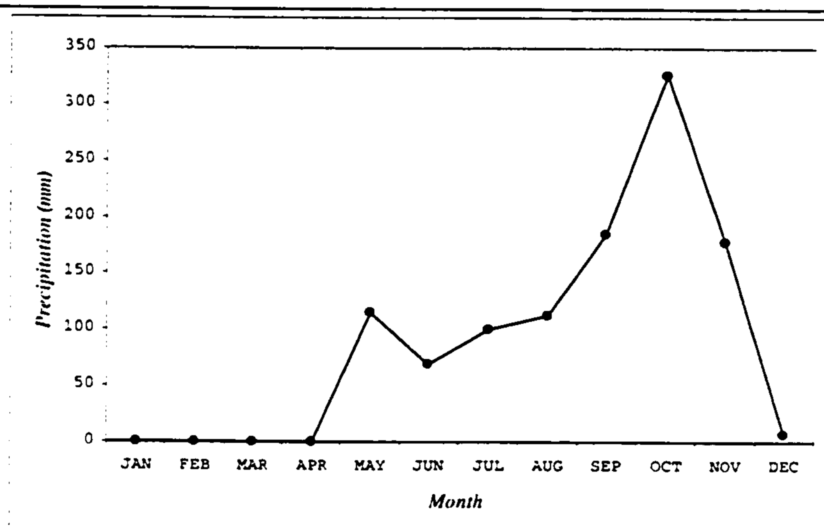


Figure 2.1. a) Location of the Santa Rosa National Park in the province of Guanacaste. Costa Rica. b) Distribution of annual rainfall (Llano Grande Liberia Meteorological Station 1957-1990).

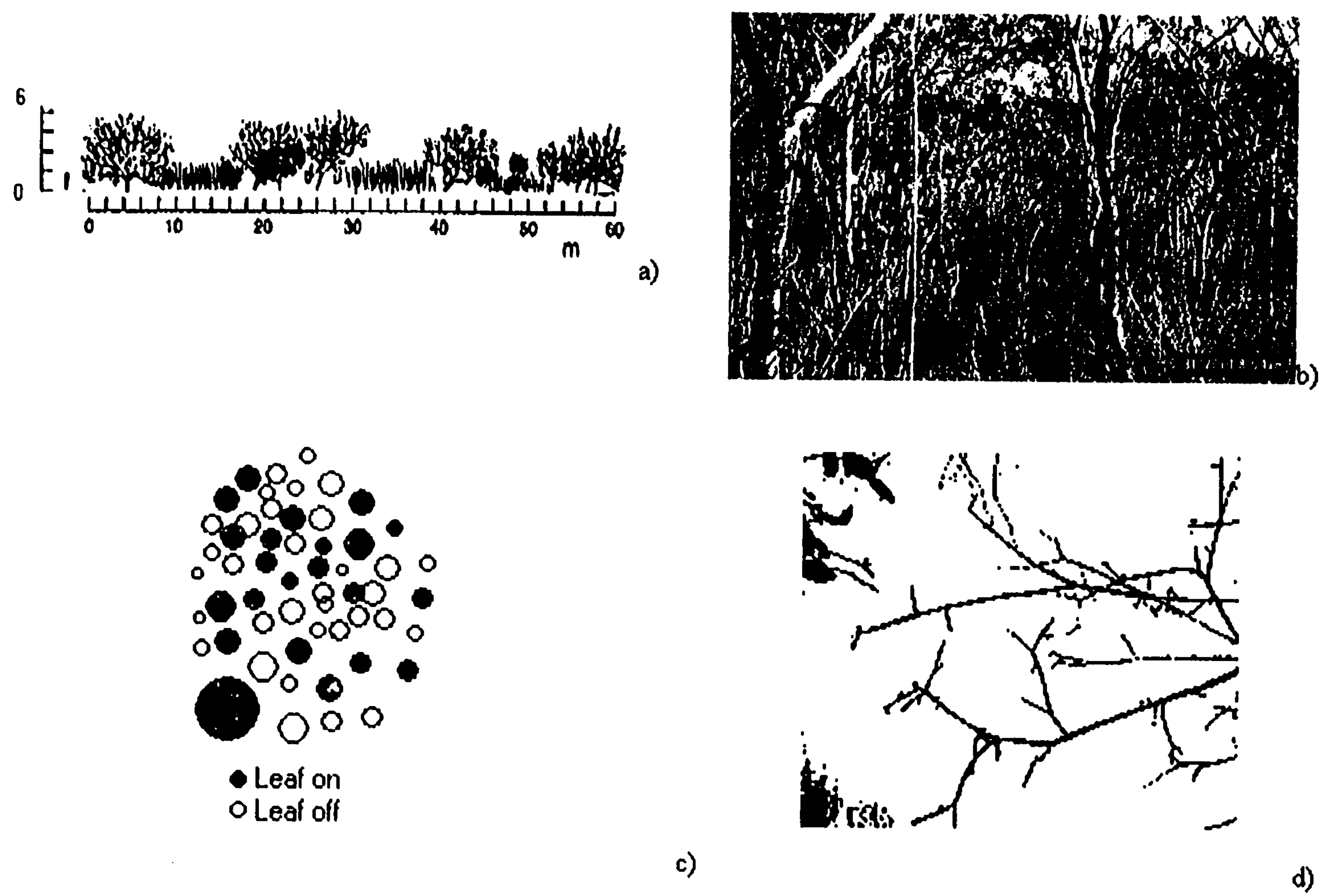


Figure 2.2. Successional stage: Early. a) Horizontal profile (modified from Holdridge et al. 1971). b) Santa Rosa national park vegetation. c) Theoretical sensor view. d) Canopy view from the ground.

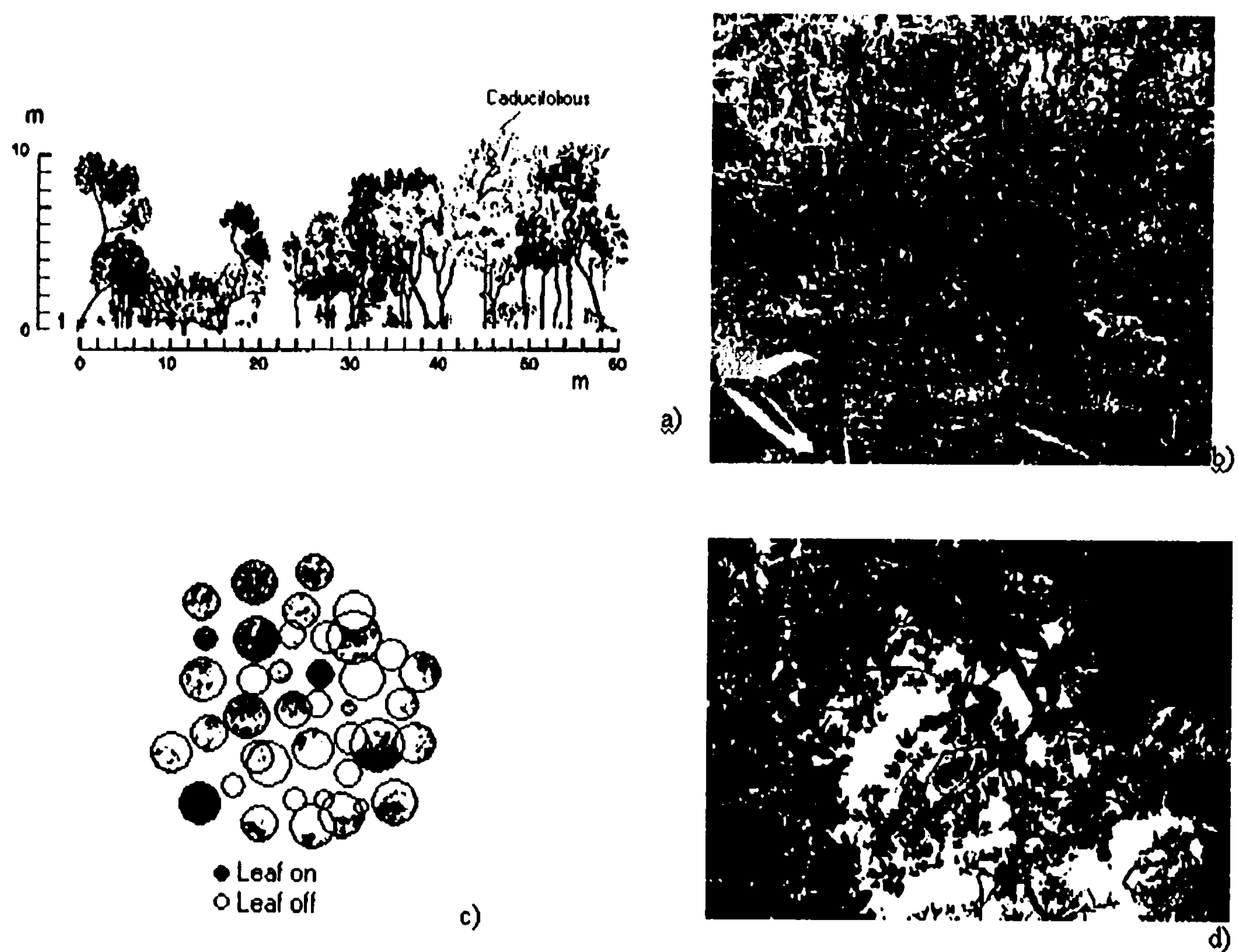


Figure 2.3. Successional stage: <u>Intermediate</u>. a) Horizontal profile (modified from Holdridge et al. 1971). b) Santa Rosa national park vegetation. c) Theoretical top sensor view. d) Canopy view from ground.

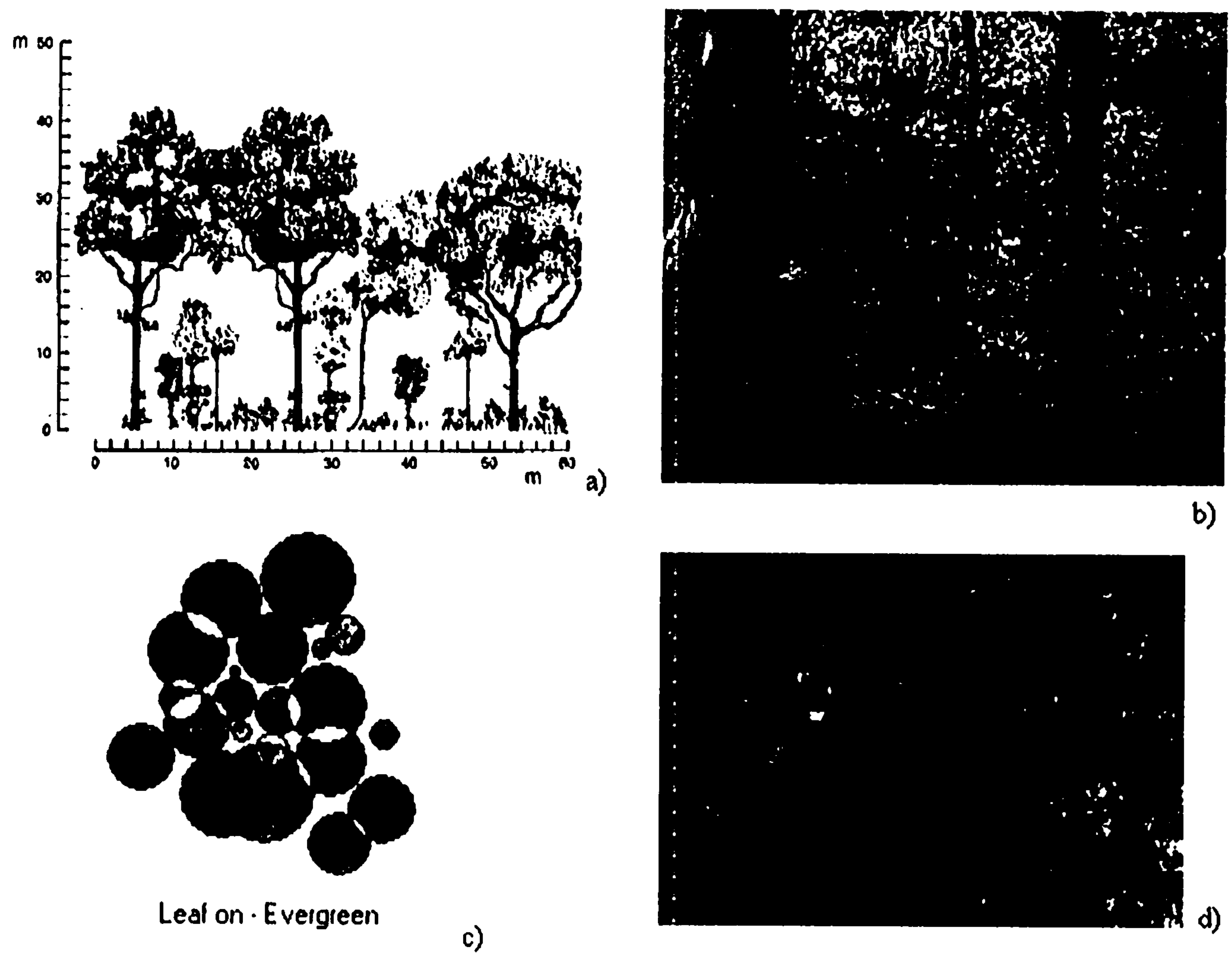


Figure 2.4. Successional stage: Late or mature. a) Horizontal profile (modified from Holdridge et al. 1971). b) Santa Rosa national park vegetation. c) Theoretical sensor view. d) Canopy view from the ground.

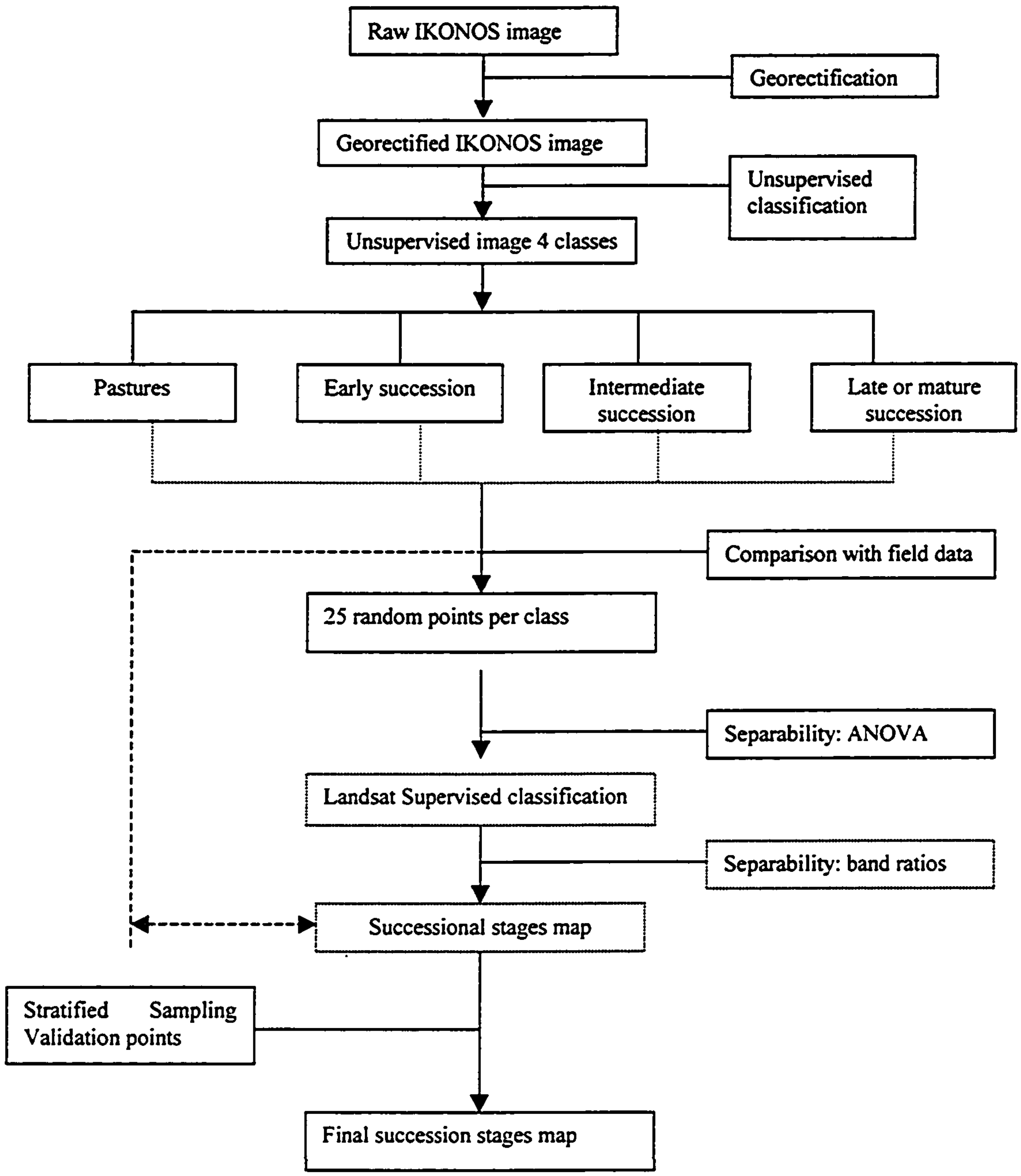


Figure 2.5. Process followed to extract from an IKONOS image detailed ground truthing information for the classification and validation of a Landsat ETM+ image.

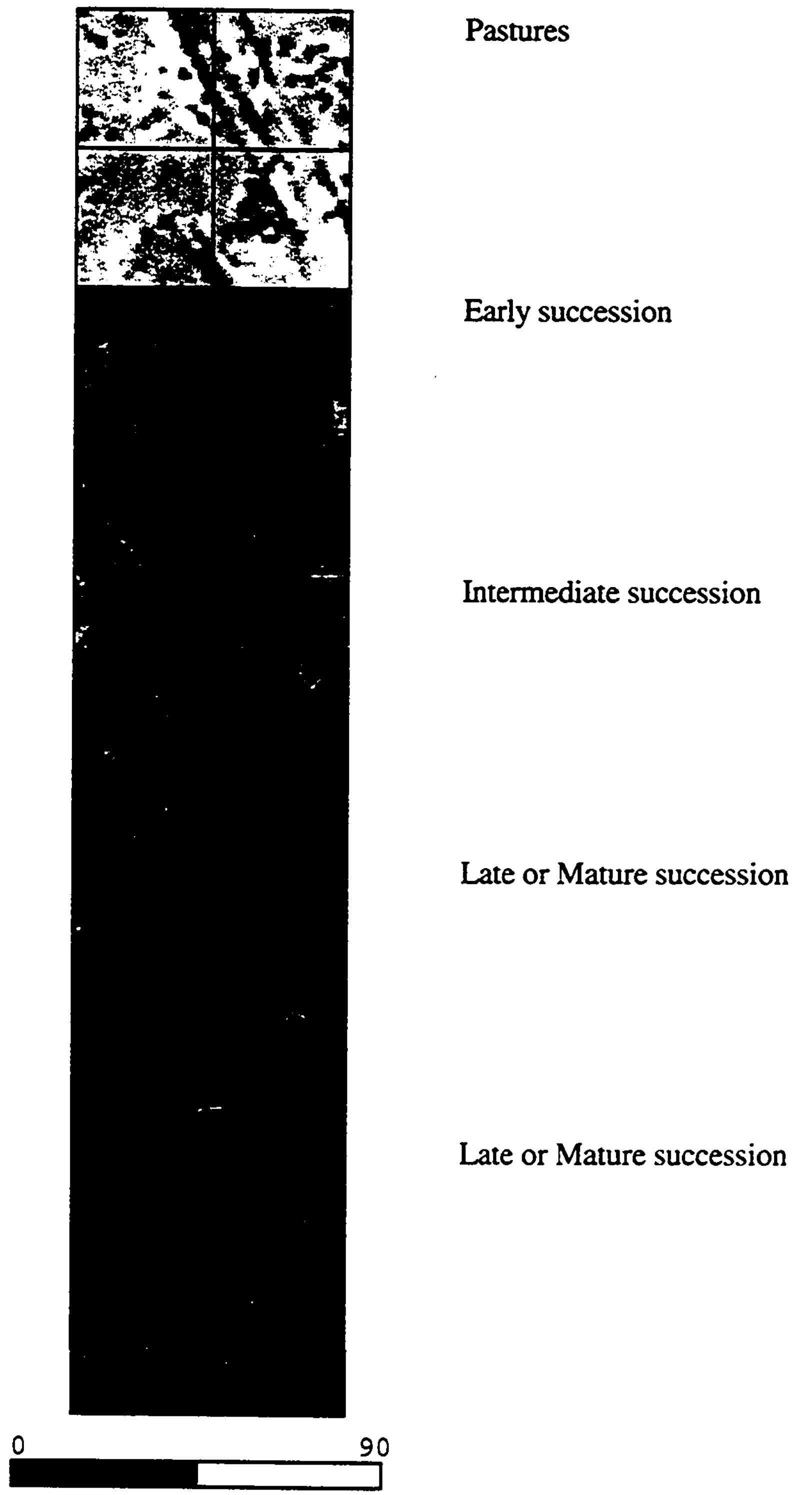


Figure 2.6. Visual interpretation of the successional stages from an IKONOS image (March 2001) for the T-df ecosystem, Santa Rosa National Park, Guanacaste.

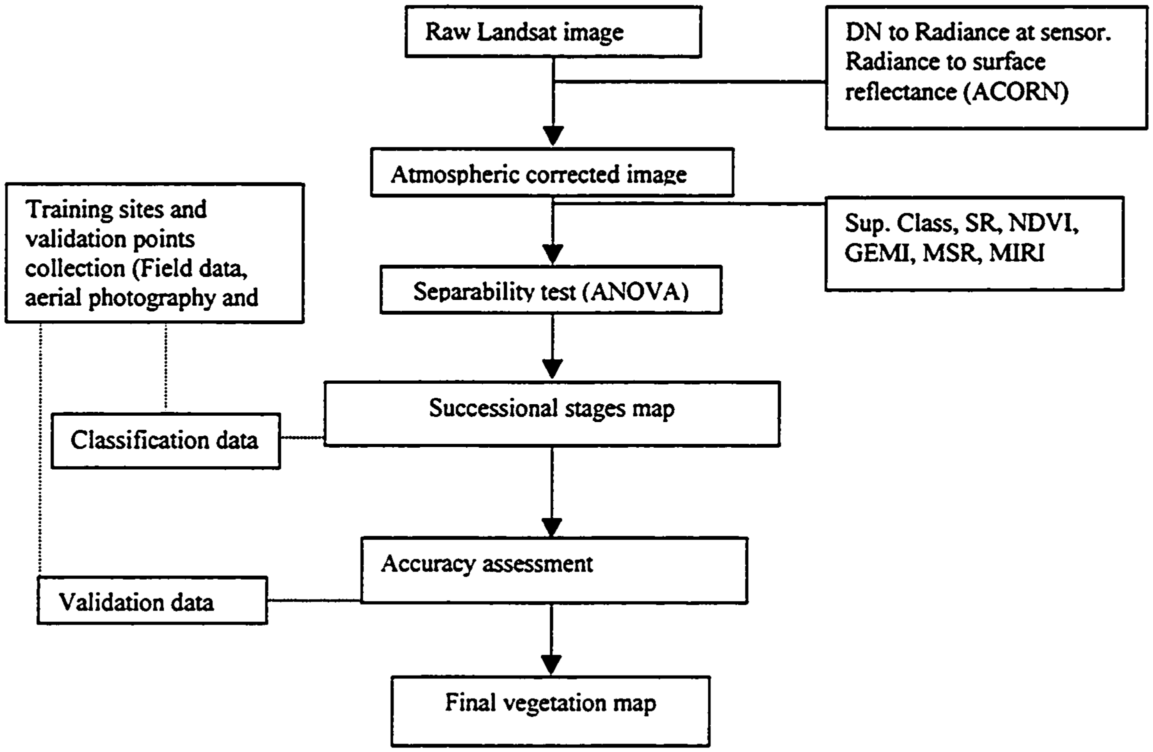


Figure 2.7. Flow chart describing the detections process of forest successional stages using supervised classification and vegetation indices for the T-df ecosystem in Santa Rosa National Park, Guanacaste, Costa Rica.

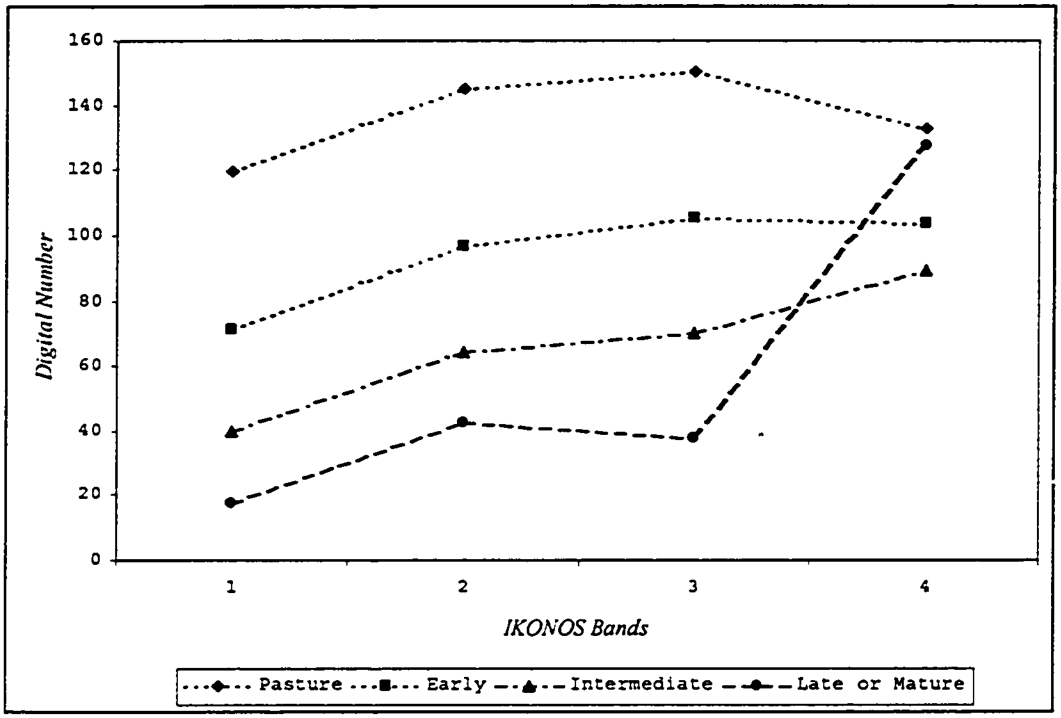


Figure 2.8. IKONOS digital values (Digital Numbers) for 4 successional stages in a *T-df*.

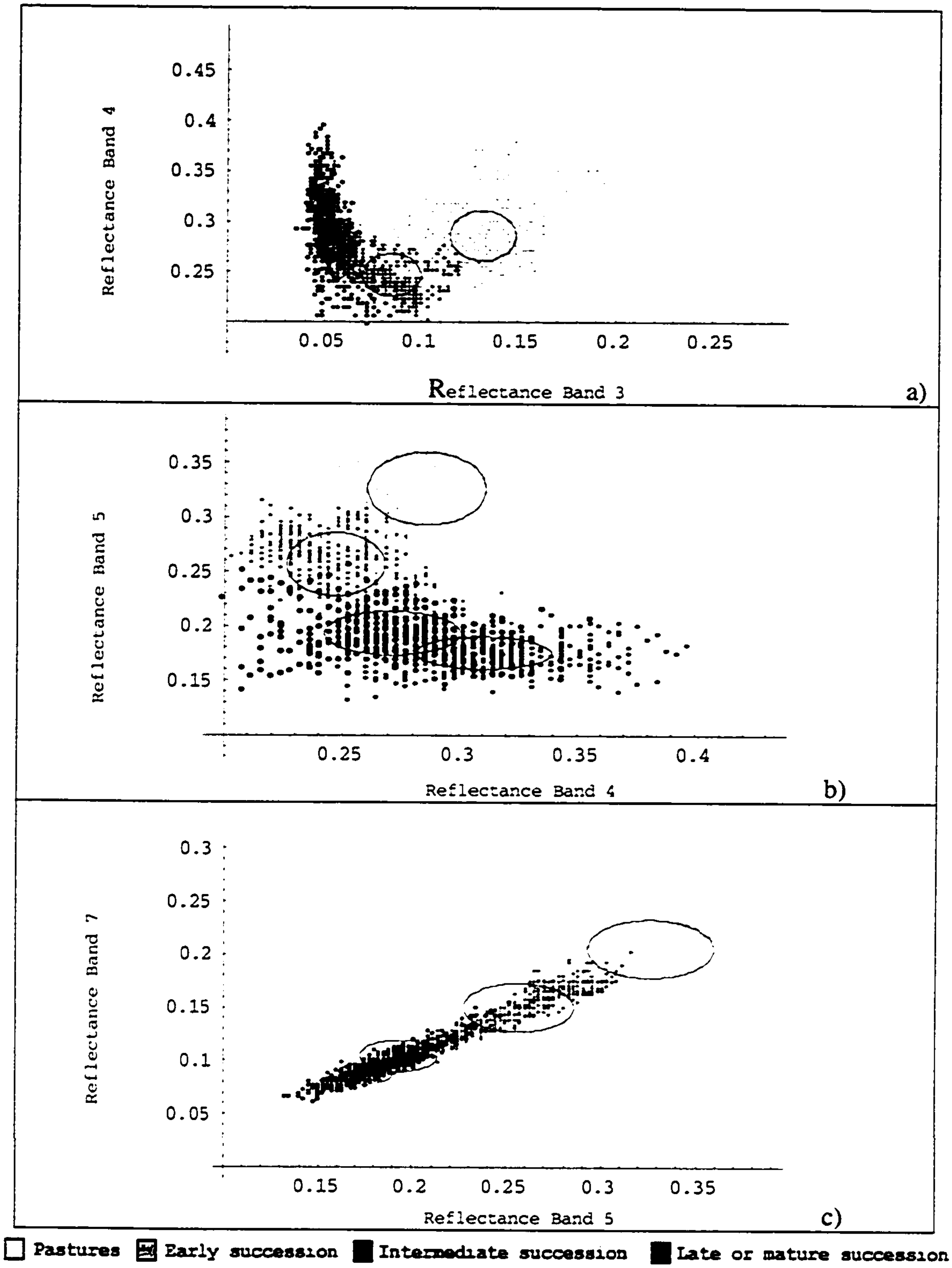


Figure 2.9. Plots of Landsat band (reflectance) per successional stage. a) Band 4 and Band 3. b) Band 4 and Band 5. c) Band 5 and Band7.

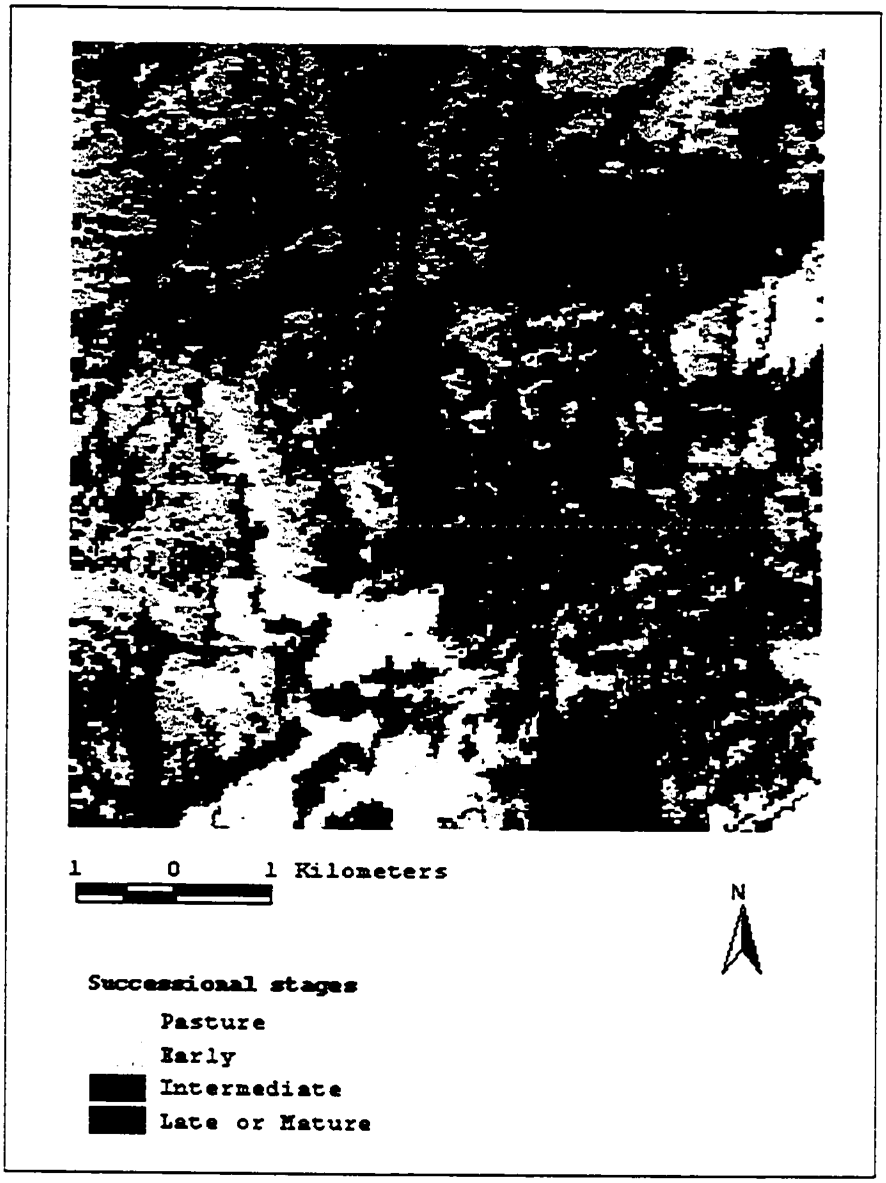


Figure 2.10. Classification map of forest successional stages for a section of T-df in the Santa Rosa National Park, Guanacaste, Costa Rica.

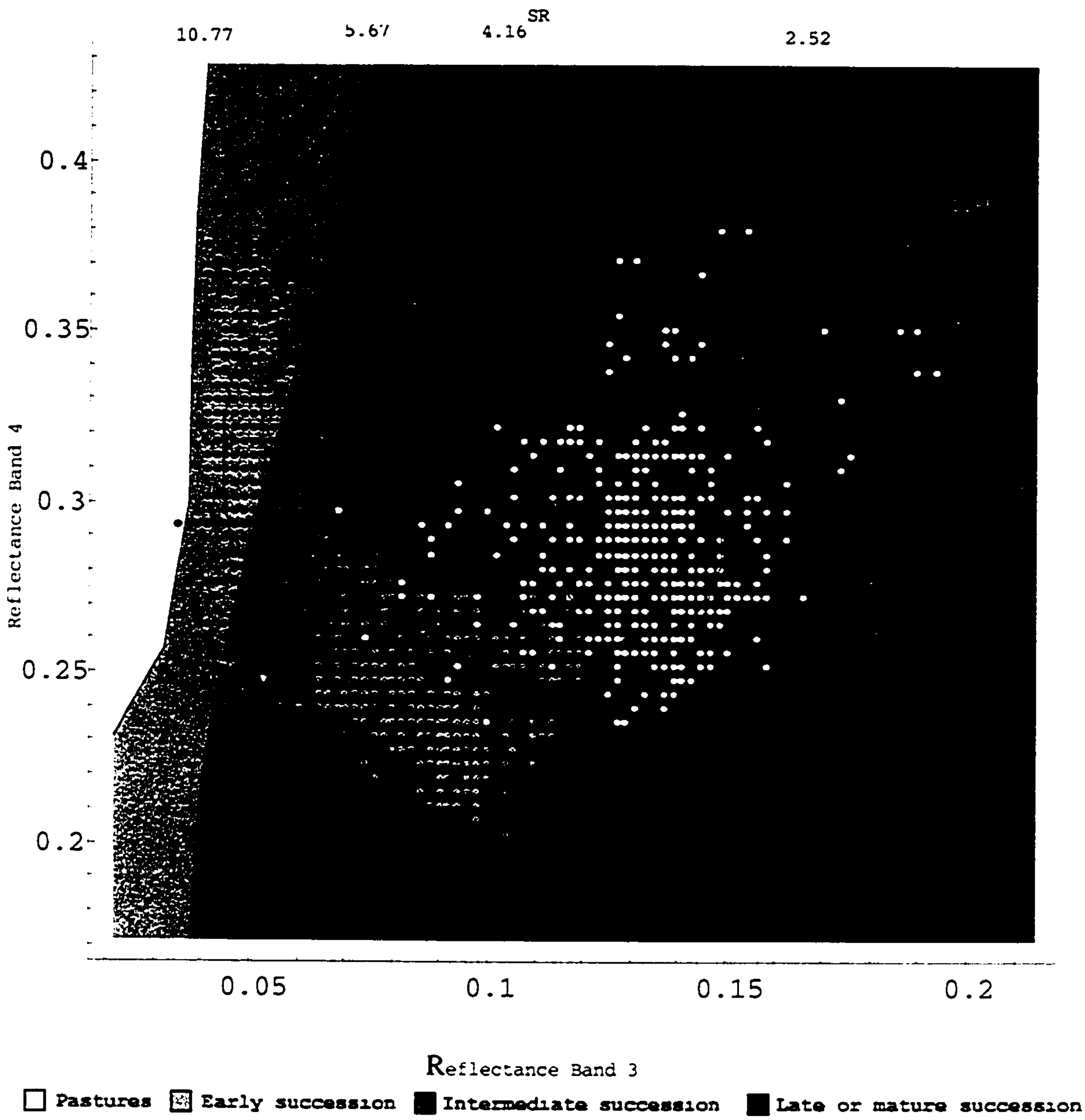


Figure 2.11. SR for Landsat ETM+ image based on successional stages data extracted from a 25 x 25 pixels window in IKONOS

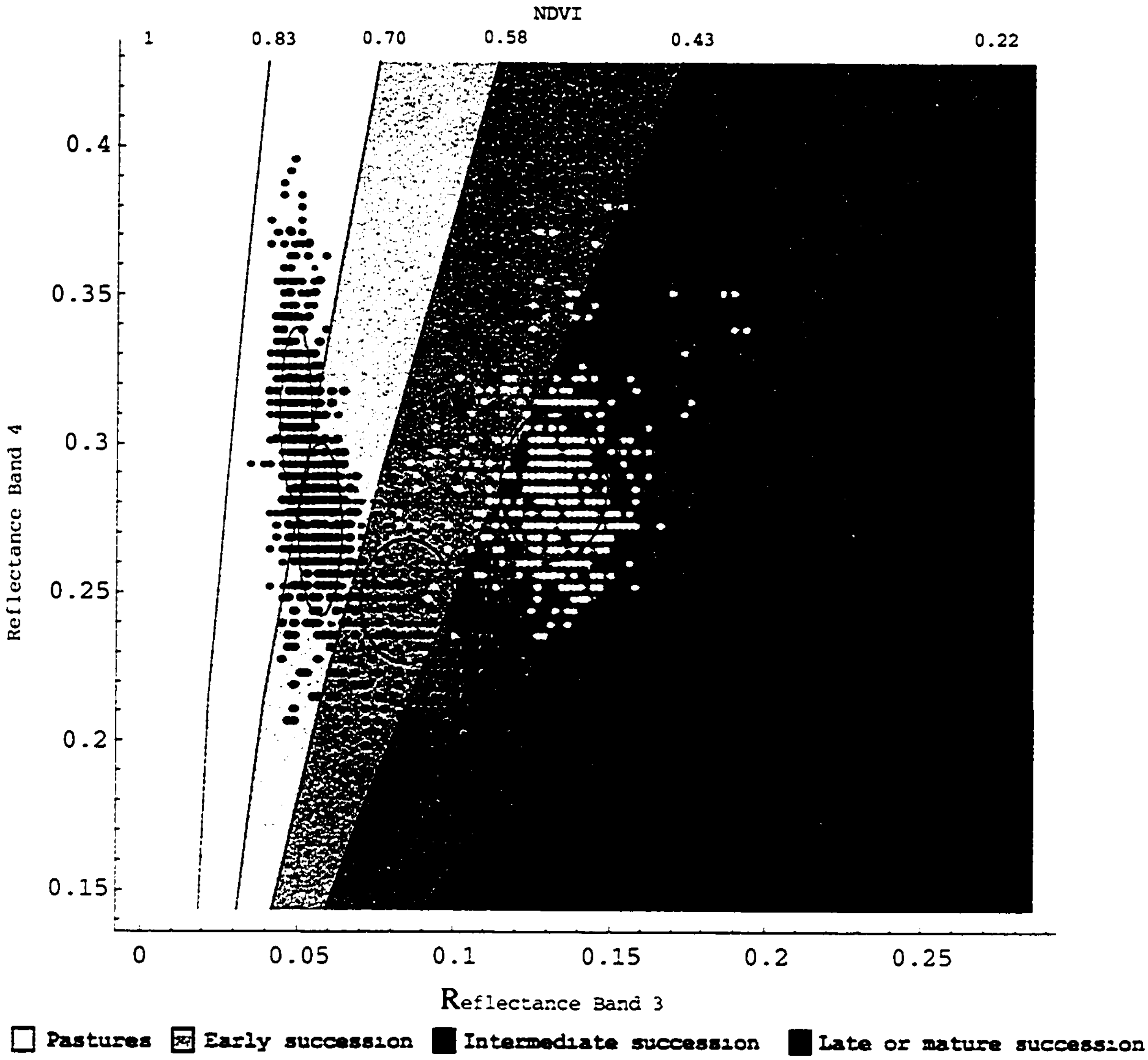


Figure 2.12. NDVI for Landsat ETM+ image based on successional stages data extracted from a 25 x 25 pixels window in IKONOS

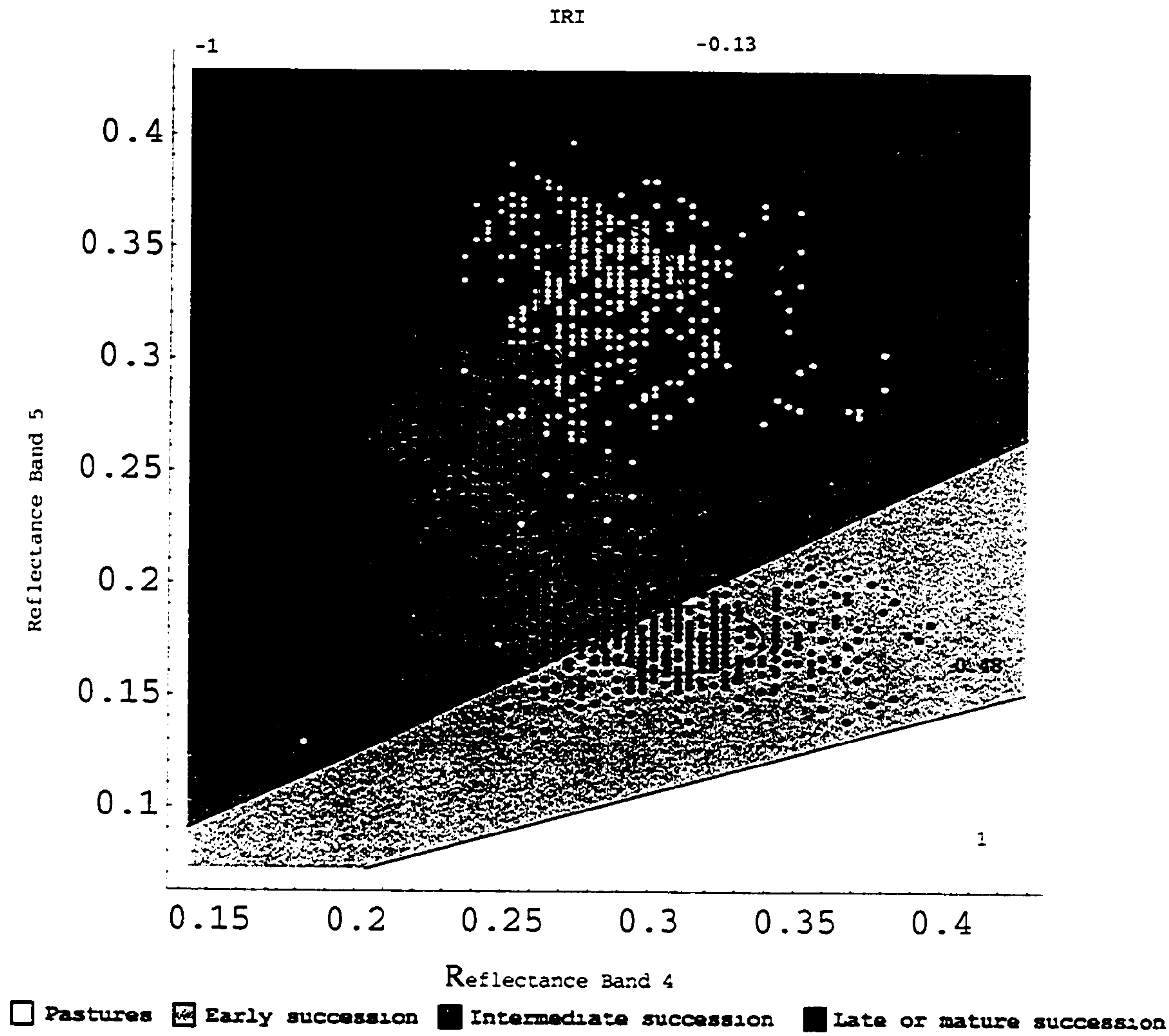


Figure 2.13. IRI for Landsat ETM+ image based on successional stages data extracted from a 25 x 25 pixels window in IKONOS

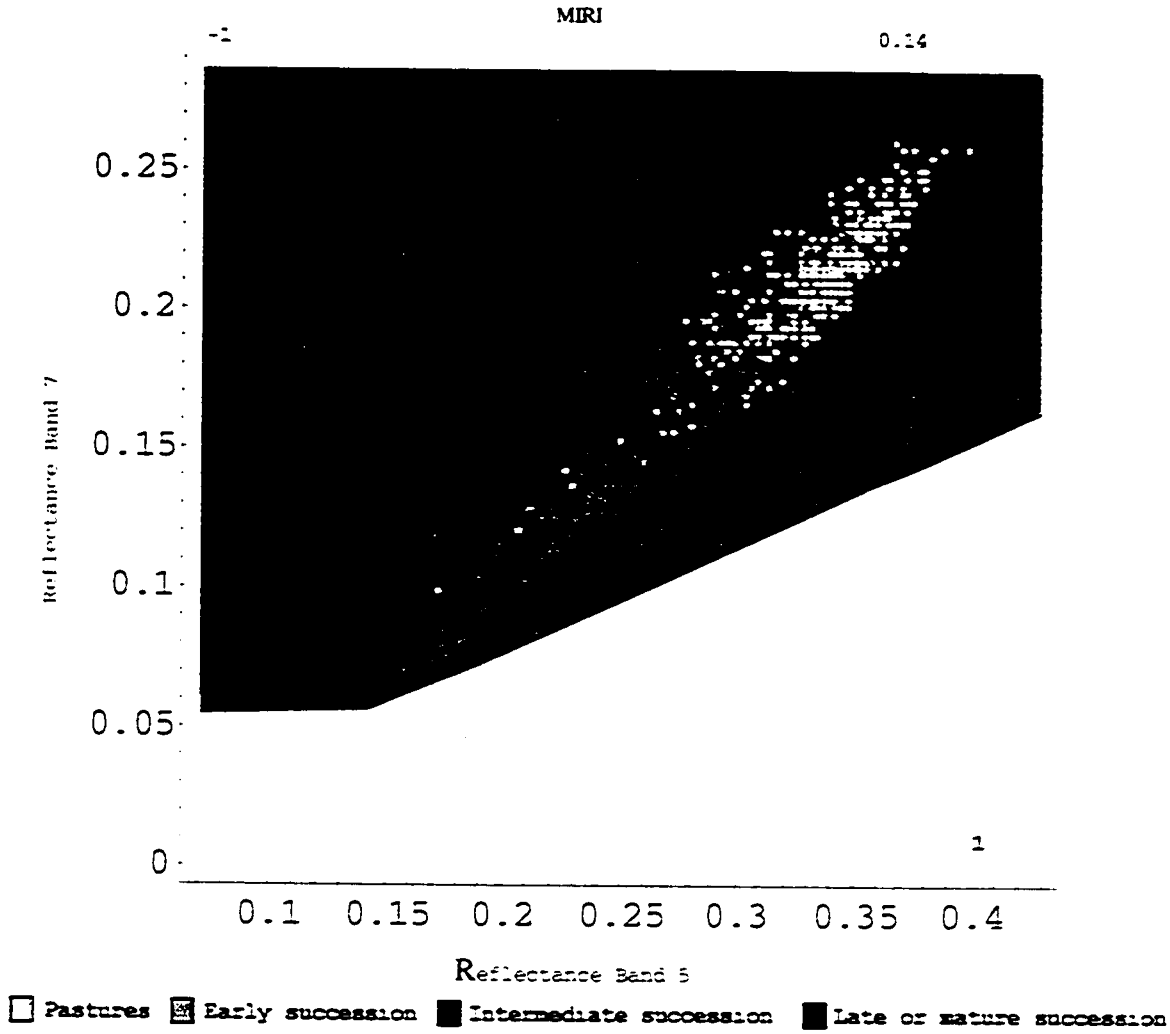


Figure 2.14. MIRI for Landsat ETM+ image based on successional stages data extracted from a 25 x 25 pixels window in IKONOS

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APPENDIX A

Definition of Life Zone

The World Life Zone System defined by Holdridge (1967) takes into account the mean annual precipitation, the mean annual biotemperature and the potential evapotranspiration to predict vegetation characteristics for a given area. Biotemperature is adjusted from the annual temperature to define a range where plants are able to grow (> 0 °C and < 30 °C). Evapotranspiration is defined from the above-mentioned climatic parameters and a constant empirical value. This first level of life zone definition is very general, thus the Life Zone Classification System includes a second and a third level. The second level is more specific and refers to associations, which consider factors such as water availability, soil, topography, etc. The third level is the successional stage, where the development of the ecosystem after disturbance is considered (i.e. early succession, secondary succession, primary forest). Based on this classification system, three life zones are described for the province of Chorotega region. The Tropical Dry Forest (*T-df*), characterized by an annual biotemperature greater than 24°C and a mean annual precipitation of 1000 – 2000mm (Holdridge, 1967), with at least a dry period of five-months. The vegetation of the *T-df* is shorter than in the rain forest, semideciduous and with two strata of trees (Hartshorn, 1983). The Tropical Moist Forest is characterized by an annual biotemperature of greater than 24°C and a mean annual precipitation of 2000 – 4000mm (Holdridge, 1967). The vegetation in mature moist forest stands is tall, multistratal, and semideciduous or evergreen (Hartshorn, 1983). The tropical premontane moist forest is the most altered Life Zone in Costa Rica (Hartshorn, 1983). The mean annual biotemperature is greater than 18 °C, rainfall ranges from 1000 mm to more than 2000 mm (Holdridge, 1966), and the vegetation is comprised of a two layered, semideciduous, seasonal forest. Deciduousness is a characteristic of canopy trees displayed mostly during the dry season (Hartshorn, 1983).

APPENDIX B

Estimator of accuracy

The class average measures how accurate the individual classes were within the classification. It is expressed as follows:

$$C(x) = \frac{1}{r}\sum_{i=1}^{r}\frac{x_{ii}}{n_i} \qquad (1)$$

Where x_{ii} is the diagonal of the error matrix and n_i is the total number of samples

The overall accuracy is the sum of the major diagonal values divided by the total number of sample units in the entire error matrix, and can be represented by equation (3):

$$\text{Overall accuracy} = \frac{\sum_{i=1}^{k} n_{ii}}{n} \qquad (2)$$

Where

n is the number of samples and

k is the number of classes

The *KAPPA* estimator is a measure of agreement between the validation data and the classification data, which is estimated using KHAT statistics ($\hat{K}$). KHAT statistics are based on the difference between the agreement in the error matrix (major diagonal) and the chance of agreement (totals by row and column for every class) (Congalton, 1991). The following equation is used to calculate KHAT;

$$\widehat{K} = \frac{p_0 - p_c}{1 - p_c} \text{ with } p_0 = \sum_{i=1}^{k} p_{ii} \text{ and } p_c = \sum_{i=1}^{k} p_{i+} p_{+j} \qquad (3)$$

Where p_0 is the observed agreement (major diagonal) and

p_c is the chance of agreement (rows and columns totals per class).

Since *KAPPA* has been found to underestimate the overall accuracy (Fahsi et al., 2000), the Tau coefficient (T) was applied. The Tau coefficient is another measure of accuracy based on the error matrix. It adjusts the percentage of agreement better than KAPPA (Ma and Redmond, 1995). Tau is calculated as:

$$T = \frac{(P_o - p_r)}{1 - p_r} \text{ with } p_0 = \frac{1}{N} \sum_{i=1}^{M} n_{ii} \text{ and } p_r = \frac{1}{N^2} \sum_{i=1}^{M} n_{i+} X_i \quad (4)$$

Where P_0 is the agreement percentage and P_r is the random agreement.

In addition, two accuracy estimators developed by Nisshi and Tanaka (1999) were applied to the error matrix. The first estimator $J_{uni}(X)$ is a product version of the class-average accuracy and is sensitive if the classification method is poor. The second estimator $J_{pro}(X)$ takes the fluctuation of sample numbers of categories into account and is moderate even if a great portion of a small category is misclassified. The follow equations show the estimators:

$$J_{\text{uni}}(X) \equiv \prod_{i=1}^{r} \left(\frac{x_{ii}}{n_i} \right)^{1/r} \qquad (5)$$

$$J_{\text{pro}}(X) \equiv \prod_{i=1}^{r} \left(\frac{x_{ii}}{n_i} \right)^{n_i / N} \qquad (6)$$

where x_{ii} is the diagonal of the error matrix and n_i is the total number of samples