PROTECTED AREA MANAGEMENT IN THE WATERSHED CONTEXT: A CASE STUDY OF PALO VERDE NATIONAL PARK, COSTA RICA

By

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PROTECTED AREA MANAGEMENT IN THE WATERSHED CONTEXT: A CASE STUDY OF PALO VERDE NATIONAL PARK, COSTA RICA

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Understanding land-cover change (LCC) is an increasingly important part of the study of global environmental change. Establishing protected areas is one way of conserving or promoting the regeneration of natural land cover, in effort to preserve functional and organismal biodiversity. This case study evaluates the effect of Costa Rica's Palo Verde National Park on LCC in the context of changing land-management systems within the broader Tempisque Watershed from 1975 to 2000.

A novel, rule-based classification technique was developed incorporating data from a watershed knowledge base derived through land-use interviews, agricultural calendars, participatory mapping, and other data to achieve class-wise and overall accuracies $\geq$ 85% for all images. Resulting land-cover maps were used to examine LCC in the park and overall watershed, along with its relationship to the social and biophysical structure of the landscape.

The Tempisque Watershed saw a major shift in land management from extensive to intensive agriculture between 1975 and 2000. Both land-cover and land-use systems in the basin responded to landscape structure throughout this evolution. The nonprotected, lower watershed was characterized by predominance of the following trajectories: grassland to irrigated agriculture, vegetated wetlands to irrigated agriculture, and vegetated wetlands to forest. These trajectories were also dependent on proximity to river. In contrast, lowlands of the park were dominated by persistent vegetated wetland; vegetated wetland transitioning to forest; and finally, open water wetlands closing with vegetation or desiccating to become grasslands. In both the park's uplands and uplands of the nonprotected area, results indicated that reforestation of grasslands was the dominant land-cover trajectory.

The park was effective in conserving and regenerating natural land cover, though results suggest that reforestation might have occurred even without park establishment. Limitations of park management appear to result from factors that are difficult to measure, and that which are seldom considered in park evaluations (such as altered hydrologic connectivity). This unique contextual approach (evaluating LCC in a protected area, while controlling for variance due to differences in landscape structure) contributes to a more complete understanding of the ways in which parks are affected by threats originating beyond their bounds. Results underscore the need to manage parks as part of the landscape rather than as natural-area islands. My case study facilitates a predictive understanding of what LCC might be expected if protection were not in place, and may be useful in scenario planning for integrated watershed management.

CHAPTER 1
GENERAL INTRODUCTION

Land-cover change and Protected Areas

Land-cover change (LCC) is an important component in the study of global environmental change. The dynamic nature of land-cover patterns and changes therein is a multi-scale phenomenon affecting many ecological and physical processes such as trophic structure, species composition and dispersal, sequestration of carbon, climate patterns, water balance and other hydrological processes (Kepner 2000). Moreover, in tropical regions of the world, land-cover change, specifically deforestation, is considered to be one of the most significant threats to biodiversity (Vitosuek 1992). One controversial line of defense that assumes ever-increasing importance is the establishment of protected areas. The extent of tropical land under some degree of protection in the Americas alone has increased dramatically over the last 30 years (Harcourt and Sayer 1996). A better understanding of the role of protected areas in conserving biodiversity and environmental services is critical to counteract potential trends of degradation that may result if parks continue to be managed as islands rather than as integral components of dynamic landscapes (Pringle 2001).

Despite various attempts to evaluate the efficacy of protected areas, their effect is still largely uncertain since the political, socioeconomic and biophysical context of each reserve is unique. Some studies have found parks to be largely effective in preventing conversions related to direct human land use (Bruner et al. 2001, Sanchez-Azofeifa 2002) or in otherwise managing land use and conversion patterns in accordance with management objectives (Walker and Solecki 1999). In contrast, other studies have found natural area conversion and habitat fragmentation to increase, despite legal protection and management activities (Liu et al. 2002).

These studies provide valuable insights regarding the effectiveness of parks, as well as their limitations. One critical element in park research that is seldom addressed, however, is connectivity of the park to larger processes and land-use systems, within a landscape context. Such contextual considerations may elucidate threats originating beyond park boundaries but that are potentially manifested within. Additionally, conservation value in the larger land-cover matrix may be identified that would increase and complement the function of the park (Daily et al. 2003).

One important component of this contextual setting is the park's position in its watershed, yet this theme is rarely treated in the literature on reserve selection, design and management considerations (Pringle 2001). Parks in the upper watershed may become habitat fragments if downstream processes or alterations in hydrologic and habitat connectivity isolate them in ways that preclude species migrations and other related effects that may ensue. In contrast, reserves located at the middle or lower portion of their watersheds must integrate changes in land-use or hydrologic regime, and sources of pollution that occur generally upstream of them (in the broad sense of the term referring to the complete hydroscape). Evaluations of LCC within the watershed context may illuminate combined social and environmental processes driving landscape change and the potential effects of such forces on protected areas. Thorough case studies incorporating these dimensions of protected areas may provide a greater understanding of how parks are performing, and how their management might be better integrated into landscape processes.

Study Region: Palo Verde National Park and the Rio Tempisque Watershed

In this study, watershed context refers to the historic and current land-management systems in the watershed, their implications for land-cover dynamics, and the ways in which the biophysical and social structure of the landscape either constrains or facilitates certain land-cover conversions. This evaluation of protected area management in the watershed context is a case study of Palo Verde National Park (PVNP), located at the bottom of the Rio Tempisque drainage basin in Guanacaste, Costa Rica. The Tempisque Watershed has an extent of 5,404 km^2 with a mean temperature of 27.5^{o} C and mean annual precipitation of 1817 mm falling between May and November (Mateo-Varga 2001). The Tempisque River runs generally north to south through the center of the basin, while the Guanacaste Mountain Range runs northwest to southeast, defining the eastern border of the basin.

Within the larger watershed is PVNP, residing in the central, southern portion and defined by the Tempisque River along its western boundary. PVNP is approximately 18,760 ha in area and protects a diverse mosaic of habitats, including the world's most endangered habitat type, tropical dry forest. Less than two percent of the tropical dry forest's original extent remains along the Pacific slopes of the Mexican and Central American isthmus (Janzen 1988), making PVNP critical in its conservation effort. Other forest types within the park include lowland deciduous forest, moist evergreen forest, flooded forest and limestone forest. Over one-third of PVNP is composed of a wetland mosaic that historically provided critical habitat for migratory waterfowl. For this reason, the site was given RAMSAR protection in 1991 (Mateo-Varga 2001).

Remote Sensing of Tropical Land Cover

Remotely-sensed satellite data of the earth's surface are increasingly being used to quantify the extent and pattern of land-cover change. Such land-cover data may also be combined with other variables measured on the ground, to derive land-use information and changes therein. Though at times the distinction between land use and land cover may be subtle, the definitions used in my study are those set forth by Jensen (2000) where land use refers to how land is being used or managed by humans. In contrast, land cover consists of the actual biophysical covering on the ground (e.g.,, forest, rock, or grain).

A given land use may have many different associated land covers, depending on the nominal resolution of the classification scheme. Different phenological stages of wetlands or of crop cycles for agricultural land may constitute different land covers. Likewise, a given land cover may have many different land uses. For example, grassland may serve as pasture or road margin. Clearly, both land uses and land covers are defined within nested hierarchies with taxonomic resolution increasing at each higher level of the hierarchy. A coarse land-cover resolution might be forest while increasing resolution may define different types of forest (deciduous versus evergreen) and even different successional stages of each type (leaf out versus senescence for deciduous forests). Similarly, coarse land-use categories may include the broad category of agricultural land use, while increasing taxonomic resolution may specify a given crop and its management regime.

Despite the utility of satellite-based datasets, in many tropical regions, remotely-sensed land-cover data yield unacceptable levels of classification accuracy. Factors such as intra- and inter-annual differences in precipitation, along with structure of the landscape (e.g.,, topography or spatial frequency of patterns under study) all affect the degree to which land-cover change can be accurately quantified (Langford and Bell 1997, Ortiz et al. 1997). Increasing the taxonomic resolution of classification schemes may exacerbate the challenges of accurately classifying land cover and derived land use.

An inherent advantage of satellite-based landscape change evaluations, however, is the ease with which a protected area can be placed in the context of its host landscape. The extent of common satellite imagery (such as Landsat or mosaics made with multiple Landsat scenes), is large enough to examine land-use and land-cover change within a given protected area and its surrounding watershed using the same, consistent data source. Remotely-sensed LCC data may comprise one of many components in a Geographic Information System (GIS). A GIS of the region of interest may define, in a spatially explicit manner, features of the social landscape (such as roads and property boundaries) along with gradients of the biophysical landscape (such as elevation and slope).

This integration of remote sensing and GIS facilitates analysis of the historic and current land-management systems in a protected area's watershed, and the implications of these systems for land-cover dynamics over time and space. Understanding the ways in which biophysical and social landscape structure constrains or facilitates land cover trajectories allows for a much more robust evaluation of the effect of protected area management by controlling for extraneous factors. Such an understanding is also requisite in better integrating the management of protected areas and those land-use activities occurring outside their bounds.

Research Objectives

My first objective was to develop a technique that adequately classifies the land use and land cover of interest for the study region, and to compare results of this technique to results achieved using a standard classification algorithm. This advanced and novel approach circumvents many of the challenges associated with remote sensing of tropical land cover. Specifically, this technique uses a rule-based approach to image classification that incorporates the products of two distinct, standard classification algorithms, along with knowledge of the spectral, spatial and temporal domains to classify land use and land cover in the study region. This detailed classification procedure is described in Chapter 2.

The second objective, covered in Chapter 3, is to present a case study of the effectiveness of protected area management in its larger, watershed context. Specifically, I ask (1) how have land use and land-cover changed in the Tempisque River Basin and Palo Verde National Park over the last 25 years? and (2) what is the effect of Palo Verde National Park on land-cover change given the watershed context?

The way in which Palo Verde fits into the larger biophysical and social landscape was examined by comparing several landscape variables for the park and nonprotected watershed. In this study, effectiveness is defined as the successful conservation and regeneration of natural land cover. Thus, effectiveness of Palo Verde National Park is evaluated by examining net area land-cover change across the three dates in the study and also by trajectory analysis in which the conversion sequences explaining net-area trends for all land covers are summed over the landscape. Comparisons for protected and nonprotected areas are made to determine how protected status may explain differences in land cover patterns.

In Chapter 3, I evaluate the effectiveness of Palo Verde National Park in conserving or promoting the regeneration of natural land cover in several different ways. First, I examine net area land cover trends over the study dates. Next, I perform a spatially explicit analysis to understand, when summed over the entire landscape, which land covers are converting to which. I determine the domains of competing land cover trajectories, as defined by a series of landscape variables, for both the park and the nonprotected area of the watershed. Finally, I project what land cover trajectories might be observed if the park had not been established by comparing the bivariate domains, as defined by linear combinations of the landscape variables from Principal Components Analysis, for the nonprotected area against the park. In Chapter 4, I synthesize the results from the classification technique and the analysis of the protected area performed using land cover data produced from it, and suggest directions for future research.

CHAPTER 2
INCORPORATING DOMAIN KNOWLEDGE AND SPATIAL RELATIONSHIPS INTO LAND-COVER CLASSIFICATIONS: A RULE-BASED APPROACH

Introduction

Regardless of the methods and techniques employed, efficacy and accuracy of remote sensing technology in constructing land cover models and performing change-analyses vary by geographic regions due to a number of considerations. Factors such as seasonal and inter-annual differences in precipitation, along with differences in landscape structure, play a part in this variation. Also, the differing abilities of available sensor platforms to accommodate the temporal and spatial challenges posed by these factors (Berberoglu et al. 2000) affect the ways in which land cover dynamics may be studied through remote sensing. In certain tropical environments remote sensing of land cover using traditional techniques often yields unacceptable results in terms of surpassing a pre-determined threshold for classification accuracy (Langford and Bell 1997a). The growing array of environmental changes that researchers and practitioners seek to monitor via remote sensing underscore the need for reliable techniques that accurately and consistently classify problematic tropical land cover.

Given preeminence of tropical deforestation issues and the inherent advantages of model simplification, many land-cover classification schemes for tropical landscapes are dichotomized into forest and non-forest land-cover types (e.g.,, Sanchez-Azofeifa et al. 1999, Peralta and Mather 2000, Southworth, Munroe and Nagendra 2004). Depending on the study area, however, the landscape dynamics and processes of interest may only be understood with finer resolution classification schemes. Such schemes come at a price though since increasing the number of information classes often confounds the process of achieving sufficient accuracy (Congalton 1991). This accuracy penalty is particularly significant when land cover maps' application includes cell-based analyses of land-cover change. In such spatially explicit change-analyses, misclassified cells propagate error and may multiply its effect in analyzing cell-based land cover trajectories (Mertens and Lambin 2000).

Many of these considerations are relevant in the current study region, an area in northwestern Costa Rica, where land cover maps will ultimately be used to understand spatially explicit land cover conversion dynamics (Daniels, in prep.). Key land cover classes of interest include rain-fed, seasonal wetlands and deciduous dry tropical forest ecosystems, both of which are problematic in remote sensing. Both vary dramatically in terms of their spectral characteristics and ecological processes, between the wet and dry seasons. Ideally composite classifications may be produced across seasons to reduce classification error associated with phenological differences (Maxwell et al. 2002). In this way, land cover classes of interest are classified when their spectral signatures are most easily distinguished from other possible overlapping spectral classes (Vogelmann et al. 1998). Alternatively, radar platforms are being increasingly used for mapping tropical land cover, particularly in areas of usual cloud cover or below-canopy inundation (Simard et al. 2002).

Constraints on the utility of paired-season imagery and radar platforms abound, however, including resource limitations or inadequate historic archives of non-Landsat imagery to capture the phenomena in question. For these reasons, the study of tropical land cover dynamics, recognized as an increasingly important element of global change phenomena, stands to benefit greatly from experimentation with alternative methodologies that remedy some of the conundrums discussed here.

Spatial Relationships and Domain Knowledge

A considerable amount of the information held in remotely sensed data lies in the spatial domain (Curran 2001). Spatial context for pixels of satellite imagery may be defined in terms of pixel neighborhoods (e.g.,, Chen et al. 1997, Murai and Omatu 1997, Sharma and Sarkar 1998, Chan et al. 2003) whereby the relationship between proximate pixel values adds to the spectral information that can be potentially used to distinguish classes of interest (e.g.,, in the form of texture). The sensor-based rationale for using pixel neighborhoods lies in an artifact of data collection whereby measured radiance may be smeared from one pixel to the next. The geostatistical rationale is based on the idea of spatial autocorrelation wherein spatial dependencies amongst adjacent pixels can be modeled (e.g., through a semivariogram) to increase accuracy of the classification (Atkinson and Lewis 2000). In either case, this approach to incorporating the spatial domain is top-down in that it relies on statistical manipulation of reflectance data alone, a single spatial interpretation element among several available in any given remotely sensed dataset.

Another way of invoking the spatial domain is through incorporating broader landscape contextual information. In traditional image interpretation, such information is fundamental to remote sensing. King (2002) argues that since the inception of digital, automated processing, however, interpretation of contextual data such as position in landscape, association, and an understanding of dominant land use systems has long been underutilized. Integration of Geographic Information Systems (GIS) and remote sensing allows for the incorporation of ancillary data that may bring in such landscape contextual information into the classification criteria in a semi-or fully automated fashion. For example, Ortiz et al. (1997) used GIS to integrate historic, multi-source databases about agricultural land use systems into the classification of croplands in Brazil. The authors observed a substantial increase in accuracy after using the databases (0.47 to 0.67 for the Kappa statistic) compared with results from maximum likelihood classification of spectral data alone.

Rule-based classification, possibly more than any other technique, lends itself to incorporation of a wide array of ancillary data. The synthesis of contextual, biophysical, land use and spectral data achieved through rule-based approaches captures some of the advantages of bottom-up image interpretation (e.g.,, visual, manual techniques) without sacrificing many of the benefits of automated, digital processing. Hutchinson (1982) employed Boolean logic rules on slope, aspect and spectral classification data to improve classification of several prominent classes of a California desert region that exhibited considerable spectral overlap. In a more sophisticated approach, Bolstad and Lillesand (1992) constructed an expert system that was executed through rules to classify land cover in northern Wisconsin. Ancillary data in the expert system included soil texture and topographic position. The authors observed a 14 % improvement in accuracy with the rule-based expert system compared to a standard maximum likelihood classifier of spectral data alone. The additional time involved in the construction of the expert system may be warranted in cases where high accuracy is vital.

In addition to the intended application of land-cover classifications, many factors are considered in determining the methodology used to derive land cover from satellite imagery (Lambin 1997). These include the available datasets, number and types of land cover classes, along with time allowance and financial budget. Another important consideration is the efficacy of standard methods to adequately classify the landscape into categorical land cover components. A number of alternative or complementary techniques have been developed that are applicable to cases where standard supervised classification methods are not appropriate and/or yield less than acceptable accuracy. These alternatives include post-classification sorting, rule-based classifiers, decision trees and artificial neural networks (ANN).

While the various methods differ markedly in their underlying and operative rationales, in most cases they share a common theme of incorporating domain knowledge to facilitate ‘intelligent’ classification. In this research, domain knowledge refers to knowledge of the region or range of values --of any measured gradient such as location, slope, spectral space-- within which an information class of interest can be described as occurring. For example, the domain of riparian vegetation may be at less than five percent slope, within 100 m of a stream and with a near-infrared reflectance value greater than 75 and less than 125.

Post-classification sorting exploits knowledge of discriminating variables to improve upon classification results by adding criteria that split mixed spectral classes or that reclassify them into their corresponding information classes (Vogelmann et al. 1998, Janssen et al. 1990). Similarly, rule-based methods classify land cover according to compliance with set criteria or an expert system that defines each information class of interest (Onsi 2003, Sader et al. 1995, Bolstad and Lillesand 1992). Decision tree classification is a particular, statistically sophisticated case of the rule-based approach wherein a hierarchy of rules is employed in an automated, top-down, dichotomous fashion (Hansen et al. 1996, De Fries et al. 1998, Simmard et al. 2002). At each decision node, the parent group is split into increasingly homogenous sub-groups. ANN is a sophisticated, automated, pattern-recognition process that acts on complex, heterogeneous data sources according to the selected network architecture such that learned patterns are used to classify remotely sensed data into categorical information classes (Augusteijn and Warrender 1998, Murai and Omatu 1997). Here I develop a simple, weighted rule approach to classifying land cover and land use but the approach draws conceptually from these various methods that incorporate domain knowledge.

Specifically, this research proposes a classification method via Boolean logic rules that is tailored to the challenges posed by the study region's landscape and to the need for highest conceivable classification accuracy. This rule-based approach incorporates the products of two distinct standard classification algorithms, along with domain knowledge in the form of many ancillary datasets used to form a knowledge-base upon which Boolean logic is founded. Relatively few, if any, studies have sought to apply techniques that incorporate logical reasoning in the classification of tropical land cover. Similarly, little if any work has been done to explore the utility of logic-oriented, rule-based classification on historic satellite imagery. The purpose of this research is one of comparing results of the land-cover classification series from the proposed method with those of supervised classifications of spectral data alone via the Gaussian maximum likelihood classifier.

Materials and Methods

Study Area

The study area is the Tempisque-Bebedero River Watershed in the northwestern province of Guanacaste, Costa Rica. The eastern limit of the watershed is defined by the Guanacaste Mountain Range running Northwest to Southeast and reaching over 2000 m in elevation. The 5,404km2 basin lies within the limits of geographic coordinates 84o 49’ 30” W to 85 o 47’ 44” W and 10 o 06’ 20” N to 10 o 53’ 46” N. The annual mean temperature is 27.4 o C with mean annual precipitation of 1817 mm falling from May through November. Thirteen Holdridge life zones (Holdridge 1967) are found within the basin hosting a great diversity of vegetation communities from tropical dry forest, to moist premontane forest, to vast seasonal wetlands. Agriculture is the dominant economic activity within the watershed with sugar cane, paddy rice, and melons (Saccharum sp., Oryza sativia, and Cucumis melo respectively) being the principal crops. Cattle ranching has served as a defining economic and cultural force in the landscape since Spanish colonization, though less important in recent years after changes in the beef market and implementation of a regional irrigation system which motivated new land uses in the region.

Satellite Images

Four separate Landsat multi-spectral remotely sensed images covering the study area were obtained from two sources for years 1974 (MSS), 1975 (MSS), 1987 (TM), and 2000 (ETM) during the dry season (Table 1-1).

All bands were used in processing MSS imagery. For TM and ETM imagery, bands 1-5 and 7 were used. MSS images were resampled to a pixel size of 30 x 30 m in order to match that of later imagery without sacrificing their finer spatial resolution, though quite obviously this resampling affords no greater resolution to the MSS images. Sixty ground control points were located on the 2000 image and their geographic coordinates taken in the field with a handheld GPS unit whose mean uncertainty was approximately 6.5 m. The RMS error achieved from this first order geometric transformation was 0.4880 or less than 15 m. All other images were co-registered to the 2000 image via image to image registration using first order transformations and up to 139 reference points to achieve RMS error values of less than 0.5 or 15 m. Final positional accuracy of geocorrected images was validated in the field with the aid of a handheld GPS.

Radiometric data were converted from radiance to ground reflectance (Jensen 2000) by correcting for sensor gain, atmospheric distortion and differences caused by non-anniversary dates using the calibration technique of Green et al. (1999). Despite these calibration procedures, images had to be trained separately and classified using unique signatures since the range of data were not comparable for the images in the series. The first World Reference System (WRS1) used by Landsat platforms 1-3 did not contain a single path/row combination to cover the entire study area. Thus, MSS images from 1974 (Path 17, Row 53) and 1975 (Path 16, Row 53) were mosaiced together with a RMS error less than 0.5. This image mosaic is hereafter referred to as 1975 since approximately 85% of mosaic is comprised of the 1975 image. Exact vertical pixel correspondence for all images when stacked was verified with an overlay function. Cloud cover on the slopes of the cordillera along the eastern fringe of the watershed was eliminated from all images such that the final area matched exactly for each image year. This means that the area of the satellite images used in the classifications was slightly less than the true extent of the watershed. All image processing was carried out using ERDAS Imagine 8.5.

Precipitation Data

Vegetation biomass is positively correlated with precipitation (Fang et al. 2001). Precipitation trends prior to image capture have been shown to affect red and near-infrared band reflectance (Ji and Peters. 2004). The Pacific slope of Costa Rica experiences both drought and periods of unusually high rainfall and flooding associated with ENSO events (Waylen and Laporte 1999). In order to take into account the effects of climatic variability on land cover dynamics throughout the temporal and spatial extents of the study, precipitation data were compiled from seven meteorological stations managed by the Costa Rican Institute of Electricity (Instituto Costaricense de Electricidad, ICE) and the National Meteorological Institute (Instituto Meteorológico Nacional, IMN).

A time series of precipitation across the entire study period was constructed using the mean of several meteorological stations positioned throughout the watershed [Appendix A]. The 12 months and roughly 30 days preceding the date of each image were highlighted to examine how image years fit in with overall climate patterns. Also, mean monthly precipitation was calculated, using a greater number of stations, for the twelve months preceding each image date and also that for the thirty preceding days [Appendix A]. Precipitation for the 12 months preceding the 1987 image was substantially lower than that of the other image dates (99.36 mm/month versus 132.92 mm/month and 192.49 mm/month for 1975 and 2000 respective), but since the image was taken at the beginning of the dry season, the preceding 30-day average was substantially higher (27.8 mm versus 0 mm and 2.19 mm for 1975 and 2000, respectively). The year 2000 image's mean monthly precipitation (calculated using the preceding twelve months) was higher than the other images due to the cold phase (characterized by high precipitation and flooding) following the 1997-1998 ENSO event. Matching spectral transects of all land-cover types for regions of no-change were explored on each of the calibrated images in order to understand how variability in precipitation affected reflectance.

Training Samples

Training sample data for the 2000 image were collected via ground-based field work conducted in August and September of 2002. Due to inability to locate sufficient numbers of adequate randomly generated training sites (private property and other access issues), training data for the 2000 image were not all random, as they would have been ideally (Congalton 1988). To compensate for this limitation, a high number of training samples were collected with locations spread evenly throughout the watershed. In addition, special attention was paid to collect a plethora of training data in the lower watershed where high land cover heterogeneity was expected to pose more difficulty during the classification process.

For 1987 and 1975 images, training data consisted of randomly generated ground truth points projected on historic aerial photo mosaics covering portions of the total watershed. Aerial photos were purchased from the Costa Rican National Geographic Institute (Instituto Geografico Nacional, IGN). They were scanned, mosaiced and georeferenced to within less than 20 m of their corresponding satellite images. For the 1987 image, 298 training sites and 393 reference sites were located on a mosaic of 1987 dry-season photos of 2854 km2 in extent at a scale of 1:35,000. For the 1975 image, 200 training sites and 368 reference sites were located on a 1450 km2 mosaic of 1:20,000 scale dry-season photos. Training sample data were used in image classification to characterize statistical distributions (per band) for each land cover class. In contrast, reference sites were used only in accuracy assessment to determine how well the classification algorithm had performed.

Land Use Interviews

A total of 29 semi-structured land use/parcel history interviews were conducted throughout the watershed [Appendix B]. These interviews served several important functions. They were used to inform the creation of agricultural calendars [Appendix C] to aid in photo and satellite interpretation of various land-cover types associated with common agricultural land uses, along with their corresponding phenological cycles. They were used to qualitatively assess classification accuracy beyond the limits of the area referenced by photo-mosaics. And finally, the interviews, in conjunction with GPS-based participatory mapping activities, were used to create vector data for the knowledge-base that informed rules for the classification process. These vector data included polygons and point locations of historic wetlands that have since been converted to other land uses, historic pasture boundaries, current and past agricultural field polygons and historic river beds.

Classification Scheme

Ultimately, the land cover maps generated are used to examine the effects of irrigated agricultural land use on the trajectories of other land-cover types relative to gradients in the biophysical landscape and whether or not land is protected for conservation purposes (Daniels, in prep.). This application guided the classification scheme adopted in this paper. More specifically the effects of irrigated agricultural land use on the trajectories of other land-cover types relative to gradients in the biophysical landscape are examined. As such, the final information classes of interest were comprised of an amalgam of both land cover and land use classes. Land cover classes employed were water (representing open, non-vegetated wetlands), vegetated wetlands, grasslands, and forest. Land use classes were urban and irrigated agriculture. For land use classes, several distinct land cover classes were grouped under their headings, aided by the agricultural calendars created with land use interviews. Specifically, the information classes of interest were defined as follows:

- **Irrigated agriculture**: Dominant land covers include irrigated crops *Oryza sativia* (rice), *Saccharum sp*. (sugar cane), *Cucumis melo* (mellon), bare soil, water (flooded rice fields prior to germination), and *cachaza* (by-product of sugar refinement used as an organic fertilizer). Minor crops include *Cucumis sativus* (cucumber) and *Allium cepa* (onion). Agricultural calendars [Appendix C] offer chronology and detailed descriptions of land cover throughout each major crop's planting cycle.

- **Water**: This class was intended to correspond to the land cover of *non*- or sparsely vegetated wetlands. However, several phenological phases of flooded rice cultivation gave nearly or precisely the same reflectance signals. Thus, pixels described by the latter case were properly classified into desired information classes through the rule-based algorithm, despite that the actual land cover and spectral classes were nearly identical.

- **Vegetated Wetlands:** The Ramsar interpretation of wetlands was adopted for the purpose of defining wetland land cover in this study.[1] A great diversity of flood regimes and hydroperiods is evidenced by myriad types of wetland communities. The Tempisque Watershed has lotic systems, mangroves, flooded forests, fresh marshes and fresh meadows. Vegetation community characterizations of the various wetland communities is found in Appendix D.

- **Urban:** This land use class covers all anthropogenic land cover in population centers. For example, spectral classes for urban land use include those of mixed concrete and asphalt and residential areas (mixed vegetation and houses). Because of the heterogeneity of reflectance surfaces within each pixel area, nearly all of the spectral classes for urban land use were comprised of averaged spectral signals for a given 30 x 30 m area.

[1] "Wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters" (Article 1.1, Ramsar Convention on Wetlands, 1971).

- **Grasslands:** This land cover class was divided into sub-groups, the first three in which land use largely determined dominant vegetation and thus reflectance characteristics. These sub-groups were as follows: strict pasture (often actively managed) with grasses only, pasture with occasional trees, recently fallowed pasture (approximately $\leq$ 3years) that was still largely dominated by grasses, grassy areas where soils or fire frequency does not support abundant tree growth (e.g., areas of volcanic slopes) and finally, miscellaneous grasses lining roads and other public works. Vegetation characterization of each type is found in Appendix D.

- **Forest:** The diversity of Holdridge Life Zones and biophysical niches in the watershed is evidenced by myriad forest types. The watershed is characterized by limestone forest, deciduous lowland forest, evergreen lowland forest and pre-montane moist forest. Rainy season canopy closure of $\geq$ 40% was required to qualify as forest land cover. Vegetation community characterizations of each type of forest is found in Appendix D

Land-cover classifications

Spectral signatures were created for the six information land cover and land use classes of interest (irrigated agriculture, water, vegetated wetlands, urban, grassland, forest) using the training data gathered from field work (for 2000) or from photo-interpreted training data (for 1987 and 1975). Each information class was comprised of a number of spectral classes since a single information class may represent more than one successional or phenological stage of its land-cover type, etc. Classifications were performed using two distinct algorithms: the Gaussian maximum-likelihood classifier and the parallelepiped classifier. The former is a relative classification algorithm that relies on effective training data from all classes and assumes that reflectance data for each class in each band has a Gaussian distribution (Jensen 2000). This algorithm is more robust since it takes the covariance of the data into consideration (Ozesmi and Bauer 2002). However, not all data are normally distributed and this classifier can perform quite poorly in such cases.

The parallelepiped classifier is an absolute algorithm wherein each pixel meeting the defined upper and lower limits for each band for a given class, is assigned to that class. The major drawback with this algorithm is that the n-dimensional spaces defined by such upper and lower limits for n bands often overlap for different classes (Jensen 1996). A given pixel is then assigned to the first class for which it meets the criteria (i.e., assignment by order). However, due to the non-normal distributions in one or more spectral classes comprising wetland, grassland and forest information classes, a separate classification using the parallelepiped algorithm was produced. The purpose of the parallelpiped classification was for incorporation into the rule-based classification for non-normally distributed data.

Other Data and Knowledge Base

Other data included a digital elevation model (DEM) of 30m spatial resolution (x,y) and 1m elevation resolution (z) which was obtained from the OTS Palo Verde Research Station. From this, a slope model was produced. Normalized Differenced Vegetation Index (NDVI) layers were produced that indirectly give an indication of the amount of biomass on a per-pixel basis. For TM imagery NDVI is calculated as (band 4 – band3)/ (band 4 + band 3) and as (band 4 – band 2)/ (band 4 + band 2) for MSS imagery.

A layer of point coordinates for all population centers was created using a GPS to record the location of each town center. Identification of population centers was informed by topographic maps of 1:50,000 scale (updated various years from 1974 to 1987). Polygons of agricultural fields of large landholders were created through photo-interpretation of the aerial photo-mosaics for 1975 and 1987. All current and, where possible, past agricultural fields/major landholdings were mapped in the field using a GPS and the assistance of employees on large-scale agricultural operations, along with manual interpretation of the 2000 satellite image.

Three spatial analyses were performed whose products were used in the rule-based algorithms to afford the classification process logical reasoning with regard to domain knowledge. The first model created a raster surface dividing all pixels into one of two groups: those that fall within the bounds of agricultural fields (as defined by created polygons) and all others. Similarly, the second model produced a raster surface which divided all pixels into those that fell within the defined buffer around population center coordinates (of varying radii depending on the size of the town) and all others. The third spatial model isolated all water pixels in the Tempisque and Bebedero Rivers and calculated the nearest distance to river pixels from every other pixel in the watershed. When coupled with other criteria, the surfaces created with these models provide a means of incorporating spatial context and association into automated algorithms. These and all other ancillary data comprising the knowledge base upon which the class domains, and thus classification rules were based, are summarized in Table 2-1.

Processing Flow for Rule-Based Classifications

As mentioned above, the maximum likelihood and parallelepiped classifiers each have advantages and disadvantages. The methodology proposed in this paper, summarized in Figure 2-1, is novel in that it employs a simple, rule-based, classification technique wherein the advantages of the parallelepiped and maximum likelihood classifiers, along with domain knowledge, are combined without resorting to advanced statistical approaches developed for unique scenarios like partial classifications (see Fernandez-Prieto 2002). Furthermore, logic-oriented processing is afforded by the incorporation of domain knowledge and landscape contextual information via IF/THEN Boolean logic rules. Such advantages and disadvantages of the proposed technique relative to using a single classifier alone are summarized in Table2-2.

Each rule defines spectral, spatial and other criteria, developed from the knowledge base, for the classification of all pixels (Table 2-3). Select rules are based upon the concept of post classification sorting (e.g., Rule 1c in Table 2-3). This sorting approach was used to address systematic errors noted in the products of the traditional classifications. That is to say, in cases where a spectral class represents a land cover (e.g., water) belonging to more than one information class (in this case irrigated agriculture or non-vegetated wetland), spatial context was used to sort pixels belonging to that spectral class into the correct information class.

As shown in Table 2-3, a given class has multiple rules. If all of the criteria for any single rule are satisfied, the result is assignment of the pixel of consideration to that class. The criteria for each rule, however, are not necessarily mutually exclusive. However, each rule has an associated probability or weight carefully based on confidence and logic developed through the knowledge building process. Any pixel meeting the criteria of more than one rule is assigned to the class whose rule has the highest weight setting up a hierarchical structure amongst rules. If a pixel is not classified by any of the applicable knowledge-based rules, the default assignment of any given pixel in an image is to the class that the pixel in question would be assigned by the maximum likelihood algorithm. In essence, this default rule for each class ensures that if the classification process cannot be improved upon through the knowledge-based rule criteria, accuracy can get no lower than what would be achieved through a traditional maximum likelihood classifier alone. This default rule is assigned the lowest weight of all rules defining a given information class.

Accuracy Assessment

Standard accuracy assessment was performed for all images wherein independent reference test pixels based on fieldwork (for 2000 image) or photointerpretation (for 1975 and 1987) were compared with the classification results. Reference pixels were obtained in two rounds: one round concomitant with training samples and one round of additional points after stratifying the landscape according to land cover categories. Accuracy was assessed for the products of traditional classifiers and for the proposed method in order to determine the level of improvement afforded by the rule-based technique. Indeed, some of the post-classification sorting rules (such as Rule 3c) were informed through careful assessment of errors observed in the matrices and classified image from the maximum likelihood classification. All accuracy assessment was based on comparisons at the information class level since that was the maximum taxonomic resolution gathered for reference points. That is to say, spectral classes were merged into their corresponding information classes for accuracy assessment.

Measures of classification performance calculated in the accuracy assessment process included overall accuracy, class-wise producer's accuracy (index of errors of omission), class-wise user's accuracy (index of errors of commission) and both overall and class-wise KAPPA statistics (see formula in Appendix E).

Results

Comparing results from the traditional maximum likelihood classifier versus the rule-based product (Figure 2) shows unambiguous improvement in both producer's and user's accuracies, along with substantial improvement in the Kappa coefficient (Table 2-4). This trend holds for each class-wise comparison for each year (Figure 3) as well as the overall classification comparisons per year (Table 2-4). Overall accuracy and Kappa coefficients from each method are summarized in Table 2-4. Overall classification accuracy was improved about 12%, 13% and 29% for the 2000, 1987 and 1975 images respectively. These figures suggest that incorporating ancillary data for logic-oriented processing has greatest potential for increasing accuracy in the classification of historic satellite imagery and, perhaps, particularly such imagery with coarser spatial resolution like that of the 1975 MSS image employed in this case study.

Despite that values for specific criteria in rules were adjusted according to the defined domain for that land cover in a given year, the overall structure and hierarchy of the classification rules proved consistent throughout the series. This suggests that there is great potential for the heretofore unexplored territory of incorporating ancillary data in a rule-based fashion into series' of land-cover classifications (as opposed to this research which explicitly defines rules for each unique year in the series).

Errors of omission and commission shown in each year's error matrix (Table 2-5), along with visual inspection of anticipated problem areas, elucidate the nature of misclassified pixels from the maximum likelihood algorithm. The land cover classes of vegetated wetlands and forest both demonstrated consistent misclassification trends for all three years. Vegetated wetlands were either over-classified (1987) or under-classified (1975 and 2000) due to confusion with irrigated agriculture, forest and grassland. Misclassification of grasslands as vegetated wetlands in 1987 was primarily due to anticipated spectral overlap between grassland and seasonal wetland that was further exacerbated by low precipitation in the months preceding the 1987 image capture. In all years, spectral characteristics of irrigated, high biomass, monoculture sugar cane fields overlapped considerably with wetland vegetation such as monotypic stands of cattail

(*Typha dominguensis*) resulting in confusion between irrigated agriculture and vegetated wetlands classes. Similarly, flooded riparian forest and mangrove areas were misclassified as forest instead of being included in the vegetated wetland class. While the rule-based approach did not eliminate these systematic errors, it did ameliorate them largely due to domain knowledge introduced in Rule 1b, Rule 3a, and Rule 3b (in Table 2-3).

Consistent misclassification trends for forest land cover throughout the image series was due to confusion with vegetated wetland (as addressed above) and grassland. Spectral overlap between forest and grassland occurred for several reasons. Similarity between forest and a grassland sub-class called ‘pasture with trees’ caused some of this overlap. Though ‘pasture with trees’ exhibited substantially less than 40% canopy required for meeting forest criteria as defined in this study, the crowns of common pasture trees like the Guanacaste (*Enterolobium cyclocarpum*) are sufficiently large so as to bias reflectance measured within its respective pixel area. Another challenge was presented in distinguishing between fallowed grasslands (< 3 years fallow) and early successional forest, a sub-class of forest land cover. Clearly, this is an arbitrary distinction and illustrates a common problem in discrete, nominal classification of land covers. Making this distinction via interpretation of aerial photo-mosaics for training and reference sites for the 1987 and 1975 images was particularly challenging and arbitrary, though land use interviews did prove to be an invaluable resource in this process. Nonetheless, if such categorical land cover classes are the desired product, incorporating domain knowledge as in Rule 5a and Rule 6d proved effective in improving the accuracy of classification into these pre-defined categories.

Irrigated agriculture land cover was confused with vegetated wetland (as addressed above) for all years, with urban land use for 1975 and 1987 and additionally with grassland for 1987. Confusion with urban land use occurred at the edge of agricultural fields where mixed reflectance from narrow, terrain roads and crops gave signals similar to those of population centers. The urban buffer analysis, as applied in conjunction with other criteria in Rules 1d and 4, was effective in eliminating most of this error. Confusion of irrigated agriculture with grasslands in 1987 was related to spectral similarities between irrigated crops and high-elevation, vibrant pasture along the cloud-bathed slopes of the Guanacaste Mountain Range. Rule 5b applied elevation and near infrared criteria which eliminated this systematic confusion.

Open wetland (water) was over-classified in the 1975 image due to great confusion with forest in the upper watershed occurring at substantial slopes and thus often in topographic shadows due to the time of day at which the image was captured. Rules 2a and 6a exploit slope criteria to effectively eliminate this misclassification tendency. Similarly, flooded rice paddies (within the irrigated agriculture class) prior to germination were systematically confused with open wetland. Spatial relationships incorporated in Rule 1c proved effective in ruling out this misclassification.

Urban land use was wholly misclassified in the 1975 maximum likelihood classification because their smaller size, coupled with coarser spatial resolution, allowed them to go undetected by in the MSS image. While the urban buffer analysis applied in Rule 1d and 4a (as discussed above) did facilitate the detection of urban land use, the class was still under-classified in the first image. While classification for the 1987 and 2000 images by the maximum likelihood classifier was reasonably accurate, confusion with irrigated agriculture for these years was eliminated (see above) and misclassification of grasslands as urban was ruled out via application of the urban buffer model in Rule 5c.

Finally, grassland land cover was confused with several classes as has been discussed in the context of these classes' misclassification tendencies above. Though domain knowledge applied in the rule-based approach definitely enhanced the ability to discern between confused classes, classifications from the rule-based method still demonstrated slight misclassification with forest (1975 and 1987) and vegetated wetland (2000).

Discussion

Consistent with many other studies employing ancillary data in the classification process, the proposed rule-based approach suggests that incorporation of appropriate domain knowledge is an effective way of achieving high classification accuracy for complex, heterogeneous landscapes such as the Tempisque Watershed. One of the shortcomings of the proposed methodology is that, despite final digital/automated algorithms, the logic behind each rule was derived through an extensive process relying on human interpretation of complex datasets. The costs and benefits of classification improvement via logic-based processing and incorporation of domain knowledge must be carefully considered.

Murai and Omatu (1997) employed a neural network, pattern-recognition algorithm on spectral data alone and then incorporated a rule-based correction phase reliant upon geographical knowledge that reduced misclassifications due to cloud shadows and averaged reflectance over a given pixel's ground area. While this method was computationally more complex than that proposed in the current paper, intelligent processing was achieved in a semi-automated fashion (the advantage of any form of true artificial intelligence). In contrast to the landscape contextual approach emphasized here, geographical knowledge was limited to using adjacent pixel associations in the form of pixel neighborhoods, a top-down approach that incorporates no new or independent information to complement satellite data. However, the actual utility of integrating pixel associations was afforded by human reasoning. That is to say the construction of IF/THEN rules was still largely dependent upon human input. The error correction rule-based algorithms eliminated some but not all error.

Other studies have reported no improvement in accuracy as a result of incorporating additional data for consideration in the classification criteria or algorithm employed. Southworth (2004) explored the utility of incorporating thermal data in classification of land cover in the dry forest region of Yucatan, Mexico. While blackbody temperatures were show to be strongly correlated with land cover classes and have great potential in land cover analysis, the incorporation of thermal data did not statistically improve classification results over what was achieved with spectral data alone. Similarly, Sader et al. (1995) developed a hierarchical, rule-based method for the classification of forested wetlands. The classification rules integrated spectral data, National Wetlands Inventory (NWI) maps, a DEM, a slope model, hydrography, hydric soil data, and association/location. Despite this exhaustive ancillary dataset, classification results from the rule-based classifier did not have improved accuracy over a conventional hybrid classification.

Clearly, the utility and outcome of any cost/benefit analysis when considering the use of ancillary data and logic-oriented classification techniques depends upon landscape structure, desired accuracy, and geographic context, amongst myriad other factors.

Insufficient exploration has been performed of when, where, how and which ancillary data is useful to attempt to construct any valid heuristics. Moreover, many studies employing alternative classification techniques, including logic-oriented or intelligent processing do not focus explicitly on exploring the utility of the employed methodology for accuracy improvement. Thus they do not compare achieved results with traditional products (e.g., De Fries et al. 1998, Vogelmann et al. 1998, Murai and Omatu 1997). This makes it difficult to use the literature as a resource when exploring the possible techniques for classification during the exploratory/training phase of remote sensing studies.

Conclusion

The primary objective of this research was to explore the utility of incorporating domain knowledge into a rule-based classification technique for accuracy improvement by comparing results from the proposed technique with those of maximum likelihood classifications on spectral data alone. Secondary objectives were to illustrate the advantages of integrating domain knowledge informed by ancillary data, along with more than one traditional classifier, in the classification of problematic tropical land cover and to demonstrate a methodology for logic-oriented processing of historic satellite imagery. Classification accuracy was unequivocally improved for all classes and all years of the classification series relative to the results from the traditional maximum likelihood method. Domain knowledge constructed from interpreting and integrating ancillary data facilitated the correct classification of challenging tropical land cover like dry tropical forest and seasonal wetlands. Finally, results from this research suggest that not only are ancillary data valuable in the classification of historic satellite imagery, but perhaps this is where their greatest utility lies.

The major cost of the proposed rule-based technique is in the time involved in creating spatial data layers and the degree of knowledge necessary about land-management systems and land tenure across the spatial and temporal extent of the study period. However, as GIS becomes increasingly employed by local institutions in tropical regions, much of the data and knowledge may be available for future applications of such knowledge-based applications. The final accuracies of rule-based classifications across all dates in the study are amongst the highest in literature on land-cover classifications for the tropics. Moreover, this method allows for the accurate classification of all major land covers rather than the more commonly used forest/non-forest dichotomy. Anticipated extensions of this research include more rigorous statistical analyses of the optimal number of rules used for each information class to better determine the threshold at which increasing knowledge of land cover domains and processing efforts deliver little improvement in accuracy.

Table 2-1. Datasets comprising the knowledge base upon which domain knowledge was derived. Abreviations used in data description include “ML” for Gaussian maximum likelihood; “PP” for parallelepiped and “ag.” for agriculture; USGS for United States Geological Survey; “OTS” for Organization for Tropical Studies; and “IGN” for Instituto Geografico Nacional.

Data	Description	Source
MSS Image	(bands 1-4) 1974	USGS EROS Center
MSS Image	(bands 1-4) 1975	USGS EROS Center
TM Image	(bands 1-5 & 7) 1987	OTS
ETM Image	(bands 1- 5 & 7) 2000	OTS
Training Samples	(>40 per class per year)	n/a
Agricultural Field Polygons	photointerpretted - unique for all year	n/a
Polygons of all Large Landholdings	fieldwork with GPS - unique for all years	n/a
Land-cover classifications - unique for all years	via ML and PP algorithms; served as baseline classifications	n/a
Qualitative Data & Participatory Mapping Polygons	from 29 land use and land history interviews	n/a
Digital Elevation Model	resolution = 30 m for XY & 1m for Z	OTS
Slope Model	calculated from DEM	n/a
Normalized Differenced Vegetation Index	calculated from satellite imagery - unique for all years	n/a
Aerial Photo-mosaics	1:20,000 for 1975 & 1:35,000 for 1987	photos from IGN
Agricultural Calendars	constructed through interviews and other data	n/a
Population Center Coordinates	recorded by GPS in field	n/a
Spatial Models: unique for all years	ag. surface, urban buffer surface, & distance from river surface	n/a

Table 2-2. Advantages and disadvantages of the proposed rule-based technique relative to traditional maximum likelihood classifier

Advantages	Disadvantages
Facilitates sorting of land cover classes into the appropriate information classes. This is particularly useful when constructing land use maps where a particular land cover may correspond to multiple land uses.	Significantly more time and data intensive than traditional supervised classification methodology (to the extent that the overall benefits of remote sensing are lost if the extent of study region is relatively small).
Integrates GIS in the remote sensing process to make maximum utility of both systems in relation to the intended application of the land cover maps produced.	Ancillary data compiled for the rule-based approach may not have been created with this end-use in mind. Differences in geometric accuracy, spatial and temporal resolution must be considered for every data set integrated into classification criteria.
Boolean logic, rule-based approach facilitates integration of domain knowledge, spatial context and association into the classification algorithm without requiring advanced programming or specialized software.	Depending on the structure of the landscape and the spatial frequency of problematic land covers in a given classification scheme, incorporation of ancillary data may not appreciably improve classification accuracy.
Good for international/tropical work since it is not dependent upon any particular dataset, such as National Wetlands Inventory maps.	Depending upon temporal resolution and total number of images in the classification series, corresponding ancillary data may not be available.
Though this technique cannot bring greater spatial resolution to actual satellite image, use of ancillary data in this context facilitates successful integration of coarser imagery (e.g., MSS whose classification accuracy is likely to be lower) into land cover map series.	Depending on the structure of the landscape and the spatial frequency of problematic land covers in a given classification scheme, incorporation of ancillary data may not appreciably improve classification accuracy.

Table 2-3. Three sets of criteria (for 1975, 1987 and 2000) defining rule-based algorithms used to classify six information classes

	Rule Criteria	1975 Value (weight)	1987 Value (weight)	2000 Value (weight)	Description
Class 1. Irrigated Agriculture					
Rule 1a	Elevation NDVI ML Classification Class	< 125 m ≥0.52 1 (0.90)	< 125 m ≥0.48 1 (0.90)	< 125 m ≥0.4 1 (0.90)	Classify as irrigated ag. all irrigated ag. pixels in the ML classification < 125m in elevation and with an NDVI < 0.52/0.48.
Rule 1b	Elevation Ag. Polygon Surface PP Classification Class	<= 125 m 1 3 (0.80)	<= 125 m 1 3 (0.80)	<= 125 m 1 3 (0.80)	Classifiy as irrigated ag. all veg. wetlands pixels in the PP classification occuring at an elevation below 50/60 m that fall within agricultural fields where crops are cultivated.
Rule 1c	Ag. Polygon Surface ML Classification Class	1 2 (0.90)	1 2 (0.90)	1 2 (0.90)	Classify as irrigated agriculture all water pixels in the ML classification that fall within the bounds of a particular year's agricultural polygons.
Rule 1d	Urban Buffer Model Elevation Ag. Polygon Surface ML Classification Class	0 < 125 m 1 4 (0.90)	0 < 125 m 1 4 (0.90)	0 < 125 m 1 4 (0.90)	Classify as irrigated agriculture all pixels falling outside of the urban buffer region at an elevation below 125 m that would be classified as urban land use by the ML classification.
Rule 1e	ML Classification Class	1 (0.10)	1 (0.10)	1 (0.10)	If no other rule is triggered, default is classification to the assignment determined by ML algorithm.
Class 2. Open Wetland					
Rule 2a	Slope NDVI ML Classification Class	<=9% <=-0.2 2 (0.80)	<=9% <=-0.15 2 (0.80)	<=9% <=-0.2 2 (0.80)	Classify as open wetland all water pixels in the ML classification that occur at a slope <=9% and with an NDVI value less than -0.2/-0.15.
Rule 2b	ML Classification Class	2 (0.10)	2 (0.10)	2 (0.10)	If a given pixel meets no other criteria to trigger classification by rule, default assignment is determined by ML algorithm.
Class 3. Vegetated Wetlands					
Rule 3a	Elevation PP Classification Class Ag. Polygon Surface	<= 60 m 3 0 (0.90)	<= 50 m 3 0 (0.90)	<= 50 m 3 0 (0.90)	Classifiy as veg. wetland all veg. wetlands pixels in the PP classification occuring at an elevation below 50/60m that do not fall within agricultural fields where crops are cultivated

Table 2-3 Continued

	Rule Criteria	1975 Value (weight)	1987 Value (weight)	2000 Value (weight)	Description
Rule 3b	Elevation Distance from River PP Classification Class	<= 22 m 500 m 5 (0.60)	<= 20 m 500 m 5 (0.60)	<= 20 m 500 m 5 (0.60)	Classify as veg. wetland all pixels classified as grassland in the PP classification that occur within 500 m of river and at an elevation <=20 m.
	Rule Criteria	1975 Value (weight)	1987 Value (weight)	2000 Value (weight)	Description
Rule 3c	Distance from River Elevation NDVI ML Classification Class	<=25 m <=10 m >=0.40 6 (0.90)	<=30 m <=10 m >=0.35 6 (0.90)	<=30 m <=10 m >=0.40 6 (0.90)	Classify as veg. wetland all pixels classified as forest in the ML Classification that occur less than specified distance from river, with an elevation <=10m, and an NDVI value >= than 0.40/0.35.
Rule 3d	ML Classification Class	3 (0.10)	3 (0.10)	3 (0.10)	If a given pixel meets no other criteria to trigger classification by rule, default assignment is determined by ML algorithm.
Class 4. Urban					
Rule 4a	Urban Buffer Model ML Classification Class	1 4 (0.90)	1 4 (0.90)	1 4 (0.90)	Classify as urban all pixels classified as urban in the ML classification if they fall within the urban buffer zone.
Rule 4b	ML Classification Class	4 (0.10)	4 (0.10)	4 (0.10)	If no other rule is triggered, default is classification to the assignment determined by ML algorithm.
Class 5. Grassland					
Rule 5a	NDVI NDVI PP Classification Class	<0.28 >=0.0 5 (0.50)	<0.23 >=0.0 5 (0.50)	<0.28 >=0.0 5 (0.50)	Classify as grassland all pixels that were classified as such with an NDVI >=0.28/0.23.
Rule 5b	Near Infrared Band Elevation ML Classification Class	<58 >=125 m 1 (0.80)	<58 >=125 m 1 (0.80)	<58 >=125 m 1 (0.80)	Classify as grassland all pixels that were classified as irrigated ag. In the ML Classification if they have a NIR <58 and occur at an elevation >= 125m.

Table 2-3 Continued

	Rule Criteria	1975 Value (weight)	1987 Value (weight)	2000 Value (weight)	Description
Rule 5c	Elevation Elevation Urban Buffer Model ML Classification Class	>=125 m <=250 m 0 4 (0.60)	>=125 m <=250 m 0 4 (0.60)	>=125 m <=250 m 0 4 (0.60)	Classify as grassland all pixels classified as urban in the ML Classification if they fall outside of the urban buffer zone and occur at an elevation between 125 and 250 m.
Rule 5e.	ML Classification Class	5 (0.10)	5 (0.10)	5 (0.10)	If a given pixel meets no other criteria to trigger classification by rule, default assignment is determined by ML algorithm.
Class 6. Forest					
Rule 6a	Slope ML Classification Class	>=9% 2 (0.80)	>=9% 2 (0.80)	>=9% 2 (0.80)	Classify as forest all pixels classified as water in the ML Classification if occuring at a slope >=9%
Rule 6b	Urban Buffer Model ML Classification Class NDVI	0 4 >=0.35 (0.70)	0 4 >=0.30 (0.70)	0 4 >=0.35 (0.70)	Classify as forest all pixels classified as urban in the ML Classification if occuring outside of urban buffer zone with an NDVI value >=0.35/0.30.
Rule 6c	Elevation Near Infrared Band Near Infrared Band ML Classification Class	>=125 m >=58 <=95 1 (0.80)	>=125 m >=58 <=95 1 (0.80)	>=125 m >=58 <=95 1 (0.80)	Classify as forest all pixels classified as irrigated ag. in the ML Classification if they occur at an elevation >=125 m and have a NIR reflectance between 58 and 95.
Rule 6d	Elevation NDVI PP Classification Class	>125 m >0.35 5 (0.50)	>125 m >0.30 5 (0.50)	>125 m >0.35 5 (0.50)	Classify as forest all pixels that were classified as grassland if they have an NDVI >=0.35/0.30.
Rule 6e	PP Classification Class	6 (0.20)	6 (0.20)	6 (0.20)	Classify as forest all pixels classified as such in the PP Classification.
Rule 6f	ML Classification Class	6 (0.10)	6 (0.10)	6 (0.10)	If a given pixel meets no other criteria to trigger classification by rule, default assignment is determined by ML algorithm.

Table 2-4. Comparison of performance of the maximum likelihood and rule-based classifications by the following means: confusion matrices, class-wise producer's and user's accuracies, overall classification accuracy and overall KAPPA statistic. Rows refer to number of pixels classified as the named class while columns refer to the reference or actual values of such pixels. Abbreviations of land use and land cover classes are as follows: I.Ag = irrigated agriculture, Wa = water (open wetland), Wtlnd = vegetated wetland, Urb = urban, Glnd = grassland, and For = forest.

	Maximum Likelihood Classification *Reference Data*								Rule-Based Classification *Reference Data:*							
2000	I.Ag.	OW	VW	Urb	Glnd	For	**Clas'd Total**	**User's Acc.**	I.Ag.	OW	VW	Urb	Glnd	For	**Clas'd Total**	**User's Acc.**
I.Ag.	**51**	3	23	5	1	2	**85**	0.600	**53**	2	0	5	0	1	**61**	0.869
OW	0	**39**	3	0	0	0	**42**	0.929	0	**39**	2	0	0	0	**41**	0.951
VW	4	0	**17**	0	3	1	**25**	0.680	3	0	**48**	0	1	0	**52**	0.923
Urb	0	0	1	**40**	0	0	**41**	0.976	0	0	1	**40**	0	0	**41**	0.976
Glnd	0	0	10	2	**56**	3	**71**	0.789	0	0	4	2	**60**	2	**68**	0.882
For	1	1	3	0	2	**56**	**63**	0.889	0	2	2	0	1	**59**	**64**	0.922
Ref. Total	**56**	**43**	**57**	**47**	**62**	**62**	**327**		**56**	**43**	**57**	**47**	**62**	**62**	**327**	
Prod.'s Acc.	0.911	0.907	0.298	0.851	0.903	0.903			0.946	0.907	0.842	0.851	0.968	0.952		
	Overall Accuracy = 79.20% Overall K = 0.7493								***Overall Accuracy = 91.44% Overall K = 0.8935***							
1987	I.Ag.	OW	VW	Urb	Glnd	For	**Clas'd Total**	**User's Acc.**	I.Ag.	OW	VW	Urb	Glnd	For	**Clas'd Total**	**User's Acc.**
I.Ag.	**40**	2	1	1	1	2	**47**	0.851	**64**	1	0	1	0	0	**66**	0.970
OW	0	**50**	1	1	1	1	**54**	0.926	0	**50**	0	0	0	0	**50**	1.000
VW	6	0	**42**	2	2	3	**55**	0.764	1	0	**53**	1	0	1	**56**	0.946
Urb	5	0	1	**42**	1	1	**50**	0.840	0	0	0	**44**	0	0	**44**	1.000
Glnd	12	0	5	0	**81**	13	**111**	0.730	0	0	0	0	**86**	8	**94**	0.915
For	2	0	3	0	8	**63**	**76**	0.829	0	1	0	0	8	**74**	**83**	0.892
Ref. Total	**65**	**52**	**53**	**46**	**94**	**83**	**393**		**65**	**52**	**53**	**46**	**94**	**83**	**393**	
Prod.'s Acc.	0.615	0.962	0.792	0.913	0.862	0.759			0.985	0.962	1.000	0.957	0.915	0.892		
	Overall Accuracy = 80.92% Overall K = 0.7672								***Overall Accuracy = 94.40% Overall K = 0.9318***							

Table 2-4. Continued

	Maximum Likelihood Classification *Reference Data*								Rule-Based Classification *Reference Data:*							
1975	I.Ag.	OW	VW	Urb	Glnd	For	**Clas'd Total**	**User's Acc.**	I.Ag.	OW	VW	Urb	Glnd	For	**Clas'd Total**	**User's Acc.**
I.Ag.	**30**	0	16	11	5	0	**62**	0.484	**34**	0	1	2	3	0	**40**	0.850
OW	1	**12**	0	4	21	0	**38**	0.316	0	**17**	0	0	1	1	**19**	0.895
VW	0	1	**29**	0	11	9	**50**	0.580	0	0	**69**	0	1	2	**72**	0.958
Urb	0	0	0	**0**	0	0	**0**	0.000	0	0	0	**16**	0	0	**16**	1.000
Glnd	4	3	13	4	**100**	7	**131**	0.763	1	1	0	1	**132**	3	**138**	0.957
For	1	2	18	0	1	**65**	**87**	0.747	1	0	6	0	1	**75**	**83**	0.904
Ref. Total	**36**	**18**	**76**	**19**	**138**	**81**	**368**		**36**	**18**	**76**	**19**	**138**	**81**	**368**	
Prod.'s Acc.	0.833	0.667	0.382	0.000	0.725	0.802			0.944	0.944	0.908	0.842	0.957	0.926		
	Overall Accuracy = 64.13% Overall K = 0.5310								***Overall Accuracy = 93.21% Overall K = 0.9099***							

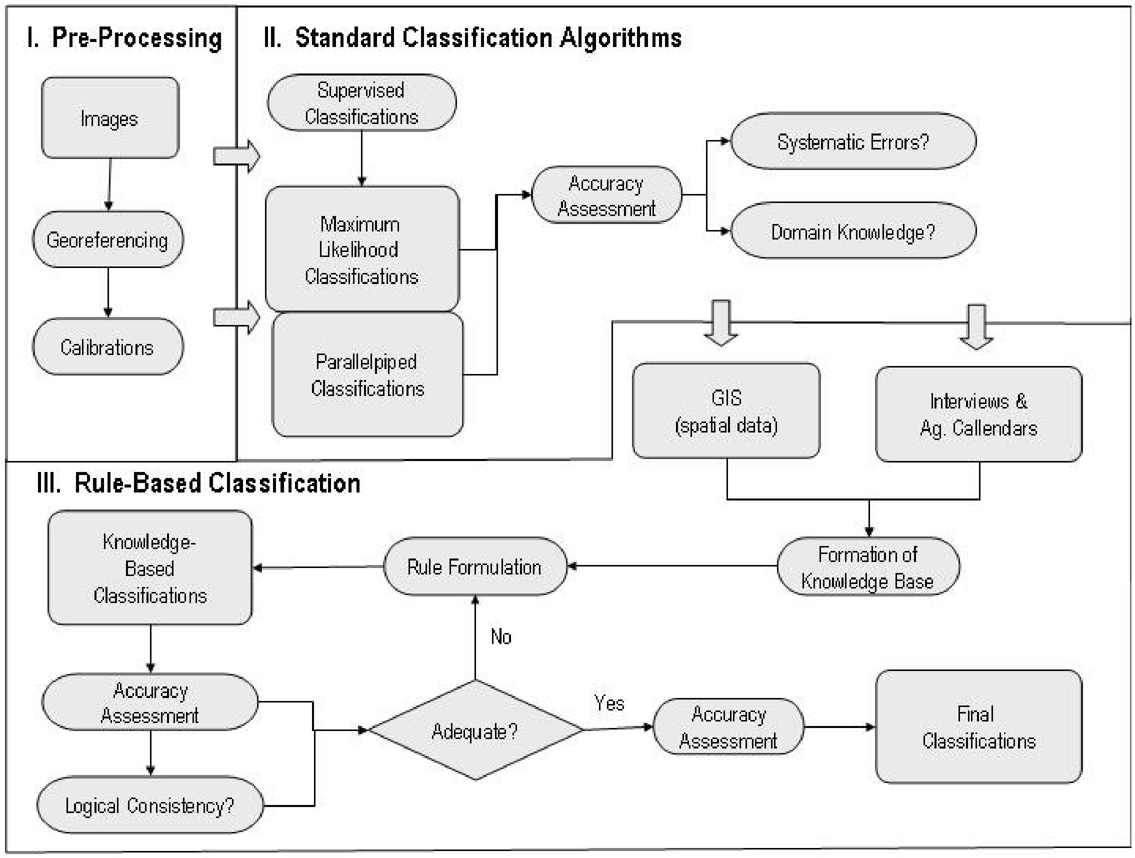


Figure 2-1. Schematic flowchart of rule-based classification methodology

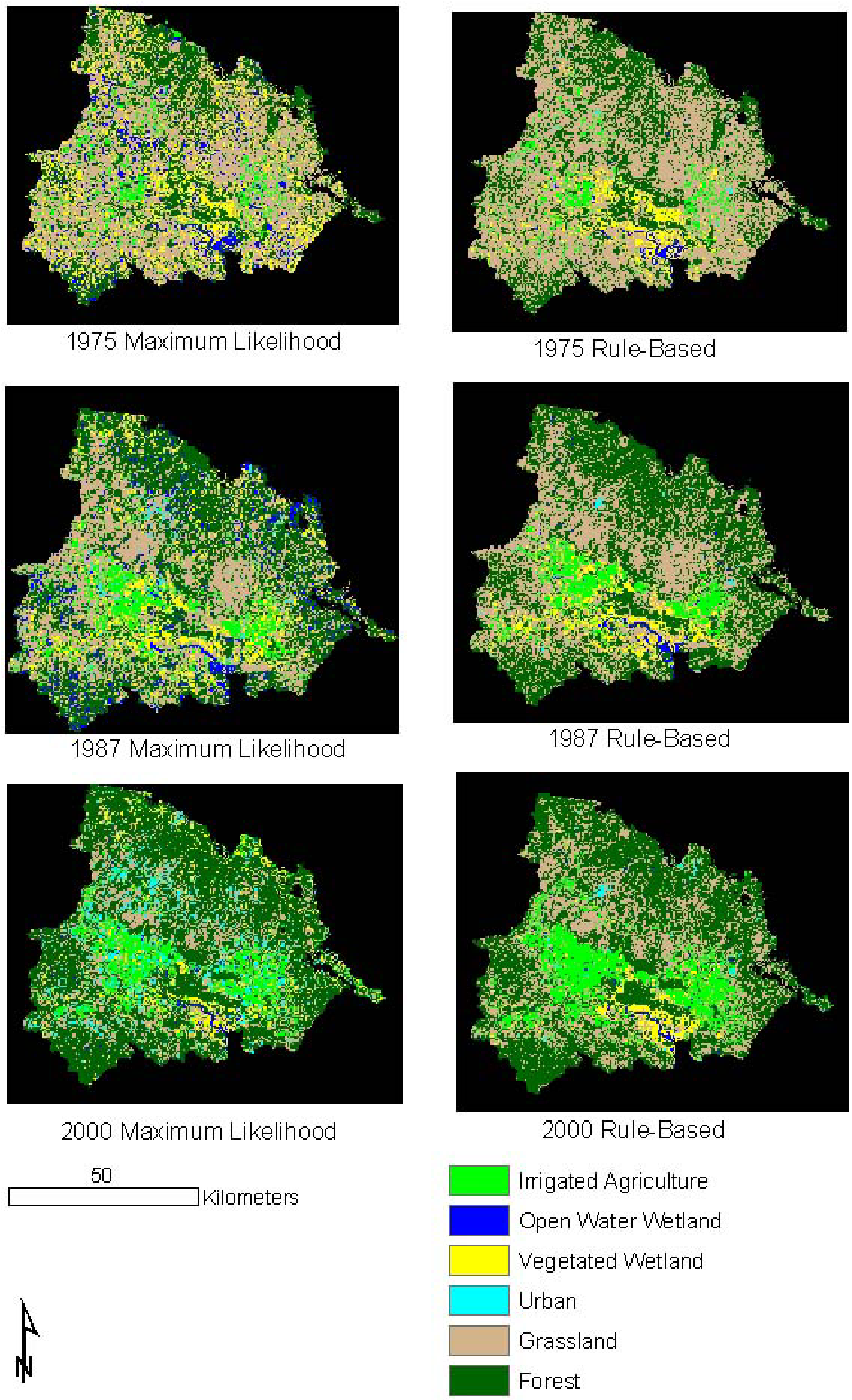


Figure 2-2. Land cover maps for all three years in classification series by the two different techniques. The column on the left shows results of traditional maximum likelihood classifier and the column on the right shows results of the rule-based technique.

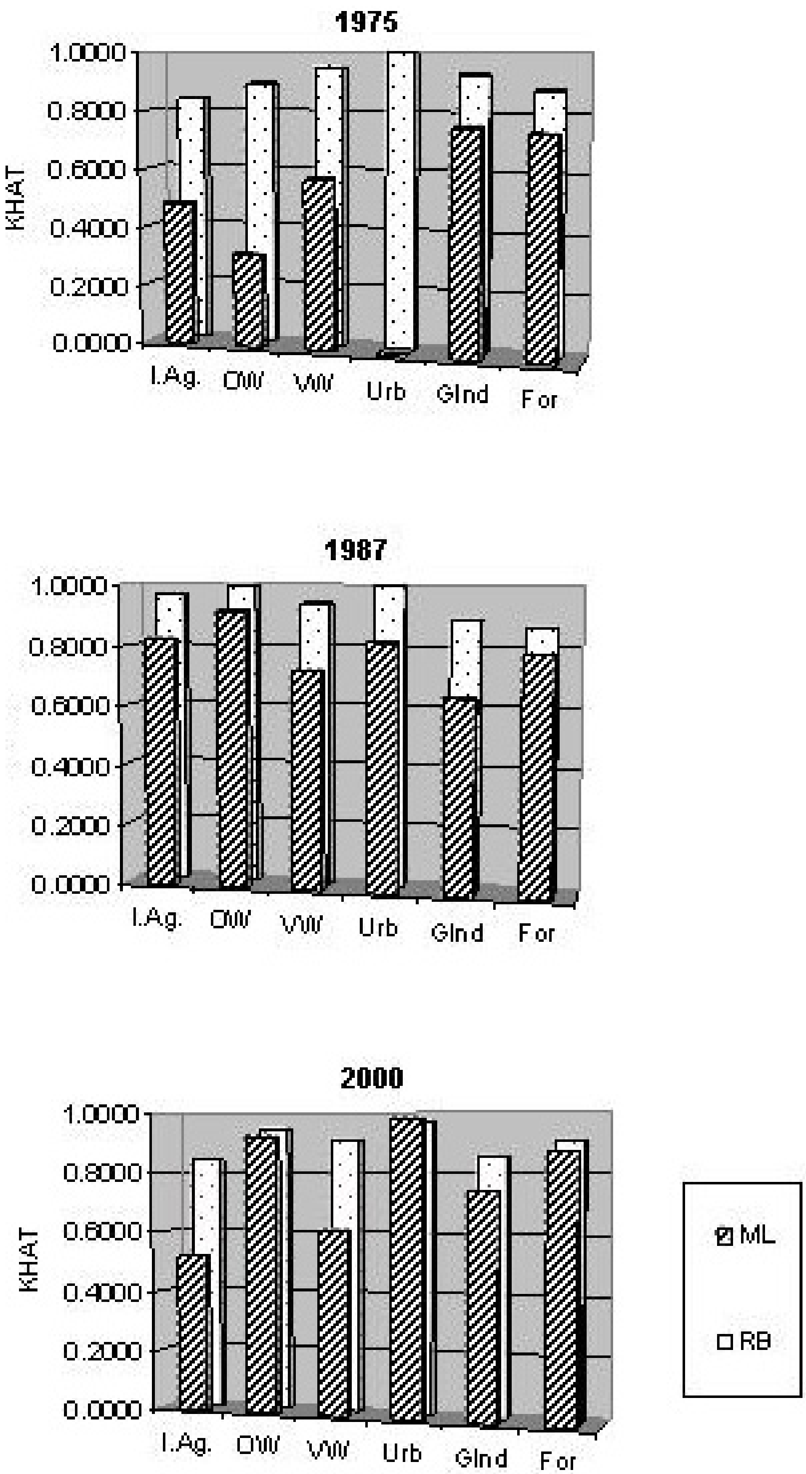


Figure 2-3. Comparison of class-wise KAPPA statistics for the maximum likelihood and rule-based methods for all three years (1975, 1987, and 2000). Abreviations are as follows: I.Ag. = Irrigated Agriculture, OW = Open Water Wetland, VW = Vegetated Wetland, Urb = Urban, Glnd = Grassland, and For = Forest.

CHAPTER 3
LANDCOVER DYNAMICS IN THE TEMPISQUE RIVER BASIN: PALO VERDE NATIONAL PARK IN THE WATERSHED CONTEXT

Introduction

The concept of protected area management has provoked a contentious and long-standing debate in both the biological and social sciences (e.g., Terborgh1997, Bhagwat et al. 2001, Bruner et al. 2001, Wilshusen et al. 2001). Overall efficacy of protected area management for the conservation of biodiversity is still largely unclear. This is, perhaps, in part due to different notions about what criteria constitute success with regard to conservation goals. Also, because protected areas reside in dynamic landscapes, their 'effectiveness' changes over time and space in ways that have yet to be sufficiently addressed. Narrowing the degree of uncertainty on the performance of protected areas in achieving defined conservation goals is increasingly important and has exaggerated implications in tropical environments where much of global biodiversity and provision of environmental services like carbon sequestration occur.

One approach to assess the effectiveness of protected area management is to examine its impact on land cover patterns and conversion processes since the time of park establishment. Effectively managed reserves are expected to conserve and/or promote the regeneration of "natural" land-cover types. Changes in land cover may result directly from land use activities occurring within park bounds. Alternatively, land-cover changes may occur as an indirect effect from activities physically removed from the park but which are manifested within its bounds. The dynamic nature of land cover patterns and changes is a multi-scale phenomenon that affects ecological attributes like trophic interactions, species composition and dispersal, carbon sequestration, climatic patterns and water balance (Kepner 2000). Land cover data are thus an essential tool, despite their coarse ‘ecological resolution,’ for assessing the state of protected areas. These data can, in turn, inform and direct finer analyses of the changing ecology within protected areas.

A modest but expanding body of literature addresses the issue of land-cover change in relation to the effectiveness of protected areas as a general management regimes. Bruner et al. (2001) surveyed park officials for 93 protected areas throughout the tropics to assess the degree to which parks effectively prevented land clearing, amongst other threats. Along similar lines, Rao et al. (2002) conducted site visits to 20 protected areas in Myanmar to determine the nature and level of occurrences of incompatible land and resource use. More commonly, researchers have used satellite-based land cover data to compare rates of deforestation and degree of forest patch fragmentation within parks and their surroundings (Sanchez-Azofeifa et al. 1999, Sanchez-Azofeifa et al. 2002, Southworth et al. 2004). The explicitly spatial design of biosphere reserves with their characteristic cores and buffers has also been evaluated with remotely sensed data in terms of preventing deforestation (Hayes et al. 2002) and ‘natural area’ conversion (Walker and Solecki 1999).

While this body of work provides valuable insights into the issues surrounding protected area management, case studies that document land-cover change (LCC) within established protected areas since the time of their establishment are still scarce. This scarcity is particularly true for higher levels of taxonomic resolution in land-cover classification schemes. As an illustration, all of the aforementioned evaluations of land-cover change in protected areas employ a dichotomous forest/non-forest classification. Such simplification has been justified by the preeminence of deforestation as a major driver of the global environmental change (Geist and Lambin 2002) and by the difficulty and expense of obtaining greater taxonomic resolution (Langford and Bell 1997b, Mertens and Lambin 2000, Daniels in prep.). However, in many landscapes dichotomous land cover models eliminate, through land cover aggregation, important information about the patterns and processes of LCC and its drivers. This may be particularly true for protected areas where subtle land cover transitions are sometimes driven by processes less obvious than those of the nonprotected landscape. Furthermore, non-forest land covers, like wetlands, may comprise a smaller extent of the landscape but are critical for ecological services and regulation of regional environmental processes (Sparks 1995).

Criteria and guidelines for reserve site selection, design and management approaches using concepts from landscape ecology and island biogeography theory have been treated extensively in the literature (e.g.,, Arnold 1995, Primack 1993, Schwartz 1999, Sanderson et al. 2002). These concepts are largely drawn from theoretical models on habitat connectivity and minimum dynamic area for foci species and ecological processes (Pickett and Thompson 1978), however, rather than based on empirical data. As a possible result, the position of protected areas in their watersheds is one critical factor virtually ignored in the literature on reserve design, selection and management (Pringle 2001). Understanding the water balance characteristics and over-land surface flows in the area surrounding the park and vice versa is critical but largely overlooked. Understanding of hydrologic function and its implications at the landscape level and beyond is nascent (Pringle 2003, Vorosmarty 2002) and thus incorporating park management into its respective hydroscape poses even greater challenges. Watersheds provide natural, hierarchical units within which park function can be conceptualized and studied, particularly if greater detail in land cover and land use can be achieved.

In essence, park boundaries are arbitrarily-drawn political lines while the geographic area defined as a park fits into a complex, dynamic, biophysical and land-use matrix that must be recognized and understood (Poiani et al. 2000). Even optimally functioning and connected reserve networks per se are likely to support but a mere fraction of the biodiversity and ecological services we seek to preserve. Nonetheless, opportunities for creative land use configurations, conservation policies and scenario planning that complement reserve function are possible if the ecological values and threats of the surrounding biophysical and socioeconomic matrix are considered (Harvey and Haber 1999, Daily et al. 2003).

Historic and current land use patterns and population settlement at the time of reserve establishment are often the primary factors affecting the ways in which parks sites are selected, established and managed (Runte 1979, Hunter and Yonzon 1993, Pressey 1994). Rivard et al. (1999) found land use patterns in Canada's national parks to be highly correlated with patterns surrounding the parks. Similarly, both species richness and extirpations were more highly correlated with regional characteristics than to those of the parks in which they occurred. The extinction of large mammals in western U.S. parks was found to correlate significantly with surrounding human density, but surprisingly enough, not with park area (Parks and Harcourt 2001). And finally, many common agriculture-related land-management systems are known to affect both land cover dynamics and ecological processes at scales beyond their actual temporal and spatial extents (Shankman

1996, Lemly 2000). All of these factors underscore the need to move away from merely theoretical models of park design and function to consider the unique context of each protected area for the determination of best integrated management practices.

This research presents a case study of protected area management in the watershed context for Palo Verde National Park (PVNP) in Guanacaste, Costa Rica. This site was chosen because of its unique mosaic of habitat types. Also, by virtue of its position at the bottom of a large drainage basin, this park serves as an instructive case study of the role of hydrologic connectivity between parks and their host watersheds. The watershed surrounding PVNP has undergone drastic landscape transformation in the past 25 years and thus the region provides an appropriate context for exploring the effect of protected area management on land cover transition. Specifically, I address the following questions: (1) How have land use and land-cover changed in the Tempisque River Basin and Palo Verde National Park over the last 25 years? and (2) What is the effect of Palo Verde National Park on land-cover change given the watershed context? By watershed context I refer to the historic and current land-management systems, their implications for land cover dynamics, and the ways in which the biophysical and social structure of the landscape either constrains or facilitates certain land cover conversions.

Regional Context

Study Region Description

The Tempisque River Watershed is in the northwestern province of Guanacaste with an extent of 5,404 km^2 (Figure 3-1), or 10 % of the national area. The watershed has a mean temperature of 27.5^{o}C and mean annual precipitation of 1817 mm falling between May and November (Mateo-Varga 2001). Mean precipitation between May and November is about the same throughout the watershed. There is more variability during the dry season, however, with the lower, western watershed receiving 0 mm of precipitation on average, while higher elevation areas on the cordillera receive around 61 mm on average.

The River runs generally north to south through the center of the basin, increasing in volume in the southern watershed with the confluence of the eastern originating Bebedero River and several important tributaries. Thirteen different Holdridge life zones are found in the watershed (Holdridge 1967) with myriad habitats including tropical dry forest, moist pre-montane forest and vast seasonal wetlands. The eastern border of the watershed is defined by the Guanacaste Mountain Range that reaches over 2000 m elevation. The Tempisque River experiences semiannual floods thus making it one of Central America's more productive regions and the only part of lowland Costa Rica to be continuously inhabited since the beginning of the colonial era (Peters 2001).

Historical Context for Transformation in the Tempisque Watershed

Since the arrival of the Spanish, the landscape has been historically dominated by cattle ranching and low-intensity or subsistence agriculture of beans, maize, sorghum and indigo. In this region, beef cattle ranching proved more profitable than in other parts of the country (SEPSA in Harrison 1991). However, high capital investment was required to maintain sufficient feed during the dry season. Alternatively, green wetland areas of the lowlands or cloud-bathed pasture areas high on the *cordillera* provided ample grazing potential during the dry season. These constraints of the biophysical landscape in relation to the dominant economic activity probably contributed to the region's characteristically large landholdings and low population density, which even today equals less than 31 people per square kilometer (CCT 1998). With the construction of the Panamerican Highway in the 1950s, slight intensification and a shift in crop cultivation occurred with the increased production of sugar cane, cotton and sorghum for the national and international markets. Cattle ranching remained, however, the defining social and economic feature of the landscape.

Several conditions aligned at multiple economic and political scales, setting the stage for the transformation seen by the Tempisque River landscape beginning in the mid-1970s (Figure 3-2). When the beef market precipitously declined in the 1970s, Costa Rica was the 4th largest supplier of beef to the United States (Peters 2001) and had one of the highest per capita debt loads anywhere in the developing world (Biesanz et al. 1982). This economic shock was followed by the global economic downturn (DeWitt 1977) and the ensuing national financial crisis of 1980 in which Costa Rica defaulted on international loans (Lara 1995). Implications were grave for Costa Rica as a nation, but particularly for the land-management regime that had sustained the Tempisque Basin for nearly five hundred years (Martinez 2000).

After the crisis of 1980, economic and structural adjustments proceeded at the behest of international lending institutions. Included in Costa Rica's strategies for economic recovery and development were increased emphases on development of energy resources and investment in the budding ecotourism industry, both of which would directly and indirectly decrease dependence on petroleum imports from oil to fertilizer. In the Tempisque Basin these strategies were manifested in tangible ways with development and conservation works-in-progress that assumed greater import after the economic crisis. The works-in-progress included the Arenal-Tempisque Irrigation Project (PRAT or *Proyecto Riego Arenal Tempisque*) and conservation of the area that later became PVNP. Both projects entailed changes in the spatiotemporal patterns of resource and land use, albeit at opposite ends of the spectrum (Figure 3-2).

The concept of PRAT was born in the 1950s, but construction for the $50.5 million dollar project (DeWitt 1977) came to fruition in the mid-1970s with financing from the Inter-American Development Bank (IDB). The PRAT irrigation program forms part of a larger hydroelectric project that generates the bulk of Costa Rica's energy. In 1978, PRAT dammed a formerly Caribbean-draining river to form Lago Arenal with a volume of 1570 million m^3 and electric potential of 25,450 Mw per year. After generation of power at three drops along the Pacific slopes, PRAT channels water to the lowlands of the Tempisque Basin via some 234 km of canals whose average wet and dry season flow volumes are around 45 m^3/s and 62 m^3/s respectively. The government purchased land on the eastern side of the Tempisque that was subdivided into 5 ha lots for flooded rice cultivation and distributed at subsidized rates to farmers. Otherwise, irrigation water went to existing agroindustry operations who also extract water from the Tempisque River for irrigation (as is the case for much of the cultivated area in the western half of the basin, beyond the reach of PRAT). The project has taken over twenty years to fully implement and additional canal networks may be built in the future.

Protected Areas in Costa Rica

Costa Rica is now well-known for its virtually unmatched system of protected areas. This system forms a keystone component of the ecotourism industry that provides the country's largest source of foreign income. Since the national park service's foundation in 1970, nearly 25% of the country's national area has been placed under varying forms of protection. This conservation system is now valued at over $1.2 billion dollars (Umana 1996). The park system is based largely upon the North American caretaker and people-exclusion model. Palo Verde National Park was designated as a national park in 1990 but nearly its full extent had been protected in two separate reserves since 1977. Prior to the decree of any form of protection, the land was part of a large cattle ranch, Rancho Comelco, that stretched from the floodplains up toward the cordillera (Gill 1988).

Palo Verde covers over 18,760 ha and protects a diverse mosaic of habitats. The park includes the world's most endangered habitat type, tropical dry forest, for which less than two percent of the original extent along the Pacific slopes of the Central American-Mexican isthmus remains (Janzen 1988). Over a third of PVNP is composed of a wetland mosaic that historically provided critical habitat for migratory waterfowl. For this reason, the site was given RAMSAR protection in 1991 (Mateo-Varga 2001). In addition to attracting ecotourists, the Organization for Tropical Studies' research station housed within the park's bounds serves as an important attractant for academic tourism.

Other national parks partially located in the basin include those of Barra Honda, Rincon de la Vieja, Guanacaste and Santa Rosa. While lesser levels of protection and management also exist within the watershed, such as Diria National Forest, the Lomas Barbudal Reserve and private tracts of forest subsidized by the national government's environmental service payments program (PSA, 1996 Ley Forestal 7575), these areas comprise 1.16% of the basin and have only more recently been established.

Methods

Land-cover classification

Four Landsat images were obtained to represent baseline land cover data and two time steps thereafter. The first two images used to create a mosaic of the study region were Landsat Multispectral Scanner (MSS) images from 1974 and 1975. The middle time point was a Thematic Mapper (TM) image from 1987 and the final image was from the Enhanced Thematic Mapper (ETM) platform for the year 2000. All images used were from early in the dry season to facilitate identification of irrigated agriculture as a land use category. Geometric rectification was performed using a nearest neighbor resampling algorithm on the year 2000 image using ground control points taken in the field with GPS to achieve a root mean square (RMS) error below 0.5 or 15 m. The later images were then registered to this image and an overlay function was performed to ensure exact geographic correspondence for the extent of the watershed. To ensure that differences in satellite data across the series corresponded to changes on the ground, rather than differences at the sensor level, all images underwent radiometric calibration, atmospheric corrections and then radiometric rectification procedures. These processes eliminated sensor bias and differences due to variations in solar angle (Jensen 1996). After calibration procedures, all images were subset to the extent of the watershed for ease of processing and storage.

Training samples for the 2000 classification were collected during fieldwork in 2001. Historic photo-mosaics corresponding to the dates of the older satellite imagery were used to collect training samples for the 1974-75 mosaic and the 1987 image. Additionally, over 29 semi-structured land use/land history interviews were conducted throughout the watershed to inform agricultural calendars, verify image interpretation and better understand systems of land use over the study period. Land use and land cover classes employed were irrigated agriculture, water/open wetland, vegetated wetland, urban, grassland and forest (Table 3-1). Images were independently classified using a rule-based approach that incorporated domain knowledge. Overall classification accuracy exceeded 90% for each date and class-wise accuracy matched or exceeded 85% for each date. For details on the rule-based classification methodology see Daniels in prep.

Land-cover change Analysis: Spatially Implicit and Spatially Explicit

To ensure that the same extent of area was considered in each land cover map, areas of cloud cover for any single date were eliminated from all others. The final outer boundary of the 1974-1975 mosaic was used to define the final extent of the watershed considered in this study. This method occurred because the oldest Landsat images in the series were based on the first World Reference System (WRS 1) where the image footprint cut off a triangular area of 110 km^2 at the northern border of the watershed. The portions of Santa Rosa, Guanacaste and Rincon de la Vieja National Parks that fall within the watershed were eliminated in this process of eliminating clouds and image footprint differences. And finally, to control for the evaluation of Palo Verde National Park alone, the remaining tracks of protected lands of lesser degrees, comprising only 1.16% of the original area of the basin, were not included in land cover evaluations since the imagery series did not adequately represent the effect of management activities on land cover since protection was decreed. These adjustments resulted in a total area of 5153 km^2 or 95.35% of the true extent of the basin used for this evaluation.

Land cover composition was then assessed for each land cover map (spatially implicit) in the classification series to determine trends of net area change across the study period for protected and nonprotected regions respectively (e.g., net increase in forest cover in both regions; net decrease in wetland area for the nonprotected and net increase in wetland area for the park). The net trends identified for each land cover class for the park and nonprotected parts of the landscape were used to guide the spatially explicit analysis of land cover conversion sequences.

The analysis was completed through the creation of a single raster surface representing land cover trajectories or conversion sequences over the three dates by recoding every possible combination of original land cover classes from all three years to a unique value. For example, a single pixel followed over the three original land cover maps may have transitioned from forest to grassland to irrigated agriculture. The unique value assigned after recoding would reflect this trajectory. The relationship between land cover classes and trajectories (Petit et al. 2001) is

$$m_t = m^t_c$$

with mt being the total number of possible trajectories and mc the number of land cover classes in the single date land cover maps. Finally t is number of images in the time series. Although the single date images classified urban land use, its extent comprised such a negligible portion of the landscape that it was not included in the trajectory analysis. Accordingly, for this analysis, a total of mt = 53 = 125 trajectories were possible (versus 216 if urban had been included).

Determining Dominant Explanatory Trajectories

Because of the large number of possible trajectories in a three-image time series, analyzing spatially explicit patterns of LCC in relation to the overall biophysical landscape and protection status proved to be difficult. Thus, this research developed a set of rules to determine the trajectories that reveal the most important land-cover change trends in the watershed and simplify the LCC model into something that could be easily interpreted. If the net area change for a given land cover was positive over the study period, trajectories were examined in a backwards" manner to understand which land cover transitions explain the increase. For example, for an increase in land cover X, the areas of all possible trajectories ending in X (hereafter referred to as explanatory trajectories) for the final year in the series were compared. In contrast, if the net area change for a given land cover was negative over the study period, the trajectories were examined in a "forward" fashion to understand what land cover transitions explain that decrease. For example, if a decrease in land cover Y was observed over the study period, all possible explanatory trajectories starting in Y for the first year of the time series were compared.

In the analysis of each land cover's net-area trend, explanatory trajectories were retained for further analysis up to the point where 80% of the net area change had been accounted for or the point at which a given trajectory explained less than one percent of the net-area trend, whichever occurred first. While it may appear that valuable information is being omitted from the analysis, two important factors must be considered. The first factor is that a classification error up to 10% exists within each single date classification and this error is propagated across the land cover trajectories. The cutoff rules are justified in two ways: (1) Explaining 80% of the net-area trend is sufficient to understand dominant processes of land cover conversion for a given class and (2) Any trajectory explaining less than one percent of the net-area trend observed is likely an amalgam of classification errors. The second factor is that, as mentioned, the LCC model has extremely limited interpretability for a multi-class change study without such simplification.

After identifying the dominant explanatory trajectories (i.e., those that met the cutoff criteria) for each net area gain or loss in land cover across the study period, another round of simplification occurred prior to analyzing how the dominant trajectories relate to the overall biophysical and built landscape structure. Only trajectories with two land-cover types showing change in a unidirectional fashion were retained. The idea was to reduce error in the trajectories examined and also provide greater interpretability and manageability in understanding how trajectories relate to the biophysical and built structure of the landscape.

Landscape Location Relationships and Biophysical Variables

A total of nine different surfaces were obtained or created to provide continuous descriptions of key biophysical variables and location relationships thought to be related to land cover trajectories based on knowledge of the landscape and land use. Each surface covered the extent of the watershed with a 30 x 30 m resolution that matched that of the land cover data. These surfaces, described in greater detail below, included a digital elevation model (DEM), slope, distance to nearest road, shortest distance to park boundary, shortest distance to large forest, shortest distance to the Panamerican Highway, shortest distance to river, and distance to nearest population center. The final surface was something of a dummy variable discriminating between the park and nonprotected areas of the watershed.

The vector data of protected area boundaries and the DEM were obtained from the Organization for Tropical Studies (OTS) Palo Verde Research Station. The latter was originally 15 m spatial resolution (x,y) and was resampled to a 30 m cell size using the nearest neighbor algorithm. The z dimension was 1 m resolution for elevation. Slope was calculated from the DEM using a moving window algorithm. Vector data of public roads, including the Panamerican Highway, were obtained from the Instituto Geografico Nacional (IGN) in San Jose. Coordinates for all population centers were extracted by hand from 1:50,000 scale analog topographic maps produced by the IGN. GPS coordinates at each community's center were recorded during field visits for the actual vector layer used in the analysis. Only centers with sufficient population to have their own elementary school were recorded (verified through interviews). This served as a somewhat arbitrary criterion but proved to be reasonably consistent with regard to targeting communities with at least some minimum population threshold.

Large forests were defined as those patches that existed at the start of the study with an area of 100 ha or greater. Given the degree of deforestation and fragmentation that had occurred up to that point in the landscape, these patches served both ecologically and socially as the only large forest present in the watershed. These patches were queried and isolated from the 1974-1975 land cover map where the eight neighbor rule was employed in the patch definition (i.e., both adjacent and diagonal neighbors were allowed). Pixels classified as river in the 2000 image were extracted, vectorized and corrected through hand digitization in the upper reaches of the watershed using scanned, georeferenced portions of the topographic maps. These corrections were necessary since the given sensor resolution did not capture certain narrow reaches of the river in the northern watershed.

All vector data that were not produced first-hand were verified for positional and attribute accuracy during fieldwork. Geometric and thematic corrections were made where necessary. Finally, overlay functions were performed to ensure that all layers in the GIS for the study region conformed to acceptable position accuracy in the datum (WGS 84) and coordinate system (UTM, Zone 16 North) employed. After these procedures, distance surfaces were calculated using the Spatial Analyst extension of ArcGIS.

Statistical Analysis

If used in its entirety, the final watershed template of all raster datasets would have been a 3740 by 3257 matrix of data (12,181,180 observations per variable quantified). Thus the number of cells used in the statistical analysis was reduced by only including every twelfth cell in the database for statistical analysis, or one sample point every 360 m in grid-like fashion. After eliminating no-data sample points, this method of data reduction provided a total of more than 30,000 sample points for the explanatory trajectories of interest. The sampling interval of 360 m proved to be sufficiently frequent as even the trajectories comprising the smallest areas were sampled in large enough numbers to conduct statistical tests. For each sample point, the following data were extracted from the raster surfaces in the GIS: (x,y) coordinates, trajectory, status (protected/nonprotected), distance to road, distance to Panamerican, distance to population center, distance to river, distance to park boundary, and distance to large forest.

Principal Components Analysis (PCA) was performed on all biophysical/location variables (minus the categorical variable of status) to explore any underlying multivariate structure in the data. Since outliers bias the direction of components (Johnston 1980), all variables were first standardized and those data points occurring beyond 2.5 standard deviations from the mean were examined carefully to ascertain whether they contained valuable information about the biophysical nature or location relationships of the landscape. In nearly all cases outliers were determined to be extreme measurements but to convey meaningful landscape information. Thus, relatively few observations were deleted. Principal components were extracted from the correlation matrix of all quantitative variables and only components with eigenvalues greater than one were retained. Varimax rotation was chosen to simplify structure within components by better distinguishing between significant and non-significant loadings on each component (McGarigal 2000).

Several rounds of comparisons were made to test for differences in means of biophysical/location variables using Mann Whitney or Kruskal Wallis. First, the overall means of the variables were compared for the park and nonprotected area to determine whether the park is a representative sample of the watershed and if not, in which ways it differs. Next, all explanatory trajectories for each net-area trend were compared against each other for the park and nonprotected area respectively. Also included in this comparison was the trajectory representing no change or persistent land cover (e.g., grassland throughout the study period for the comparison of trajectories explaining the decrease in grassland). When the null hypothesis was rejected for no difference amongst k means compared with the Kruskal Wallis test, a nonparametric multiple comparisons procedure was performed. This procedure controlled for experiment-wise error in determining which pairs were significantly different from others (Siegel and Castellan 1988).

Nonparametric means comparisons procedures are known to be influenced by unequal sample variances and unequal sample sizes (Zimmerman 2003). To account for the latter amongst treatment categories (trajectories) of drastically different sizes for all three rounds of comparisons, a trajectory-stratified, spatially distributed sampling procedure in ArcGIS Geostatistical Analyst was used to create similar sized groups for comparisons. In this procedure, the smallest sample size of a given comparison was determined and that number of points was generated for the trajectory with the larger n. Spatial joins were used to locate the nearest sample points from the 360 m point grid and the latter were actually used in each of the statistical comparison tests.

Assessing the Effectiveness of Protected Area Management in Watershed Context

As the final assessment of the effect of protected area management on observed land cover patterns in PVNP, comparisons of clusters of land-cover trajectory occurrences on scatter plots of the principal component scores were made. The trajectories compared were those hypothesized to compete if not for the establishment of the park. In essence, this analysis takes into account the land use systems acting in the nonprotected watershed, along with the constraints and opportunities presented by the biophysical and built structure of the landscape, to give a better indication of the effect of protected area management on land cover patterns.

Results and Discussion

Park versus Nonprotected Area

Comparison of biophysical and location relationships for the park and nonprotected area, along with contrasting initial land cover conditions for the study period, reveal that the park is not a representative sample of the landscape. This is often the case with protected areas, as they often represent spots of elevated biodiversity that may be related to unique juxtapositions of land forms and vegetation communities. Alternatively, protected land may often be unproductive and/or inaccessible and thus, the only remaining 'natural' habitat in the landscape (Hunter and Yonzon 1993, Pressey 1994).

In the case of baseline data for PVNP relative to the surrounding watershed, the park was found to have different land cover composition with 33% less grassland, nearly four percent more forest cover, over seven percent more open water wetland, and over 26% more vegetated wetlands (Table 3-2). Irrigated agriculture comprised almost five percent of the nonprotected landscape at the beginning of the study period but was not present in baseline data for the region that became the park.

With regard to the biophysical landscape and location relationships therein, the protected and nonprotected regions differ considerably (Table 3-2). Means of all variables were found to be significantly different (Mann Whitney, $p<0.000$). In short, the average 30 x 30 m raster cell in the park can be described as being lower in elevation, slightly gentler in slope, closer to a large forest patch, closer to the park boundary and closer to the river. Cells in the park are also more isolated than the average cell in the nonprotected landscape as evidenced by larger distances from roads, the Panamerican Highway and population centers.

Many of these differences in both land cover and biophysical/location variables are functions of the park's size relative to the nonprotected watershed and its position in the landscape. Occurring as a small, low-lying area in the lower watershed along the river, the park clearly integrates effects of activities in the upper watershed and is more affected by its surroundings than vice versa. As a function of its location, the park is well-endowed with wetlands that cover over one third of its area. In light of these facts, the small difference in forest cover (four percent) between the protected and nonprotected regions becomes more significant. Similarly, given that the wetlands occupy about one third of the park and occur generally in the flattest areas along the river (less than two percent), the 7.71% mean slope represents appreciable relief (relative to the nonprotected mean that is only about three percent higher). Most topography in the park is a result of limestone karst structures that have dramatic slopes but reach an elevation of less than 200m. Because upland areas were characterized by unsuitable slopes and wetland areas served as grazing grounds for cattle, the park was more forested than its surroundings at the time of establishment. Increased forest cover existed despite the area's management by the same dominant land use system as the rest of the watershed (cattle ranching).

Net Area Land-cover change: Park and Nonprotected Area

With only one exception, net area land-cover change occurs in a unidirectional fashion, increasing or decreasing for each class across the three dates in the study period (Figure 3-4). For both the park and nonprotected watershed, grassland decreased dramatically (15% and 30% respectively) and forest cover increased substantially (about 20% each). It is important to note that relatively little area in the basin occurs naturally as grassland. Natural grassland only occurs on certain volcanic slopes where both poor soil structure and possible downwind, agriculture-related fire frequency prevents dominance of woody growth. For this reason, grassland is a somewhat reliable proxy for pasture land use in this landscape except when, due to soil compaction on heavily grazed pastures, woody succession may not ensue even several years after the land ceases to be used as pasture (Gillespie 2000, Gerhardt 1993).

Open water wetland decreased considerably in the park from eight percent to two percent, while little change was observed in the nonprotected landscape. The latter is probably true because the only considerable area of open water wetland in the nonprotected landscape is the river itself. Also, losses in natural open wetlands of the floodplain are masked in the land cover maps by the formation of several small dammed areas that are part of the irrigation program.

Vegetated wetlands decreased in the nonprotected area by one half while a slight net increase of about two percent was observed in the park. This fluctuation of vegetated wetland area in the park from 1975 to 1987 and then 1987 to 2000 is likely related to the warm and cold phases of El Nino Southern Oscillation (ENSO) respectively (Waylen and Laporte 1999). The second image date, 1987, was a particularly dry year and some true, functional wetland area may have been classified as grassland on that date. In the nonprotected region, irrigated agriculture increased about three fold from less than five percent of the landscape in 1975 to nearly 15% in 2000. Although a slight increase in irrigated agriculture was observed, this land use comprised a mere 1.5% of the park in 2000. Based on personal communication with local officials, this increase of agricultural land use within the park is a land tenure issue rather than an incursion issue that threatens to move further into the park. In essence, different government ministries planned different uses for the same parcels of land.

Figure 3-4a shows land-cover change in the nonprotected region of the watershed across the dates of the study period. Reforestation can be observed mostly in the upper watershed while increase in irrigated agriculture land use occurs in the lower watershed, near the river. Loss of wetlands occurs as the floodplain area becomes increasingly filled with irrigated agriculture fields. These maps reveal that the river itself forms the bulk of open water wetlands in the nonprotected watershed.

Land-cover change for PVNP is shown in figure 4b. Similar to the nonprotected region, reforestation is observed in the upland areas of the park. In the lowlands, some interplay between grassland and vegetated wetlands can be observed. Also in this region, the loss of open water wetlands is obvious. The small increase in irrigated agriculture clearly occurs only along the northern border, corroborating the accounts of local officials.

Explaining Net Area Changes with Dominant Trajectories

The dominant trajectories explain the actual sequences of land cover transitions that each of the five land covers moved from (in the case of net area decrease) or moved to (in the case of net area increase). To reiterate, trajectories were retained for interpretation and graphing up to one of two cutoff points, whichever occurred first: (1) the point where $\geq$ 80% of change in an initial (in the case of net area decrease) or final (in the case of net area increase) land cover had been explained or (2) the point where trajectories explained less than one percent of the change of a given initial or final land cover.

Spatially explicit analysis of decrease in grasslands

In explaining the net area decrease for grasslands, seven trajectories were retained for the nonprotected area and five for the park (Figure 6a). Both parts of the landscape show a dominant pattern of grassland reforestation (G-F-F or G-G-F for the 1975-1987-2000 land cover sequence). These trajectories explain 51% and 43% of the change in the total initial grassland area, respectively. However, the most frequent nonprotected trajectory for grasslands through the study period was to remain grassland throughout. This G-G-G trajectory explained 29% of the initial grasslands in the nonprotected area while only 11% for the area of the park. This difference suggests that the park, by virtue of legal protection, management activities or differences in initial biophysical and land cover conditions—or some combination thereof—is more effective in promoting reforestation. The G-F-G trajectory in the nonprotected landscape reveals that, despite net gain in forest area, some 25,000 ha or about eight percent of the area classified as grassland in 1975, experienced both forest re-growth and clearing throughout the study period. While this pattern is also observed in the park, it does not describe any considerable area as evidenced with its elimination by cutoff rules.

In comparing the seven most dominant trajectories that explain grassland decrease for the nonprotected watershed, two trends or processes are evident. Aside from grassland reforestation already discussed, the conversion of grassland to irrigated agriculture consumes 12% of the land originally grassland at the start of the study. For the protected area, comparing the five dominant grassland trajectories reveals two dominant trends: reforestation of grasslands and conversion to vegetated wetlands.

Spatially explicit analysis of increase in forest

In explaining the net area increase in forest for protected and nonprotected areas, 7 and 6 trajectories were retained respectively (Figure 6b). For both the park and the nonprotected watershed, the largest percentage of forest at the end of the study period had been forest throughout. For the park, 45% of the forest present in 2000 was forest on the previous dates, whereas this was the case for 39% of the nonprotected forests in 2000. Clearly, the F-F-F trajectory (i.e., forest on all three dates in the series) is quite appreciable in both parts of the landscape.

This analysis largely illustrates the same trends observed in the decrease in grassland (namely reforestation of grasslands) since these processes are reciprocal. Within the nonprotected watershed, about 50% of the 2000 forest regenerated from grassland, compared with 24% in the park. This is related to the higher initial percent forest in the park but also to secondary processes that explain the net area increase in forest: the conversion of vegetated wetlands to forest. While the conversion of vegetated wetlands to forest may seem an odd land cover transition, be mindful that vegetated wetlands include flooded forests and mangroves. These trajectories (G-V-F and V-F-F) comprise less than two percent of the final forest cover for the nonprotected area. In the park, however, where by virtue of its position in the watershed it is more sensitive to alterations in hydrology, these trajectories (V-F-F, V-G-F, and V-V-F) explain 17% of the forest cover at the end of the study period. This transition may entail a different soil moisture signal detected in the land-cover classification process and/or it may also represent a true shift in species composition toward tropical dry forest or lowland evergreen forest. More detailed field observations and vegetation transects beyond the scope of this research would be needed to realize the ecological implications and assess the relative degree of ‘permanence’ of this land cover transition.

As with the analysis of the decrease in grasslands, the F-G-F trajectory was retained for both protected (comprising four percent) and nonprotected areas (comprising six percent). This trajectory is likely related to fire occurrence. The vegetation communities present in the park and larger watershed are not fire adapted (Murphy and Lugo 1986). Spark-over fires related to agricultural practices serve as one of the regions greatest impediments to reforestation (Janzen 1988), though fire watches, incentives and changes in agricultural technology are working to reduce fire incidence. As with evidence of hydrological changes affecting land cover in the park, clearly certain driving forces of land-cover change do not respect the boundary of PVNP, as is the case with any protected area.

Spatially explicit analysis of increase in irrigated agriculture

The small increase in irrigated agricultural land use within the park is related to a long-standing land tenure issue: contradictory government planning and nonpayment-for-inholdings. Thus, focus will be placed on examining the land cover trajectories that explain the dramatic increase in irrigated agriculture land use in the nonprotected watershed where there are two distinct conversion processes occurring (Figure 6c). Forty two percent of irrigated agriculture found in 2000 resulted from conversion of grassland (G-G-Iag or G-Iag-Iag) and 12% results from conversion of vegetated wetlands (G-V-Iag or V-Iag-Iag). When considering that wetlands comprise a much smaller area of the total landscape than grasslands, vegetated wetlands proportionately donate much more land to irrigated agriculture than grasslands. These data suggest that wetland is probably the most affected land cover in terms of the proportion of its extent converted to irrigated agriculture land use.

Spatially explicit analysis of decrease in open wetlands

There was no clear net area change for open water wetlands in the nonprotected area but the forward trajectories for open wetlands (i.e., those beginning with open wetlands in 1975), verify that the majority of open wetlands in the nonprotected watershed are open wetlands throughout (Figure 6d). Also, visual interpretation of the trajectory image reveals that this trajectory largely corresponds to the river. Thus, emphasis will be placed on understanding land cover conversions comprising the net area decrease in open wetlands within the park. Via three different conversion sequences (O-V-V, O-O-V, and O-G-V), about 52% of the initial open wetlands in the park converted to vegetated wetlands from 1975 to 2000. Oscillation from open to vegetated wetlands occurs on an annual and inter-annual basis due to the phenology of certain wetland vegetation communities, natural succession processes throughout the rainy season and draw down, and inter-annual differences in precipitation. However, the overwhelmingly dominant trend in terms of both area and trajectory frequency is the closing of open wetlands and not the reverse. This is even confirmed upon examination of 'backward' vegetation wetland trajectories for the park (Figure 6e) where conversions from vegetated wetland to open wetland do not even make the dominant trajectory cutoff.

These data imply that the natural oscillation between open and vegetated wetlands has shifted to a different state that supports the growth of emergent and floating vegetation to the likely detriment of waterfowl that depend upon expanses of shallow, open wetlands. In fact, these remotely sensed observations of land-cover change were corroborated by the accounts of park management figures who have undertaken the restoration of one of the park's smaller open water lagoons (pers. comm., personal observation). Suspected causes for the closing of open wetlands include the removal of cattle, whose grazing may have been the control mechanism on the wetlands; altered hydrologic regime in the way of altered volume, timing and surface-flow patterns; increased inorganic nutrient influx from adjacent flooded rice fields that drain into the park wetland system; or some combination of these three proposed causes.

The other retained explanatory trajectories (O-G-G) for the decrease in open wetlands within the park suggest that wetland desiccation is occurring either as part of the natural wetland dynamics in the Tempisque Watershed or as a result of hydrologic alterations.

Spatially explicit analysis of nonprotected area decrease in vegetated wetlands and protected area increase

The net increase in vegetated wetlands for the park is explained by seven dominant trajectories, though the most common trajectory across the study dates for land classified as vegetated wetland at the end of the study period was to remain vegetated wetland throughout. There appear to be three major themes of land cover transition explaining the slight increase observed for vegetated wetlands: conversion from grassland or fluctuations between grassland and vegetated wetlands (G-V-V, V-G-V, G-G-V) comprising 22%, closure of open wetlands with vegetation (O-V-V and O-O-V) comprising 12%, and finally, 11% explained by conversion of forest to vegetated wetlands (F-V-V and F-F-V). These three conversion processes suggest that both alterations in hydrology related to voluminous, non-seasonal delivery of water by PRAT and/or natural fluctuations in wetland land cover are occurring related to inter-annual differences in precipitation.

The significant decrease in vegetated wetland area for the nonprotected watershed throughout the study period is overwhelmingly due to conversion to irrigated agriculture land use (V-Iag-Iag, and V-V-Iag comprising 38% of initial V area). Another 10 and 11 % is accounted for by conversion to grassland and forest. The latter appears to correspond to areas that are adjacent to historic reaches of the riverbed that have since been dried out through channelization (e.g., the La Palma canal built in 1982) or other agriculture-related diversions. Only nine percent of the area classified as vegetated wetland in 1975 in the nonprotected watershed remained vegetated wetland throughout the study period. While this figure may be a low estimate due to the natural fluctuations between wetland and grassland cover already mentioned, irrigated agriculture and alterations in hydrologic connectivity have undoubtedly worked to the demise of wetland areas in the nonprotected watershed.

Summary: spatially explicit land-cover change for the park and nonprotected watershed

Explaining net area LCC trends in the park entailed thirty trajectories that met the original cutoff criteria. Similarly, thirty one trajectories were needed to explain the net area LCC trends for the nonprotected watershed. The second round of trajectory pairing reduced these numbers to six and four respectively, plus four 'no-change' or persistent land cover classes for each part of the landscape. For example, the increase in forest for both protected and nonprotected areas was due to reforestation of grasslands and desiccation of vegetated wetlands. Thus, for further analysis, all of the various trajectories representing these conversion processes were simplified and aggregated as follows: G-F-F and G-G-F were aggregated to become "grassland to forest" for the first conversion process and V-F-F and V-V-F were aggregated to become "vegetated wetland to forest" for the second process. Note that G-V-F and F-G-F respectively violate the simplification procedures by involving more than two land cover classes and by not being unidirectional. Again, while valuable information is being lost, the goal of the current analysis is to identify and understand the dominant land cover conversion processes for the protected and nonprotected areas of the watershed. The final retained trajectories are summarized in Figure 3-7.

Principal Components Analysis (PCA): Multivariate Landscape Structure

PCA proved moderately effective in reducing the dimensionality of the data. Two principal components with eigenvalues greater than one were extracted from the multivariate scatter of data about the eight landscape variables to explain nearly 53% of the total variance in the dataset (Table 3-3). Even though about half of the variance is not accounted for by the PCA results, these two components explain more variation than would be observed if there was no real multivariate structure to the landscape. The way in which the landscape variables load on the two components is particularly useful at defining two distinct dimensions of landscape variability.

The original structure matrix was used since loadings in the rotated component matrix failed to improve or change appreciably the interpretation of the principal components. The structure matrix (Table 3-3) reveals that the first component largely defines the biophysical gradient of the landscape with significant loadings of elevation, slope and distance to river. While these variables obviously covary, the correlation matrix suggests that this loading pattern is not merely an artifact of adding redundant variables since the bivariate correlation coefficients between pairs of the three variables range only from 0.334 to 0.537 (Table 3-4). The positive values of all loadings except distance to large forest illustrates that large forest patches occur mostly in the upper watershed. That is, small distance to forest is associated with the same end of the component as high values of elevation, slope, distance to river and distance from park boundary.

The second component largely defines the built structure of the landscape with significant loadings of distance to roads, distance to population center, distance to the Panamerican Highway and distance to large forest. Large distances from population centers are associated with same the end of the component as large distances from roads reflecting that population centers are connected by a transportation network. As distance from towns and roads increases, however, distance to the Panamerican Highway decreases as evidenced by its negative loading value. This reflects that the Panamerican Highway runs through the eastern side of the watershed whereas many of the population centers are located to the west of the river. This is understandable given that prior to the Panamerican's construction in the 1950s, most of the transport was via the river network. The negative loading of distance to large forest indicates that proximity to large forest increases with increasing distance from population centers and roads. While this reflects the fact that large forest patches persisted only in isolated areas, it also indirectly points to the fact that much of the "natural" land cover for the lower to middle watershed where the majority of population centers are located was not forest, but wetland.

Since only two principal components were extracted, many of the variables have low communalities, indicating that their values would not be effectively predicted by the principal components. The high communalities for elevation, slope and distance to river, however, again underscore the importance of these variables in overall landscape structure. The variables that load on the second component, those corresponding to the built structure of the landscape, obviously also respond to the major biophysical gradient in the landscape as evidenced by their pattern and signs of their loadings, as well as their general placement in the landscape. In other words, the reduction of these landscape data to two dimensions may be interpreted as the definition of proximate (PC2) and ultimate (PC1) sources of landscape variability given that the temporal and spatial scale of the two axes are quite distinct with regard to their effect on land cover dynamics.

Land-Cover Change as Function of Biophysical and Social Landscape

For each net area land-cover change trend, means for biophysical and location-relationship variables for each of the final, dominant trajectories were compared, along with the 'no-change' trajectory for each land cover, for both the nonprotected (Table 3-5) and protected (Table 3-6) parts of the landscape. Based on exploratory data analysis and results from PCA, distance from large forest and distance from park boundary were not included in these comparisons, as they did not generally offer any new information in contrasting the domains of dominant, competing trajectories.

Comparing means of landscape variables for nonprotected area

For the nonprotected watershed, two explanatory trajectories were compared for the net decrease in grassland: grassland to forest and grassland to irrigated agriculture. On comparing the means (Table 3-5) and distributions (Figure 8) of these trajectories for all variables measured, it is clear that these two trajectories largely occur in different landscape domains. Grassland is converted to irrigated-agriculture land use in low, flat areas near the river, with an average elevation of 33.73 m, average slope of 1.43% and half the mean distance to river as the competing trajectory (4505.47 m versus 8990.44 m, $P<0.01$). This trajectory is also closer to population centers and the Panamerican Highway than the grasslands that are reforested. On average, grasslands that are reforested occur at much higher elevations (218.04 m), steeper slopes (13.3%), farther from the river (8990.44 m), population centers and the Panamerican Highway. This comparison suggests that the land most suitable for the current land use model (intensive agriculture) is in the lower watershed, and grassland areas not falling within this domain are reforesting. Based on these results, degree of isolation may also play a role in whether reforestation occurs.

The trajectory of ‘no-change’ or grassland throughout the study period appears to occur generally between the extremes of the two dominant explanatory trajectories with a mean intermediate between the two for all six variables. This suggests that persistent grasslands occur on lands not suited for irrigated agriculture but that may still be used for cattle ranching or that may be too degraded for true forest succession to ensue.

For the net increase in forest area over the study period, the two explanatory trajectories compared were grassland to forest and vegetated wetland to forest (Table 3-5 and Figure 8). Forest comes from grassland at much higher elevation (245.49 m) and steeper slope (13.42%) than from vegetated wetlands (35.16 m and 5.29% respectively, $P<0.01$). Most notably, vegetated wetland to forest conversions occur much closer to the river (4984.63 m versus 9727.82 m, $P<0.01$), supporting the idea that channelization and increased incision of the river has dried out parts of the floodplain, facilitating the conversion of wetlands to forest. The two trajectories do not differ significantly with regard to their relationship to features of the built landscape other than vegetated wetland conversion to forest being farther from the Panamerican Highway. Compared with the ‘no-change’ forest trajectory, it is clear that grassland to forest shares nearly the same domain, except that persistent forest cover was slightly more isolated as evidenced by a significant difference in distance to nearest road (2036.75 m versus 1512.09 m, $P<0.01$, for grassland to forest conversions).

For the nonprotected decrease in vegetated wetlands, the two competing explanatory trajectories compared were vegetated wetlands to forest and vegetated wetlands to irrigated agriculture. Conversion to forest occurs at greater slope (5.29% versus 0.57%, $P<0.01$) and higher elevation (35.16 m versus 9.51 m, $P<0.01$) than conversion to irrigated agriculture.

Since the elevation and slope are considerably greater for vegetated wetlands converting to forest than those converting to irrigated agriculture or remaining wetlands throughout, this suggests that the wetlands following this trajectory are likely riparian areas that have dried out due to hydrologic alterations. However, vegetated wetlands to forest has the highest distance from river which contradicts this idea, unless total diversion of stream flow has occurred (i.e., stream removal). The persistent vegetated wetland trajectory has a distinct domain in the landscape compared with the two dominant change trajectories for vegetated wetlands. Means for all six landscape variables except distance to Panamerican Highway were significantly different ($P<0.01$). Nonprotected wetlands that persisted throughout the study period were the most isolated and occurred in the lowest, flattest parts of the watershed.

The increase in irrigated agriculture for the nonprotected landscape is explained by two dominant trajectories, vegetated wetlands to irrigated agriculture and grassland to irrigated agriculture, that have been examined already in the context of explaining net decreases in grassland and vegetated wetlands. The persistent irrigated agriculture land use trajectory suggests that the first land to be converted was closest to the river (2418.38 m versus 3187.7 m and 4153.19 m respectively for the other trajectories, $P<0.01$), which is expected since the lone water source at the beginning of the study period was the river itself. Grasslands converted to irrigated agriculture, as expected, have a higher ($P<0.01$) mean elevation and slope (30.265 m and 1.21%) than conversions from vegetated wetlands (12.9 m and 0.57%). The mean distance to road for conversion from vegetated wetlands (2338.68 m) was higher ($P<0.01$) than for conversions from grassland (1203.67 m) indicating the high level of investment in the way of infrastructure required to implement this land use system in much of the lower watershed.

In comparing the dominant explanatory trajectories across all net-area trends for land-cover change in the nonprotected portion of the watershed (Table 3-5), elevation and slope appear to be the most effective variables in defining the path of conversion for a given starting land-cover type. Not only were all pair-wise comparisons amongst competing trajectories found to be significantly different, the magnitudes of the differences in means are environmentally significant as well. Boxplots of the mean elevation for each trajectory clearly illustrate the differences in ranges (Figure 8).

Comparing means of landscape variables for protected area

The two dominant trajectories competing with the park to explain the net area decrease in grassland area were grassland reforestation and grassland to vegetated wetland transitions. Analogous to its landscape setting in the nonprotected area, grassland reforestation occurs in the uplands of the park with a higher ($P<0.01$) mean elevation (32.17 m) and slope (13.44%) than the grassland to wetland trajectory (8.99 m and 1.40% respectively). Grassland reforestation in the park is further associated with uplands by virtue of occurring farthest from the river ($P<0.01$) relative to conversions to vegetated wetland or persistent grasslands (2927.98 m versus 1740.00 m or 2252.05 m respectively).

The park and nonprotected area seem to share the same dominant explanatory trajectory, reforestation of grasslands, for reduction of grasslands and increase in forest cover in upland areas. However, in lowlands of the park, there is no conversion to irrigated agriculture. The lowland dominant trajectory for decrease in grasslands is the interplay between grasslands and wetlands. This grassland to vegetated wetland trajectory occurs in largely the same domain as persistent vegetated wetlands. That is, relative to reforesting grasslands or persistent grasslands, these grasslands that transition to vegetated wetlands occur in the lowest (8.99 m mean elevation), flattest (1.40% mean slope), and most isolated areas of the park ($P<0.01$). This suggests that the park is effective in preventing direct conversion of natural cover to direct human land use. However, since the classification method employed was reasonably effective in offsetting land cover differences due to inter-annual climate change, these data suggest that the park may be incurring land-cover changes due to alterations in hydrologic regime or climatic events such as ENSO. Though these findings are intuitive and expected, parks are still largely being managed as islands, particularly with regard to any concept of connectivity to broader landscape processes beyond that of habitat connectivity via corridors and reserve networks (e.g., Sanchez-Azofeifa et al. 2003).

Again, just as in the nonprotected area, the dominant explanatory trajectories for the increase in forest within the park are grassland to forest and vegetated wetland to forest. The latter occurs at a lower ($P<0.01$) mean elevation (15.54 m) and slope (5.94%) than grassland reforestation (32.17 m and 13.44% respectively). This corresponds to the relationship between these two trajectories in the nonprotected landscape; however, unlike the nonprotected area, distance to river for the two trajectories is the same ($P>0.05$). This may be more of a reflection of the fact that the park is a smaller, defined area where distance from river cannot vary significantly by virtue of its proximity to river. As in the nonprotected watershed, persistent forest has the same relationship to reforested grasslands in that it occurs in largely the same relative landscape domain.

Three dominant trajectories explain the increase in vegetated wetlands within the park: the closing of open water wetlands with vegetation, transition from forest to vegetated wetlands, and transition from grassland to vegetated wetlands. These trajectories, along with persistent vegetated wetlands throughout the study period, all occur within the same biophysical domain with no significant difference in elevation or slope (P>0.05). Open to vegetated wetland occurs closer to the river than conversion to vegetated wetland from grassland (1032.79 m versus 1653.10 m, P<0.01) and both of these trajectories occur in areas more isolated in terms of distance to the Panamerican and population centers (P>0.05). Otherwise, these trajectories are none-too-distinguished by their respective means for landscape variables, suggesting that an unmeasured variable such as hydrology may play a bigger part than the landscape variables measured here in determining wetland dynamics within the park.

The final net area change in land cover for the park is the decrease in open wetlands explained by both conversion to vegetated wetlands and desiccation to become grassland. The means for these two trajectories for all landscape variables measured do not differ significantly (P>0.05). When these two trajectories of open wetland change are compared with persistent open wetlands in the park, results show that the three differ only with respect to mean distance from river (P>0.05). Persistent open wetlands occur, on average, 491.37 m from the river, versus 1032.79 m and 1635.20 m for open to vegetated wetland conversions or open wetland desiccation, respectively. As with the previous case, these results suggest that hydrology, precipitation or other unmapped variables are more-closely associated with the path/trajectory taken by a given open wetland pixel over the course of the study period than the landscape domain defined by these six biophysical and location-relationship variables.

Summarizing land-cover change as a function of landscape domain per status

In summary, the nonprotected, lower watershed (low elevation and relatively flat land) is characterized by predominance of the following trajectories: grassland to irrigated agriculture, vegetated wetlands to irrigated agriculture and vegetated wetlands to forest. All of these conversion processes also appear dependant on the correlated variable of proximity to river (by virtue of the need for water for land use regime in the case of the first two, and by virtue of possibly being related to altered stream flows in the case of the latter). In contrast, the lowlands of the park are dominated by persistent vegetated wetlands, vegetated wetland transitioning to forest, and finally, open water wetlands closing with vegetation or desiccating to become grasslands. In both the upper watershed of the nonprotected portion of the landscape and the uplands of the park, results indicated that reforestation of grasslands is the dominant land-cover trajectory.

Effectiveness of the Park in the Watershed Context

The park was shown to be effective in preventing absolute conversion to irrigated agriculture and deforestation within its bounds. Conservation of wetland land cover and forest was observed in the park over the study period, as well as reforestation of grasslands. Flipping the question of park effectiveness around, then, entails asking what land use might be expected if the park had not been established based on patterns observed outside of the park and the opportunities and constraints presented by the geographic space of the park in relation to these land uses. Given that the park is not a representative sample of the larger landscape, examining park effectiveness in this way better isolates the effect of protection from other effects such as greater degree of isolation or lower position in watershed.

Vegetated wetlands in the nonprotected watershed were overwhelmingly converted to irrigated agriculture over the course of the study period. The principal component scores of these wetland to agriculture conversions were plotted to compare with the domain of the biophysical and built landscape in which protected wetlands were conserved. Figure 9a indicates substantial overlap between these two clusters, suggesting that if the park had not been established wetland areas would have been suitable for draining and use in irrigated agriculture. The other major class converted to irrigated agriculture land use in the nonprotected watershed was grassland. In order to assess whether grassland areas of the park that reforested fell within the same domain as those converted to irrigated agriculture outside the park, the same plot was made for these two trajectories (Figure 9b). Again, substantial overlap was observed in the respective clusters on the scatter plot. Based on this observation and results from comparing domains of competing trajectories for each net area land-cover change trend, it appears that grassland areas with minimal slope in the park would have very likely been converted to irrigated agriculture land use without the decree of protection, rather than reforesting as they did.

A final critique of the park's effect comes in asking whether reforestation would have been observed without protection, given that this was a dominant trend seen in the upper watershed of the nonprotected area. In addressing this question, the principal component scores of grassland to forest trajectories were plotted to compare these clusters for protected and nonprotected areas (Figure 9c). The protected grassland to forest occurrences form a cluster at the lower end of the PC1 axis indicating that reforestation in the park occurs at much lower and flatter land than reforestation in the nonprotected area, obviously a function of the park's placement in the watershed. This further corroborates the above finding that much of the grassland in the park would likely have been converted to agricultural use rather than reforested. The position of the park's grassland to forest cluster on the positive end of PC1 axis indicates the cluster's relative isolation from roads and population centers which might have served to facilitate reforestation, even without protection, in areas with slopes too great for the current agriculture/land use system.

Conclusions

Both land cover and land use systems in the basin have responded to landscape structure throughout their evolution and this interaction is an important consideration in evaluating the effect of protected area management on land cover dynamics. Historically, cattle ranching operations were arranged in space so as to take advantage of the resources offered at different seasons across the elevation gradient. This system depended on, and thus conserved to some degree, the natural land cover of the lowlands (wetlands), but promoted deforestation of uplands. In contrast, intensification of agriculture saw the cultivation of crops in the lower watershed and along the river and its tributaries where the requisite low, flat land near water sources is found (or to which water can be easily transported via PRAT). Concomitant reforestation is occurring in the upper watershed as a probable function of decreased economic dependence on extensive land management (cattle ranching), coupled with incentives for forest conservation like Costa Rica's environmental service payment program.

Examining net area land cover trends for the park over the study period demonstrates that wetland land cover has been conserved, extant forest has been conserved and reforestation of grasslands has also occurred. The park was found not to be a representative sample of the larger landscape, however, and that some of the same dominant, conservation-friendly land cover conversion patterns were observed in both the park and nonprotected area. Thus to better assess the effect of the park on land cover dynamics, comparisons of trajectories within similar domains were made in order to somewhat control for confounding factors. These comparisons supported the concept that much of the success in directing land cover patterns in accordance with park management goals was, in fact, due to management and/or protection status.

However, several subtle land cover trends indicate that land cover dynamics other than forest/wetland conservation and forest regeneration also merit attention and consideration in assessing the effectiveness of PVNP. Specifically, trends highlighted by this broad analysis include the closure of open water wetlands with vegetation, the flooding of forest to become vegetated wetlands, and the possible desiccation of vegetated wetlands to become forest or grassland. The degree of severity and ecological implications of these land cover transitions associated with alterations in the hydrologic regime or climate events deserves further study. One grave implication of the closing of open water wetlands is clear, however: loss of habitat for migratory waterfowl (McCoy and Rodriguez 1994).

Intensification of agricultural production systems has a range of positive and negative environmental effects at the landscape level. In short, the positive effect may be that intensification promotes the regeneration of natural land cover by facilitating the production of higher yields per unit of cultivated area, thus freeing up land from production systems (Gall and Orians 1992). Given the land cover patterns observed over the study period, this seems to be the case in the Tempisque Watershed. Though contrary to the dominant theme on the global change agenda of tropical deforestation, other research has also noted tropical reforestation may occur with changes in agricultural management systems. For example, Southworth et al. (2002) observed abandonment and reforestation of marginal lands in the La Campa region of Western Honduras.

The negative effects of intensification, however, are more widely recognized. These include nutrient inputs from fertilizers that contaminate water courses, contributions of gases related to climate change, soil erosion, and a suite of ecological problems related to irrigation (Gregory et al. 2002), often the cornerstone of agricultural intensification. Irrigation systems are known to affect the extent, quality and mosaic pattern of wetlands in several ways. They cause the direct conversion of wetlands through drainage (Niering 1988). They may desiccate and shrink the size of wetlands through competition for water (Lemly et al. 2000) via surface extraction, channelization (Shankman 1996) and subsurface irrigation drainage (Lemly 1994). Amplified pollution in the way of increased fertilizer; herbicide and pesticides affect the vegetation communities and wildlife species that depend upon them. And finally, cumulative alterations in natural surface flow regimes affect the spatial and temporal patterns of biological productivity and thus the potential for wetland floodplain habitats to act as sources and sinks for organic matter (Ward and Stanford 1995). All or any combination of these effects may be occurring in the Tempisque River Watershed with grave implications for the wetland mosaic and other habitats that Palo Verde National Park seeks to conserve.

The park represents a large portion of the only remaining natural vegetation left in the lowest part of the watershed. The observed changes in its wetland mosaic may have implications not only for wildlife but possibly for forest systems far upslope from it (Lawton et al. 2001). Clearly the park was shown to be effective in the immediate sense in that it conserved wetlands and promoted reforestation. However, long-term conservation of Palo Verde’s unique habitat mosaic and biodiversity must be managed within the context of the entire watershed. Similarly, continuation of the services and benefits that the upper watershed receives from the park also requires a landscape perspective.

Three major points conclude this case study of the protected area management of Palo Verde National Park within its watershed context. First, the shortcomings of Palo Verde National Park in conserving natural land cover appear to result from factors that are difficult to measure and which are rarely, if ever, included on the list of factors often considered in evaluating the effectiveness of protected areas. These include effects of fragmented or enhanced hydrologic connectivity with the wider landscape and the ability to absorb shocks posed by periodic climate events that may only be exacerbated with increasing global climate change.

Secondly, the important land cover dynamics seemingly related to alterations in hydrologic regimes in this landscape were only revealed by using a land-cover classification scheme with higher taxonomic resolution than those normally employed in remotely sensed land cover studies of tropical reserves. Nonetheless, this increase in thematic resolution poses data management and interpretation challenges that were, perhaps, not treated in the most effective possible way in this analysis, despite the attempt to establish consistent data reduction rules. Also pointed out by this study is the limitation of categorical land cover data in assessing ecological value of land cover alterations. Clearly, one direction for future research within this basin may be use of continuous land cover data (e.g., vegetation indices) to better describe and capture the nuances of land cover transitions and qualitative changes within a single, non-converting land-cover type (Southworth, et al. 2004).

Finally, case studies of protected areas and protected area networks in their watershed contexts contribute to a more complete understanding of the ways in which parks are affected by current and potential threats originating beyond their borders, including hydrologic alterations (Pringle 2001). This contextual approach also facilitates an understanding of what land cover and land uses might be expected if protection were not in place, an approach that may also be useful for predictive modeling during planning phase of reserve establishment or during adaptive management activities existing protected areas.

Table 3-1. Description of land use and land cover classes

Name	Class Type	Description
Irrigated Agriculture	Land Use	Dominant land covers include irrigated crops of rice, sugar cane, melon, bare soil, water and organic soil amendments
Open Water Wetland	Land Cover	*Non-* or sparsely-vegetated wetlands usually <2m deep
Vegetated Wetlands	Land Cover	RAMSAR definition of wetland employed[1]; covers included mangroves, flooded forests, fresh marshes with emergent and floating vegetation, fresh meadows of grasses and sedges; all phenological stages of all classes included
Urban	Land Use	All anthropogenic land cover in population centers; consisted largely of mixed concrete, asphalt and vegetation or residential areas of mixed vegetation and houses
Grasslands	Land Cover	Strict pasture of grasses only, pasture with occasional trees, recently fallowed pasture (<3 years) still dominated by grasses, grassy areas along roads, and finally, regions frequently burned as a result of being downwind of agricultural fires that cannot support appreciable woody growth
Forest	Land Cover	Limestone forests, deciduous lowland forest, evergreen lowland forest, and pre-montane moist forest; rainy season canopy closure > 40%

[1] Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.

Table 3-2. Comparison of land cover composition in 1975 and all biophysical/location variables for park and nonprotected areas (n = 1140 for park and n = 1163 for nonprotected area). For the land use/land cover category, total area of each cover type is given (in hectares) and the percent of the protected or nonprotected landscape segment that it comprises. For the biophysical/location variables comparison, the mean value of each variable is given (in meters) plus or minus one standard deviation. Differences in means for biophysical/location variables were tested using two-tailed Mann Whitney tests. Abbreviations used in the table are as follows: D_lgfor=distance to large forest, D_panam=distance to Panamerican Highway, D_rds=distance to road, D_pkbnd=distance to park boundary, D_popctr=distance to population center and D_river=distance to river.

Category	Item Compared	Park	Nonprotected Watershed
Land Use/ Land Cover (ha)	Grassland	4949.73 ha (26.4%)	286001.82 ha (59.4%)
	Forest	6463.8 ha (34.5%)	148834.53 ha(30.9%)
	Open Wetland	1572.75 ha (8.4%)	3634.38 ha (0.8%)
	Vegetated Wetland	5761.98 ha (30.7%)	19724.85 ha (4.1%)
	Irrigated Agriculture	11.16 ha (0.06%)	22387.23 ha (4.7%)
Biophysical Variable/Location Relationship (m)	Elevation*	21.45 (±29.78)	199.45 (+226.25)
	Slope*	7.71(+15.84)	10.74 (+16.24)
	D_lgfor*	742.918 (+1056.28)	1084.25 (+1432.69)
	D_panam*	18312.355 (+2561.03)	17160.6418 (+13795.55)
	D_rds*	2977.03 (+1849.02)	1671.638 (+1544.98)
	D_pkbnd*	1315.39 (+919.69)	22824.898 (+12226.81)
	D_popctr*	15698.94 (+4852.45)	10577.79 (+6277.28)
	D_river*	2277.89 (+1561.64)	8327.524 (+6175.03)

* Indicates significant difference at alpha = 0.01

Table 3-3. Principal component structure matrix showing loadings of each variable on the two retained components, along with their respective eigenvalues and the percent variance of the correlation matrix trace or diagonal explained by each component. The communality column indicates the amount of each variable's variance accounted for by the principal components.

Variable	Component Loadings I	II	Communality h2
D_Lgfor	-0.316	-0.587	0.444
D_Panam	0.435	-0.654	0.616
D_Pkbnd	0.622	0.239	0.444
D_Popctr	0.093	0.654	0.437
D_Rds	0.004	0.611	0.373
D_River	0.802	-0.281	0.722
Elevation	0.805	0.306	0.741
Slope	0.628	-0.214	0.440
Eigenvalues	2.369	1.848	
% Trace	29.611	23.095	

Table 3-4. Correlation matrix of all biophysical and location-relationship variables

	D_LGFOR	D_PANAM	D_PKBND	D_POPCTR	D_RDS	D_RIVER	ELEVA	SLOPE
D_LGFOR	1.000*	0.184*	-0.163*	-0.253*	-0.211*	-0.113*	-0.304*	-0.083*
D_PANAM	0.184*	1.000*	0.046*	-0.218*	-0.181*	0.476*	0.033*	0.377*
D_PKBND	-0.163*	0.046*	1.000*	0.101*	0.039*	0.306*	0.537*	0.146*
D_POPCTR	-0.253*	-0.218*	0.101*	1.000*	0.269*	-0.093*	0.174*	0.0189*
D_RDS	-0.211*	-0.181*	0.039*	0.269*	1.000*	-0.143*	0.135*	-0.040*
D_RIVER	-0.113*	0.476*	0.306*	-0.093*	-0.143*	1.000*	0.537*	0.384*
ELEVA	-0.304*	0.033*	0.537*	0.174*	0.135*	0.537*	1.000*	0.334*
SLOPE	-0.083*	0.377*	0.146*	0.019*	-0.040*	0.384*	0.334*	1.000*

* indicates significance ($P \leq 0.000$)

Table 3-5. Comparison of means for biophysical and location-relationship variables amongst explanatory trajectories for each net-area trend in the nonprotected watershed. Like letters after mean indicate means that do not different from one another.

Land Cover Trend	Non-prot Explanatory Trajecs.	Biophysical/Location-Relationship Means									
		D_Panam (m)		D_Popctr (m)		D_Rds (m)		D_River (m)		Elevation (m)	Slope (%)
- Glnd	glnd_for	18546.08		10501.12		1414.57	a	8990.44		218.04	13.30
(n=2343)	glnd_iag	14744.38		8097.30		1257.79	a	4505.47		33.73	1.43
	glnd	14942.86		9774.67		1602.60		7622.98		146.98	7.00
+ For	glnd_for	17717.17	a	10231.20	a	1512.09	a	9727.82	a	245.49	13.42
(n=207)	vwtlnd_for	20820.88		11452.91	a	1357.64	a	4984.63		35.16	5.29
	for	16208.77	a	10954.81	a	2036.75		10255.55	a	294.85	14.04
- Vwtlnd	vwtlnd_for	20820.88	a	11452.91	a	1357.64		4984.63		35.16	5.29
(n=213)	vwtlnd_iag	16258.04		11194.05	a	2305.52		3225.46		12.60	0.57
	vwtlnd	22445.65	a	14002.96		2723.59		2495.07		9.51	0.41
+ Iag	vwtlnd_iag	16094.23	a	11031.99		2338.68		3187.70		12.90	0.57
(n=447)	glnd_iag	14116.91	b	7893.40	a	1203.67	a	4153.19		30.27	1.21
	iag	14524.33	a,b	7672.70	a	1360.84	a	2418.38		18.12	0.64

Table 3-6. Comparison of means for biophysical and location-relationship variables amongst explanatory trajectories for each net-area trend in the protected watershed. Like letters after mean indicate means that do not different from one another within the comparisons of each land cover trend.

Land Cover Trend	Prot Explanatory Trajecs. (n)	Biophysical/Location-Relationship Means											
		D_Panam (m)		D_Popctr (m)		D_Rds (m)		D_River (m)		Elevation (m)		Slope (%)	
- Glnd (n=100)	glnd_for	18038.01	a	14912.25	a	2640.41	a	2927.98		32.17		13.44	
	glnd_wtlnd	19266.82		17669.83		3890.19		1740.00		8.99		1.40	
	glnd	18666.40	a	16667.48	a	3221.16-	a	2252.05		15.07		3.26	
+ For (n=97)	glnd_for	18038.01	a	14912.25		2640.41-	a	2927.98	a	32.17	a	13.44	a
	vwtlnd_for	17441.30	a	17827.25		4036.25		2979.14	a	15.54		5.94	
	for	17835.55	a	13701.63		2537.15	a	2470.96		33.68	a	15.75	a
+ Vwtlnd (n=57)	op_vwtlnd	20308.56	a,b	22073.34		3535.47	a	1032.79	a,c	8.61	a	0.20	a
	for_vwtlnd	17441.3	c	17827.25	a	4036.25	a,b	2979.14b	a,b,d	15.54	a	5.94	a
	glnd_vwtlnd	19276.23	a,c	17954.97		4127.32		1653.10	b,e	8.90	a	1.23	a
	vwtlnd	19647.07	b	14952.77	a	2962.12	b	1368.56	c,d,e	9.04	a	0.39	a
- Opwtlnd (n=18)	op_vwtlnd	20308.56	a	22073.34	a	3535.47	a	1032.79	a	8.61	b	0.20	a
	op_glnd	18277.86	a	20772.21	a	2978.80	a	1635.20	a	10.33	c	0.34	a
	opwtlnd	20751.32	a	22816.91	a	3377.21	a	491.37		-8.55	b,c	0.00	a

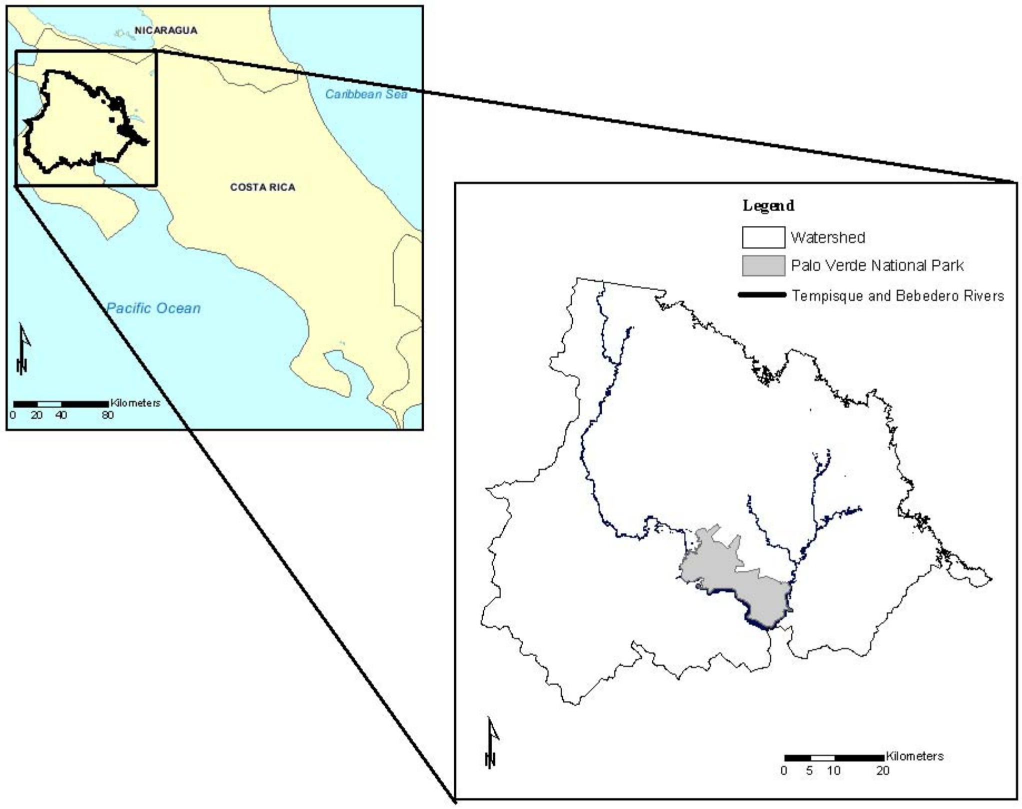


Figure 3-1. Map of study region showing the watershed boundary and that of Palo Verde National Park

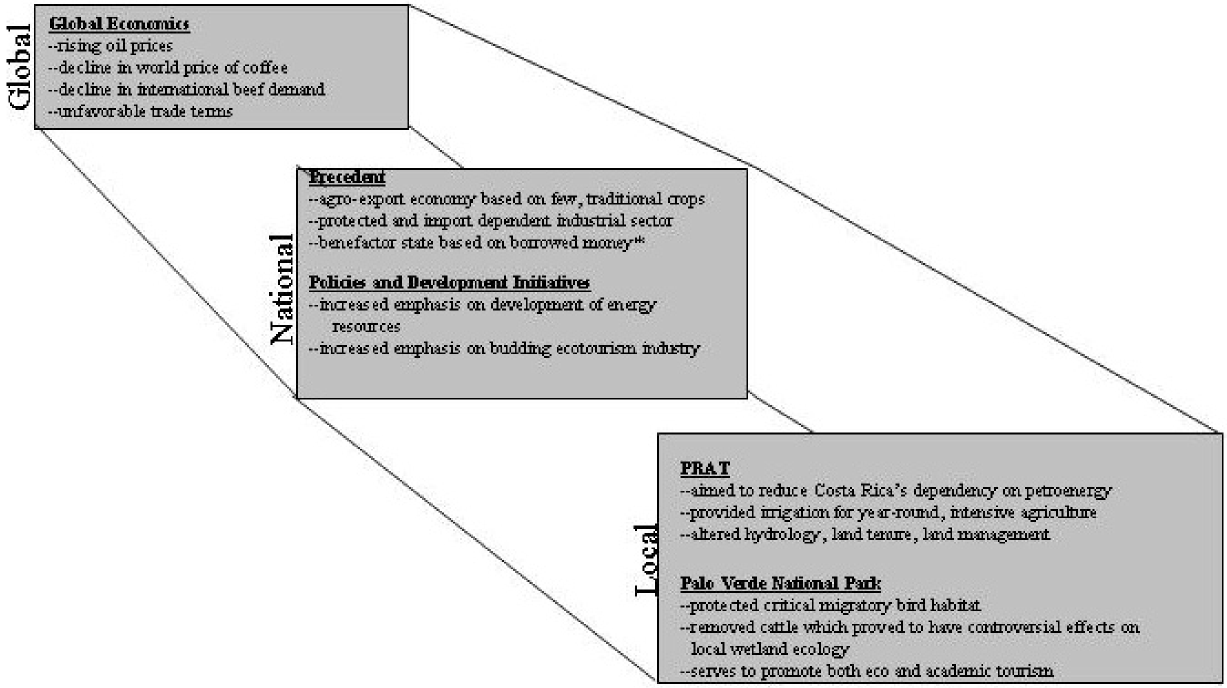


Figure 3-2. Summary diagram of multi-scale social, economic and political conditions that facilitated landscape transformation in the Tempisque River Watershed

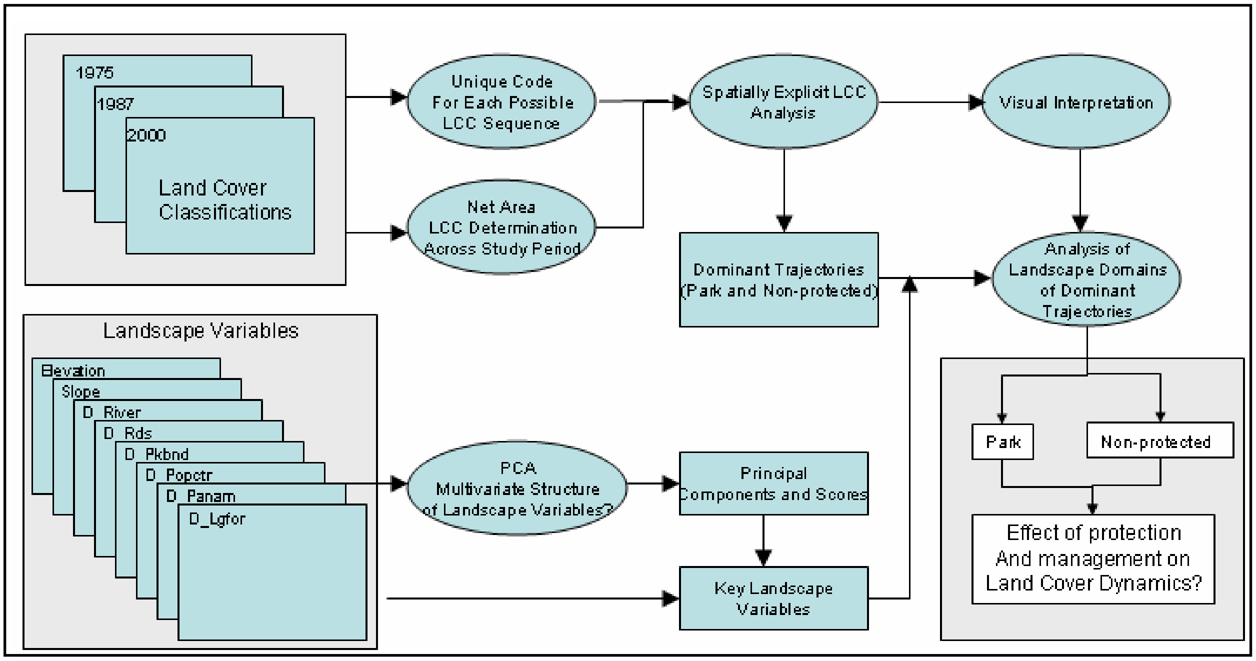
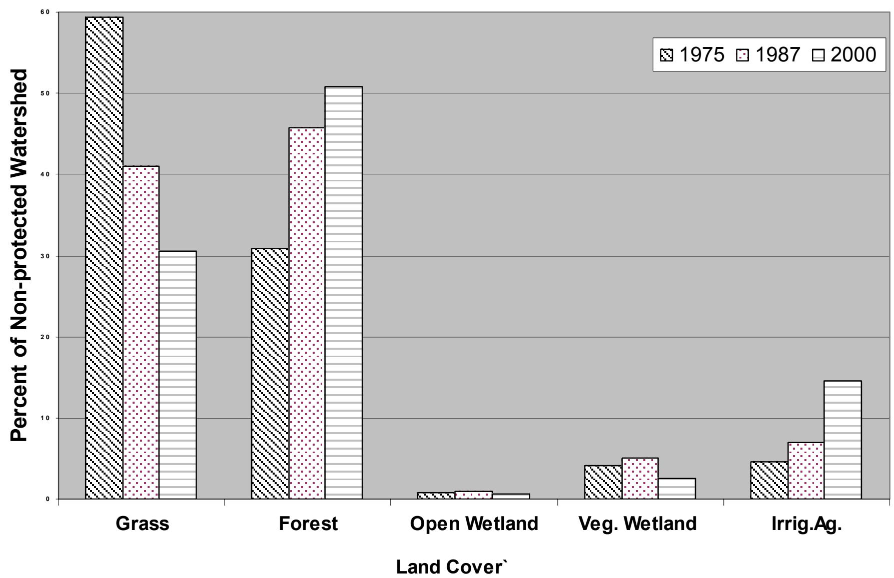


Figure 3-3. Flowchart of the analysis of land cover dynamics for protected and nonprotected areas of the landscape. Abbreviations used are as follows: D_River=distance to river, D_Rds=distance to roads, D_Pkbnd=distance to park boundary, D_Popctr=distance to population center, D_Panam=distance to Panamerican Highway, and D_Lgfor=distance to large forest.

(a)



(b)

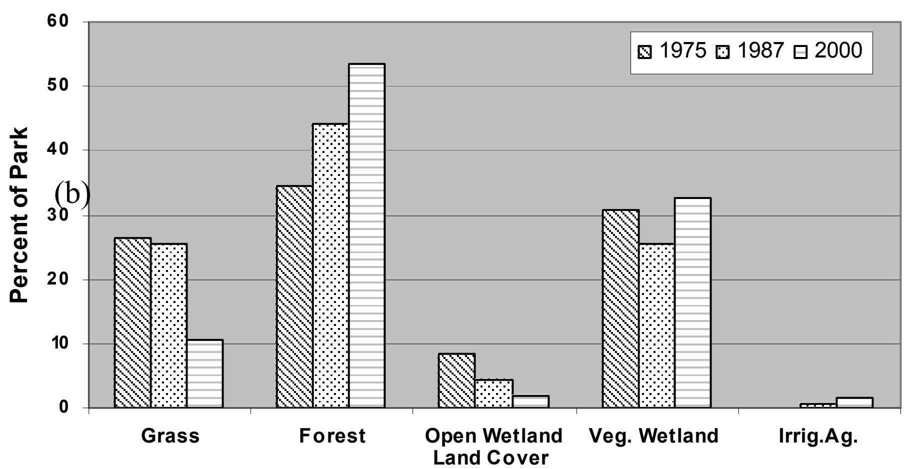


Figure 3-4. Net area land use/land-cover change across the study period (1975, 1987, and 2000) for (a) nonprotected watershed and (b) park

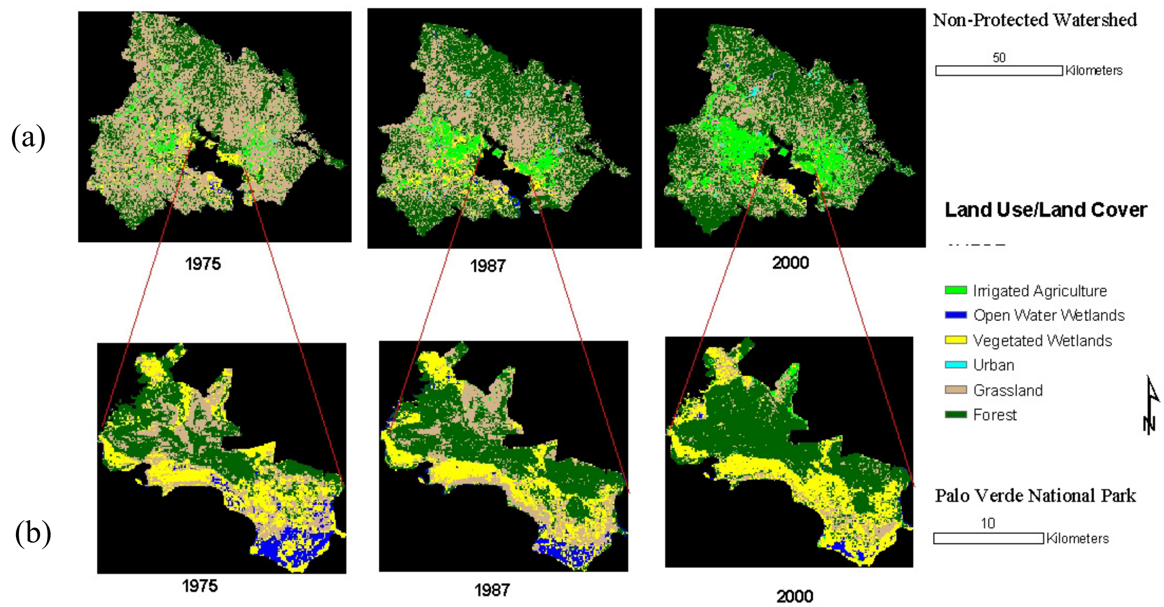


Figure 3-5. Maps of land use/land cover for 1975, 1987 and 2000 for (a) nonprotected watershed and (b) park

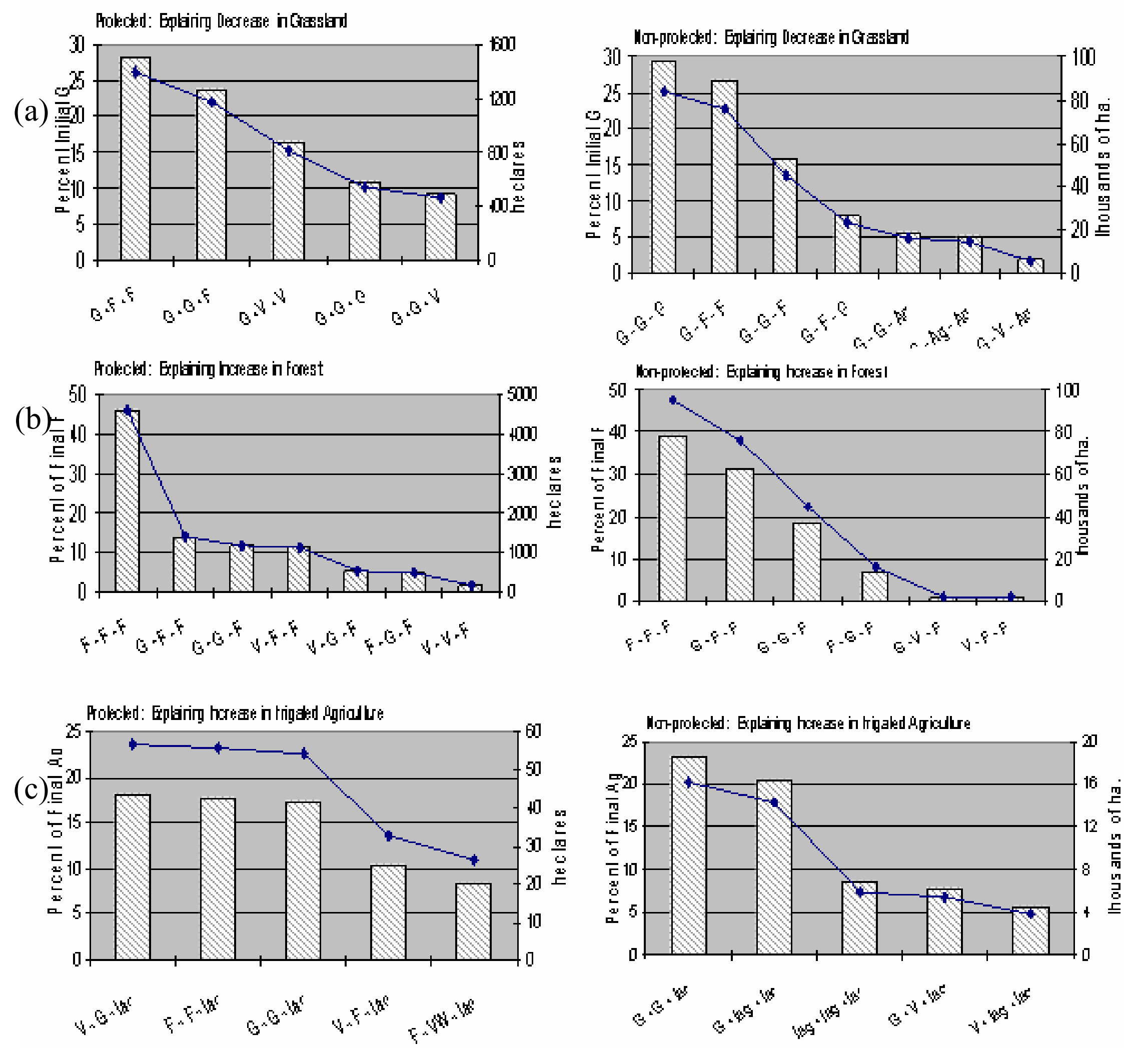


Figure 3-6. Dominant protected (left column) and nonprotected (right column) area trajectories (x axis) that explain observed net area changes in land cover. % of final land cover is graphed, along with absolute area, in the case of backward trajectories and percent of initial land cover, along with absolute area on secondary y axis, is graphed in the case of forward trajectories. The three-code sequence corresponding to each bar represents a trajectory reflecting the land cover for 1975-1987-2000. Only those trajectories meeting the cutoff criteria are included here. That is to say, trajectories for a given net-area trend were retained up until 80% of the net-area trend had been explained or the point where a given trajectory explained less than one percent of the observed net area change. Land cover abbreviations are as follows: V for vegetated wetland, G for grassland, F for forest, Iag for irrigated agriculture, and O for open water wetland.

(d)

(e)

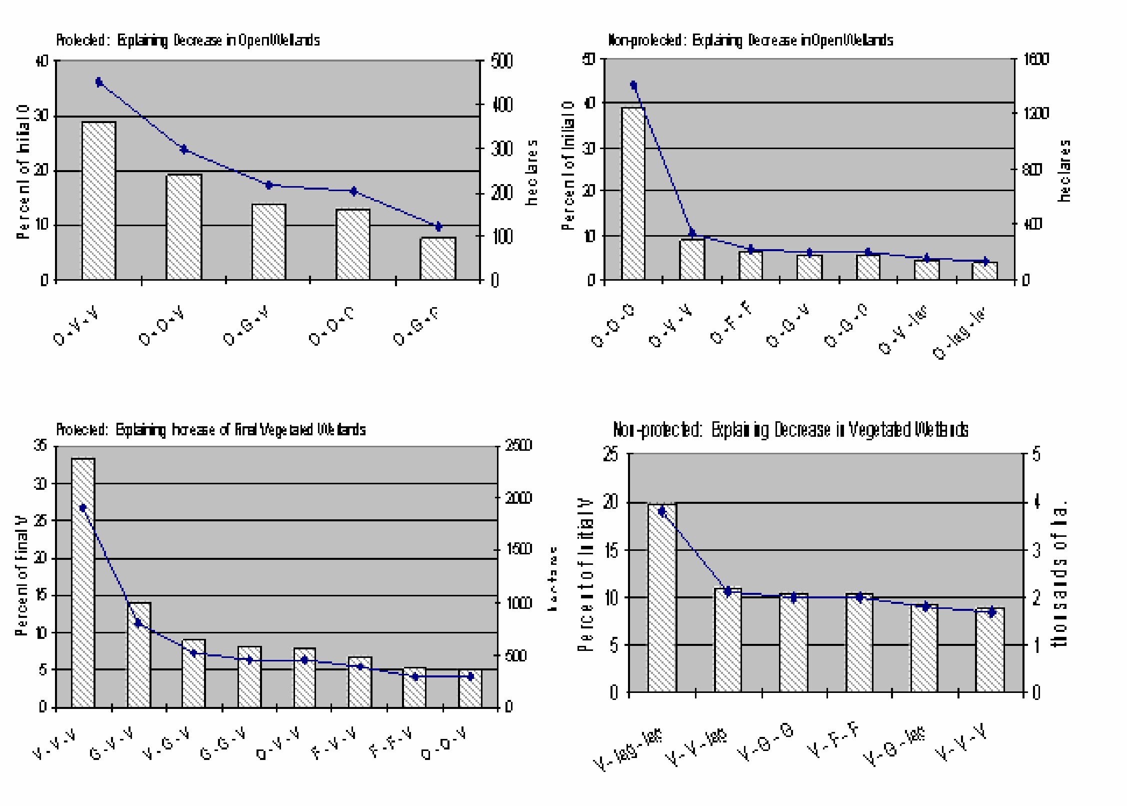


Figure 3-6. Continued

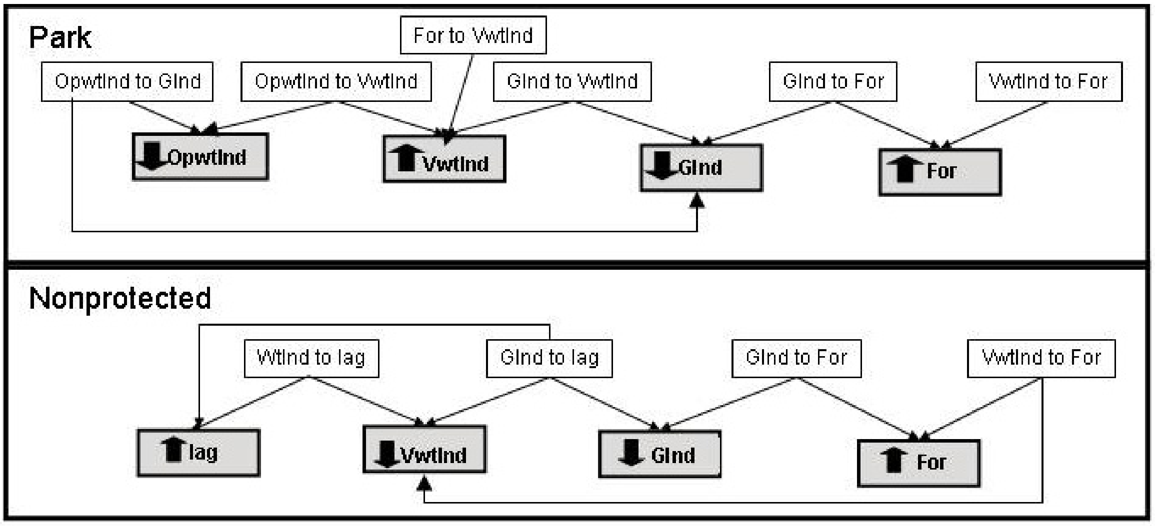


Figure 3-7. Summary diagram of net-area trends with the final, dominant explanatory trajectories (after last round of simplification) that contribute to them respectively. Abbreviations used are as follows: Opwtlnd for open wetland, Vwtlnd for vegetated wetland, For for forest, Glnd for grassland, and Iag for irrigated agriculture.

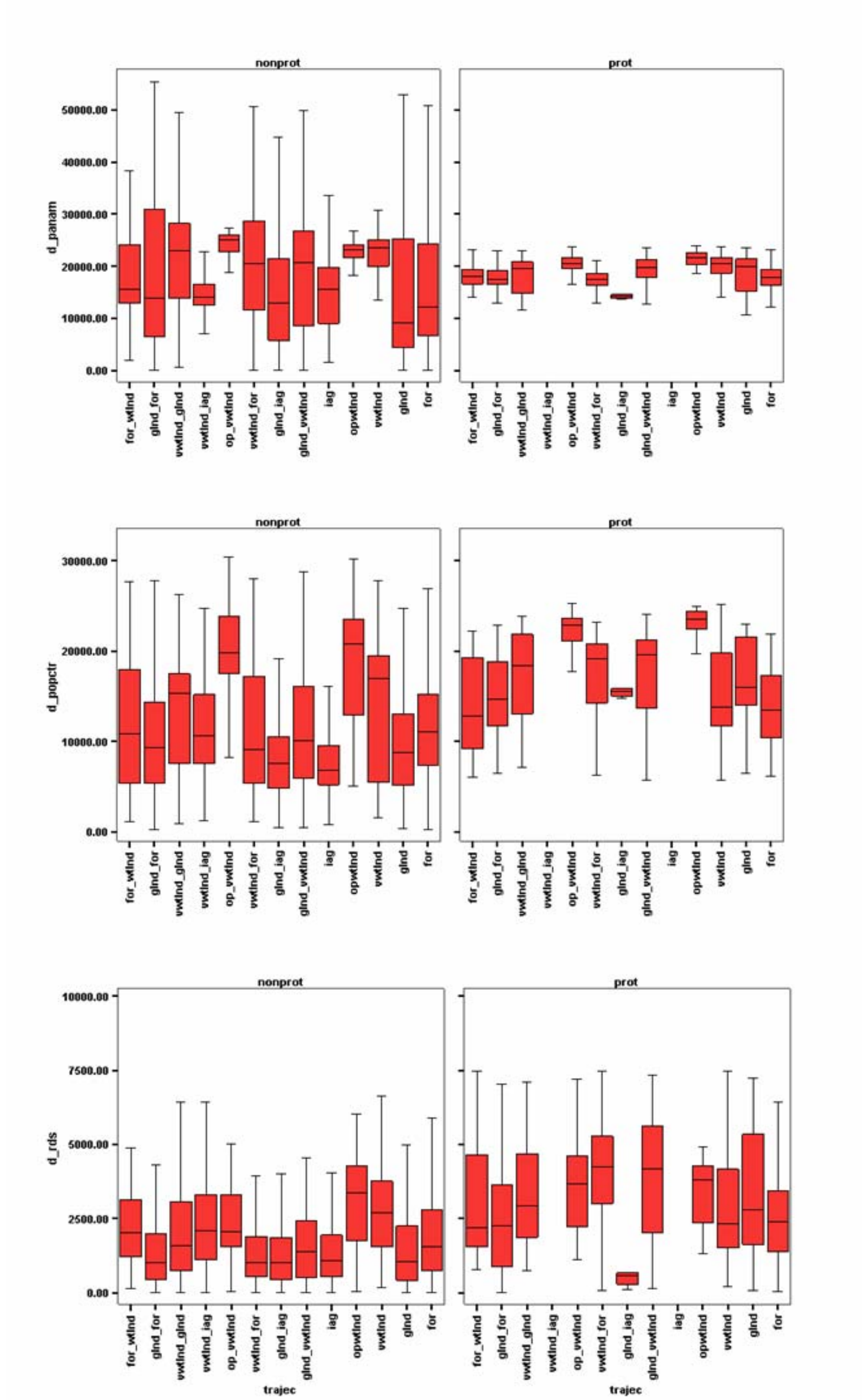


Figure 3-8. Boxplots indicating mean and 2 standard deviations for each landscape variable per trajectory. This figure complements Table 3-5 and Table 3-6 by allowing visualization of the data distribution rather than the mean alone reported in the tables.

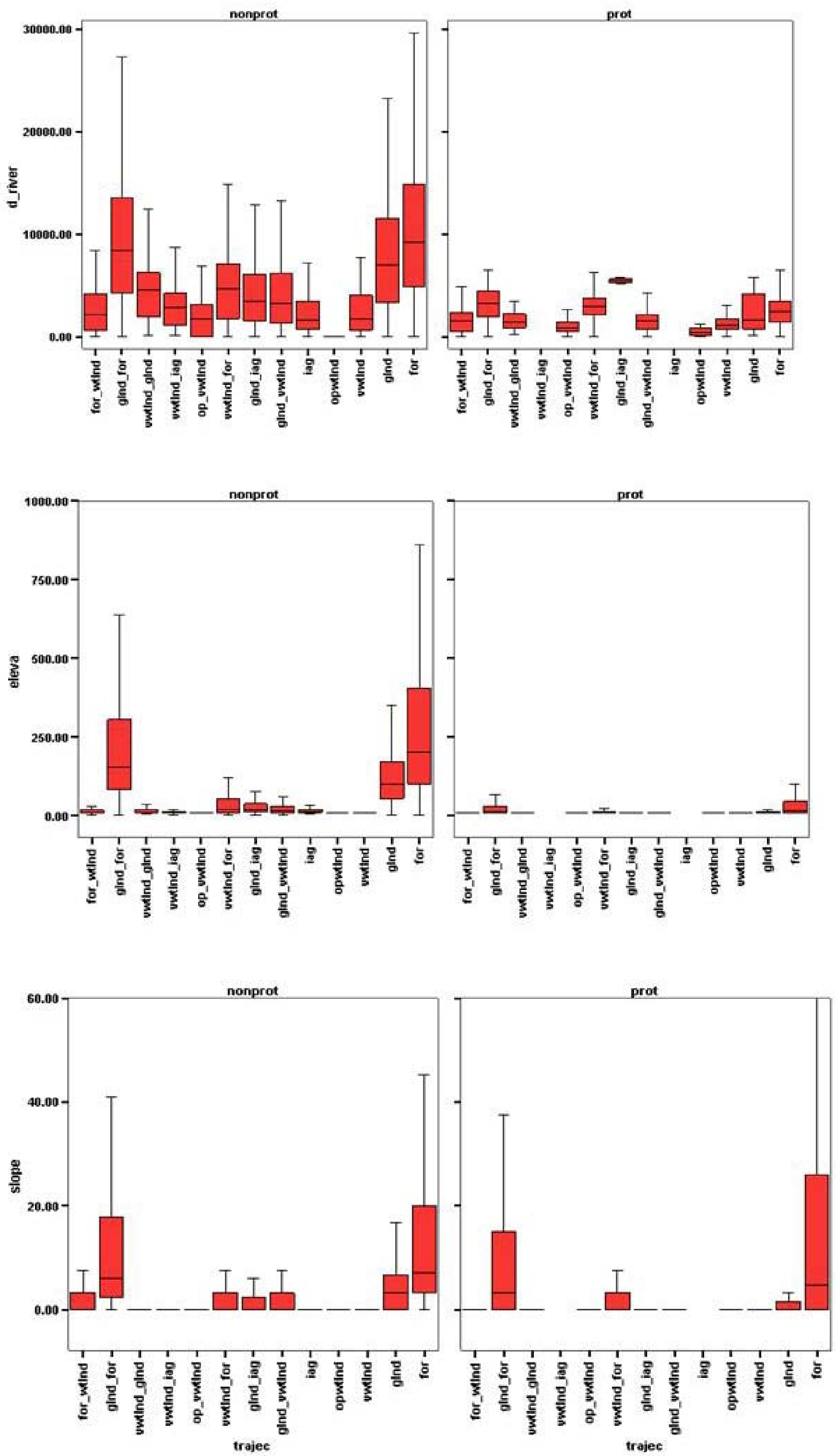


Figure 3-8 Continued

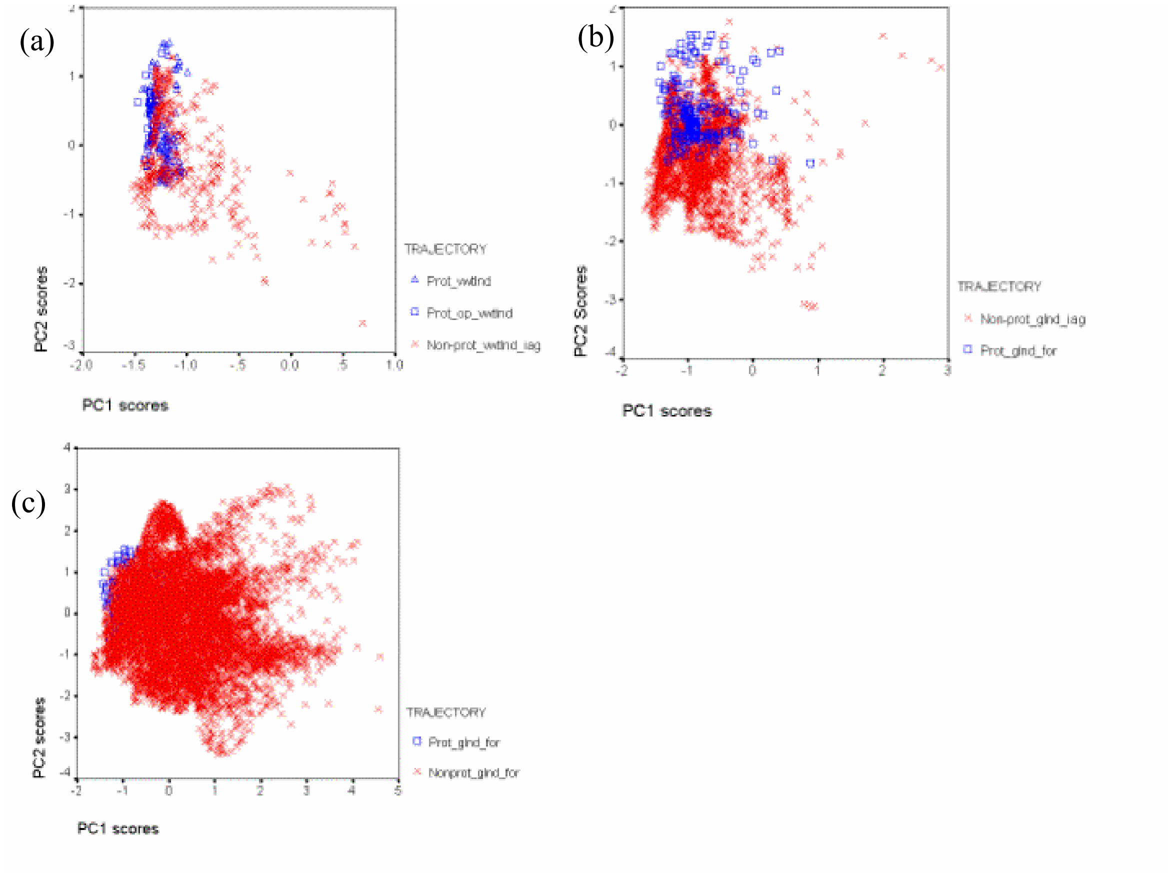


Figure 3-9. Scatter plots of the scores of the second principal component (PC2) as a function of the scores of the first (PC1). Data plotted are key trajectories from the park and nonprotected area in order to compare their domains defined by positions along the PC axes.

CHAPTER 4
GENERAL CONCLUSIONS

One approach to gaining a more complete understanding of the effect of protected area management on land cover is afforded by employing greater taxonomic resolution in classification schemes and examining reserves in their larger watershed context. Given the challenges posed by classification of land cover in landscapes with vastly different seasonal vegetation characteristics, I needed to develop a reliable method for classifying multiple cover types in a study region of relatively large extent. I explored an alternative classification technique and application of land cover data derived from it in evaluating the effect of protected area management on land cover conversion patterns.

Specifically, Chapter 2 illustrated the utility of incorporating domain knowledge in a rule-based classification technique. Logic-oriented processing via the integration of domain knowledge informed by ancillary data, along with the use of more than one traditional classifier, proved effective in circumventing many of the challenges posed in the classification of problematic tropical land cover such as deciduous tropical forest and seasonal wetlands. Comparison of results from this technique with those of maximum likelihood classifications on spectral data alone demonstrated a marked improvement in classification accuracy and the elimination of systematic errors. Accuracy was improved, without exception, for all classes in each year of the classification series relative to the results from the traditional maximum likelihood method. Results from this case study suggest that perhaps the greatest utility of knowledge-based processing of remotely sensed land cover data lies in the classification of historic satellite imagery.

In the Tempisque River Watershed, land management and the dominant spatial and temporal land cover patterns associated with it, are closely linked to landscape structure. Consideration of this interaction is important in the attempt to understand the effect of Palo Verde National Park on land cover since the time of establishment. The conservation of wetlands in the park becomes increasingly significant in light of the precipitous loss of wetland cover, to irrigated agriculture land use, observed outside of the park. Similarly, the qualitative changes in wetlands within the park, from open water or vegetation-filled wetlands, is significant and possibly related to this change in land use and resource management occurring 'upstream' from the park. And finally, the reversal of the deforestation trend that dominated the landscape for centuries is significant and would go undetected if only a buffer around the park were observed.

Results indicated quite clearly the effectiveness of Palo Verde to conserve and promote the regeneration of natural land cover within its boundary. The limitations of park management in this case study, however, appear to result from factors that are difficult to measure and which are rarely, if ever, included on the list of factors considered in evaluating the effectiveness of protected areas. These include effects of fragmented or enhanced hydrologic connectivity with the wider landscape and the effects of climate events that may exacerbate, and be exacerbated by, changes in land and resource use within the basin.

More case studies of protected areas and protected area networks in their watershed contexts will contribute to a more complete understanding of the ways in which parks are affected by current and potential threats originating beyond their borders, including hydrologic alterations (Pringle 2001). This contextual approach facilitates a predictive understanding of what land cover and land uses might be expected if protection were not in place, an approach that may be useful both during planning phase of reserve establishment and during adaptive management activities existing protected areas. Even optimally functioning and connected reserves *per se* will only likely conserve a fraction of the biodiversity and environmental services we seek to protect. Contextual analyses of the effectiveness of protected area management, and the necessary techniques to perform such evaluations, are increasingly important if parks are to be better integrated into landscapes in which they reside.

APPENDIX A
PRECIPITATION DATA

Precipitation data for months preceding images used for land-cover classifications.

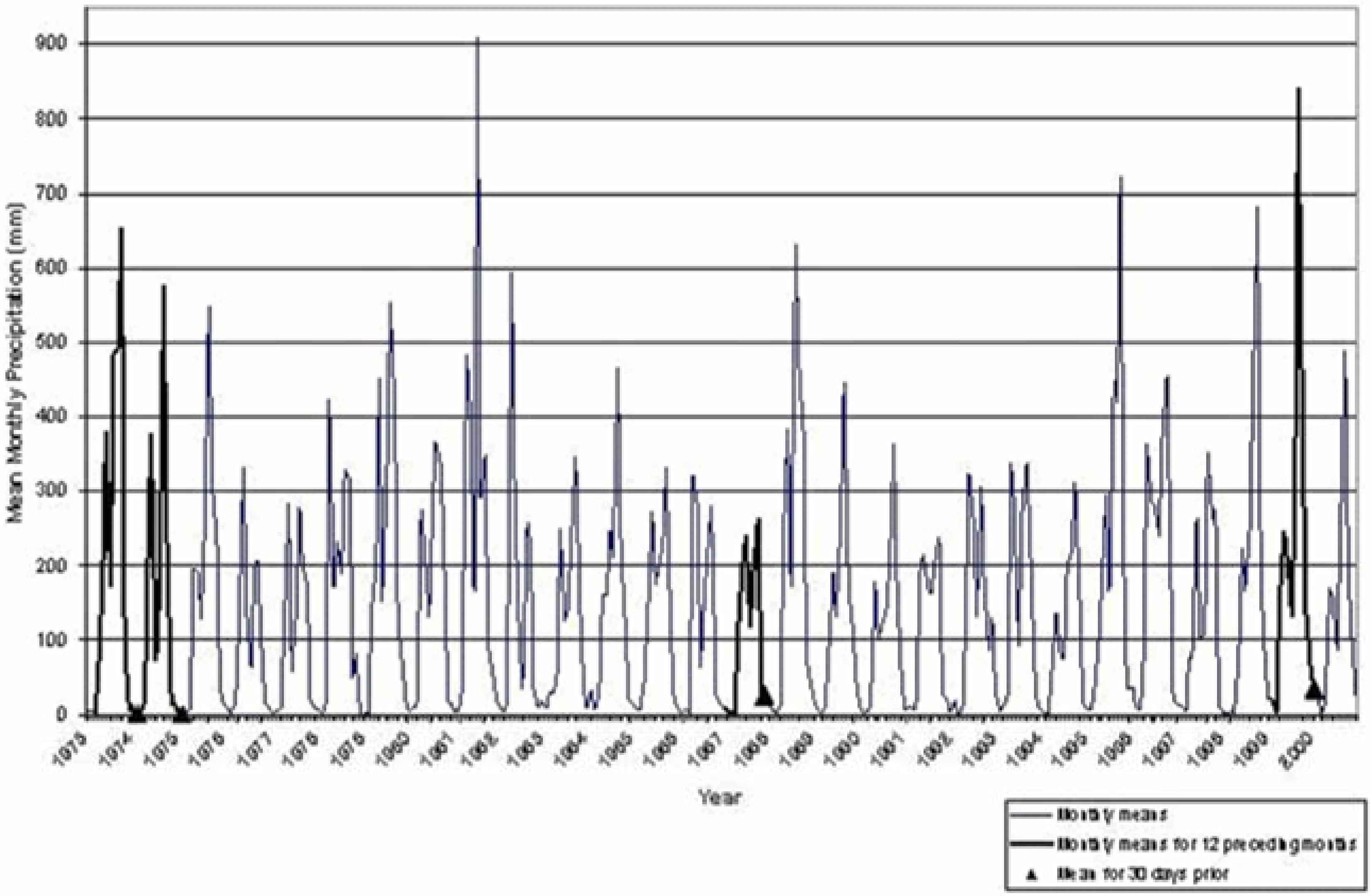
"Had" in Table A-1 is the abbreviation for hacienda.

Table A-1. Mean precipitation for each year in image series, calculated for twelve preceding months and also the month directly preceding each image capture.

Image Year and Date:	1974 (2-28-74)	1975 (3-3-75)	1987 (12-25-87)	2000 (1-27-00)
Station	Precipitation (mm/month)			
	12mo. Prior	12mo. Prior	12mo. Prior	12mo. Prior
Colorado Liberia	242.94	132.18	99.40	166.16
Had. Tempisque	208.48	153.96	82.50	252.27
Had. Guachepelin	226.39	144.58	106.46	200.94
La Guinea	219.15	118.08	95.68	197.71
Liberia Llano Grande	139.16	84.06	89.32	229.43
Quebrada Honda	129.44	173.00	137.40	136.96
Taboga	174.08	124.58	84.75	163.93
Total	1339.65	930.44	695.50	1347.41
Mean (preceding 12 mo.)	**191.38**	**132.92**	**99.36**	**192.49**
	30 days prior	30 days prior	30 days prior	30 days prior
Colorado Liberia	0.00	0.00	2.20	0.13
Had. Tempisque	0.00	0.00	0.70	1.53
Had. Guachepelin	0.00	0.00	31.00	0.00
La Guinea	0.00	0.00	0.20	0.30
Liberia Llano Grande	-9.99*	0.00	7.10	1.30
Quebrada Honda	0.00	0.00	33.60	4.01
Taboga	0.00	0.00	22.50	0.40
Total	0.00	0.00	97.30	7.67
Mean (30 preceding days)	**0**	**0.00**	**27.8**	**2.19**

*Indicates that no data were available from this station in the month preceding image capture. The column mean was calculated using the data from the seven available stations.

Figure A-1. Time series of precipitation data across entire study period averaged across five meteorological stations (La Guinea, Rio Colorado, Had. Tempisque, Guachepelin, and Tileran). The twelve months preceding each image used in the series are highlighted in bold and the points in the series corresponding to the month preceding each image is indicated by a triangle.


Mean Monthly Precipitation (mm)
900
800
700
600
500
400
300
200
100
0
Year
Monthly means
Monthly means for 12 preceding months
Mean for 30 days prior

APPENDIX B
LAND USE AND LAND HISTORY INTERVIEW GUIDE

Interviews conducted in Spanish and usually lasted anywhere between 20 minutes and 3 hours.

1) Is this your property? How long have you owned or worked on this land? Did you grow up on this land or nearby here? Are there any other people around right now that might be able to help tell the history of this land?

2) Do you know where the boundaries of this parcel are? Have the boundaries always been the same or was this parcel formerly larger/smaller? Can we take coordinates of them with GPS (present and past if their identification is possible)? Or can you show me on this topographic map approximately what the bounds of this parcel of land are and were? [If fences are present] What do these fences delineate?

3) Does your land provide you with income? If so, what do you do with your land to make money? Is this activity what you've always done? Do you have access to irrigation from the government's PRAT[2] program? If so, how long have you irrigated your land? What parts and can we visit them? Was your land leveled through the PRAT program

4) What is your land like during the wet season? During the dry season? Are there any wetlands on or near this land? What about in the past? If there are wetlands present on this land, can we visit them? Has this wetland always been here? If not, what do you think its formation is related to? How does this wetland area differ in the wet and dry seasons? Is the wetland mostly open or is there vegetation? What kind of vegetation, floating or does it grow from the soil? Is the kind of vegetation in the wetland now the same as you can remember from the past? If it has changed (e.g., from open lagoon to vegetation-filled wetland) do you remember when this change took place?

5) Depending on answers to questions 3 & 4 questions may be directed toward gaining as much detail as possible on annual cycle of cultivation, cattle grazing practices, tree plantation management, etc.

[2] Spanish acronym forProyecto Riego Arenal-Tempisque or The Arenal-Tempisque Irrigation Project.

APPENDIX C
AGRICULTURAL CALENDARS

Agricultural calendars were constructed to aid in the process of interpreting satellite imagery and aerial photographs. In addition to 29 semi-structured interviews, sources include the Ministry of Agriculture and Livestock, Rodolfo Vega (manager Finca #4 at CATSA), Water Management Meeting hosted by the Organization for Tropical Studies (Sept. 2002), and McCoy (1991).

Table C-1. Melon Cultivation

Crop Cycle	Land Cover Phase	Corresponding Land Use Activities
May - Oct growing season 2 month growth cycle 2 harvests per growing season	Weedy, herbaceous growth	· field left to fallow during non-growing season months ("*en descanso*")
	Bare soil	· field preparation: clearing of weedy growth · field covered in plastic to control weed growth and disinfect soil, or, soil left bare and disinfected through fumigation with herbicides and pesticides
	Sparse melon plant coverage	· plastic and/or soil perforated every 50cm · melon plants manually transplanted to field · fertilizers applied directly through irrigation water · irrigation delivered subteraneously (frequency calculated according to evapotranspiration rate)
	100% melon plant coverage	· pest species and damage level carefully monitored using pest traps · herbicide and plaguicide applied as needed by fumigation trucks · fertilizers applied directly through irrigation water · irrigation delivered subteraneously (frequency calculated according to evapotranspiration rate)
	Melon in flower	· bees are released to collect pollen from protandric flowers · female flowers are pollinated by bees · pest species and damage level carefully monitored using pest traps · herbicide and plaguicide applied as needed by fumigation trucks · fertilizers applied directly through irrigation water (frequency of irrigation calculated using evapotranspiration rate)
	Melon in fruit	· fruits are manually turned four times during growing season to ensure proper development and shape · pest species and damage level carefully monitored using pest traps · herbicide and plaguicide applied as needed by fumigation trucks · fertilizers applied directly through irrigation water (frequency of irrigation calculated using evapotranspiration rate) · during the final weeks of the growing season, fruits are checked twice daily for softness and texture · melons are harvested manually

Table C-2. Sugar Cane Cultivation

Crop Cycle	Land Cover Phase	Corresponding Land Use Activities
May – Feb, April growing season 9 month growth cycle 1 harvest per growing season	Bare soil	· folliage, stems and all other debris are removed from field · every fourth or fifth year soil is ploughed completely and old plants destroyed · otherwise, roots remain and soil preparation performed around them
	Semi-saturated soil	· application of lime to correct for acidicity (where applicable); soil must be moist and lime applied well-before application of fertilizers · fields are disked and airated a final time after lime application
	Bare soil	· rows of furrows 1.5m apart are made 25-30cm deep · nodal pieces of young sugar cane plants (7 months) with up to 3 buds are placed in furrows; buds have been treated with hot water (52º) for 20 minutes to prevent rickets · fertilizer (P only) is applied in furrow and then vegetative material covered with 3-5cm of soil · herbicides applied before bud emergence
	Semi-saturated soil	· soil moisture is maintained until buds emerge · herbicides applied after emergence
	Soil partially covered with sugar cane follliage	· N and P fertilizer applied in months 2-5 after bud emergence · herbicides applied periodically from 20-90 days post emergence (until folliage shades soil) · irrigation by gravity applied when needed as calculated by evapotranspiration rate (requires more during growth and less during maturation in order to concentrate sugars
	Full sugar cane coverage	· fertilizers applied (N and K, also sulfur and magnesium depending on soil chemistry) · irrigation by gravity applied when needed as calculated by evapotranspiration rate · poison applied manually in fields to control rat populations · sugar cane samples taken regularly in final 3 months of growth to calculate maturity index (based on moisture content, concentration of sugar, and concentration of reducing sugars · sugar cane field burned to eliminate non-cane folliage (some igenios have eliminated this practice, e.g., Taboga)
	Bare soil, fire residue and cane	· cane harvested mechanically and loaded into trailers for transport to refinery plant · field mowed over or hand-cut with machetes to ensure that above ground portion of plant is eliminated (reducing risk of fungal and bacterial invasion of regrowth)
	Organic layer	· organic product from sugar refinery (~33% carbon) applied to bare soil after final sugar cane harvest for particular sugar cane rotation (i.e about every 4 years); 80 tons per ha.

Table C-3. Flooded Rice Cultivation

Crop Cycle	Land Cover Phase	Corresponding Land Use Activities
Aug-Dec & Feb-Jun growing seasons 4 month growth cycle	Rice plant stems	· post-harvest; rice stems left planted after fruit is cut off in harvest
	Bare soil and ash	· rice stems are burned to incorporate nutrients into soil · some farmers harvest rice stems for livestock feed in liu of burning
2 -3 harvests per year	Saturated soil	· rice plant roots are mulched into soil by tractor with iron paddle wheels · this process occurs while field is flooded (i.e., wet tillage)
	Exposed soil	· field is drained to encourage germination of weed species in seed bank
	Flooded field (~15cm)	· wet tillage is performed to kill germinated weeds and incorporate them into soil · on second pass of tractor, pipe is dragged to level field · water in field is highly sedimented after tillage and levelling and thus left to settle for several days
	Exposed soil	· water is drained from field · as draining, pre-germinated seed (variety 1821) is mannually dispersed · fertilizers rich in P are applied · propane detonators used to deterr seed depredating water birds · soil left exposed until rice seedlings reach $\geq$2cm in height
	Flooded field (~10-15cm)	· field flooded for weed control (reducing herbicide use) · water level monitored carefully with aim to maximize weed control while simultaneously ensuring optimum level for rice plant growth · fertilizers applied (N-K-Zn, N-K and finally, KCl just prior to flowering)
	Continuous green carpet of rice plants	· water level continues to be monitored · plaguicides and herbicides are applied
	Rice in flower and fruit (field appears yellow)	· application of fungicide and insecticide · mechanical harvest through with machine that vaccums fruit from flower

APPENDIX D
CHARACTERIZATIONS OF VEGETATION COMMUNITIES

Table D-1. Major wetland types and description of vegetation communities

Vegetation Community *Dominant Species*	Common Name (English)	Common Name (Spanish)	Site Characteristics	Watershed Context
Mangroves			Saturated soils where inundation is associated with tidal movements within the Nicoya Gulf along river. At the river delta, mangroves grow in classic estuarine conditions.	Occuring along rivers from bank up to 8m into floodplain in lower watershed Also at the Tempisque delta where the river meets the Nicoya Gulf (much of this latter area falls outside watershed).
Avicennia germinans		Palo de sal		
Bravaisia integerrima		Mangle pinuela		
Conocarpus erectus	Button Mangrove	Mangle bontoncillo		
Laguncularia racemosa	White Mangrove	Mangle mariquita		
Pelliciera rizophorae		Mangle de rio		
Rhizophora mangle	Red Mangrove	Mangle colorado		
Flooded Forest			Seasonal saturation by rainfall and associated peak river flows.	Occuring in lower watershed along rivers and poorly drained areas. In riparian areas mangrove forest grades into flooded forest as distance from river increases
Acacia collinsii		Cornisuelo		
Acacia cornigera		Cornisuelo		
Acrocomia vinifera				
Bactris balanoides				
Capparis odoratissima				
Erythrina lanceolata				
Inga vera		Cuajiniquil		
Pithecellobium dulce		Michiguiste		

Table D-1. Continued

Vegetation Community *Dominant Species*	Common Name (English)	Common Name (Spanish)	Site Characteristics	Watershed Context
Fresh Marsh				
(emergent)			Saturated soils and standing water up to 1 - 2m deep, with deeper pools enduring well into the dry season. Process is driven directly by rainfall or peak river flow	Historically occurred throughout lower watershed though many lagoons have been drained or have experienced alterations of their hydroperiods from anthropogenic processes. New marshes have been created in many areas because of the introduction or increase of water flow and retention related to agriculture. Diversion, impoundment and channelization has also affected distribution of fresh marshes.
Eleocharis mutata	Scallion grass			
Ludwigia inclinata				
Neptunia plena	Dead and wake			
Paspalidium geminatum	Egyptian panicgrass			
Thalia geniculata	Fire flag	Platanilla		
Typha dominguensis	Cattail	Tular		
(floating)				
Eichornia crassipes	Waterhyacinth	Lila de agua		
Neptunia natans		Lajula		
Nymphaea pulchella		Dot leaf waterlilly		
Pistia stratiotes	Repollito de agua	Water lettuce		
Fresh Meadow				
(herbaceous)			Saturated soils (no standing water) with shorter period of inundation than marshes. Soils dry and crack during dry season, collecting dry organic matter which is worked into the soil again during	Occurs principally in the floodplain of the Tempisque and Bebedero Rivers along with other flat, poorly drained areas in the watershed.
Paspalidium germinata	Egyptian panicgrass			
Various sown pasture grasses				
(woody)				
Parkinsonia aculeata	Mexican paloverde	Palo verde		
Coccoloba caracasana		Papaturro		
Mimosa pigra	Catclaw mimosa	Sarsa		
Pithecellobium dulce	Manila tamarind	Michiguiste		
Acacia farnesiana	Sweet acacia	Aromo		

Table D-2. Description of grassland land-cover types

Vegetation Community *Dominant Species*	Common Name (English)	Common Name (Spanish)	Site Characteristics	Watershed Context
Strict Pasture Sown pasture grasses			Pasture grass is actively sown, fertilized and managed.	Occuring on areas of no or slight slope in the middle and lower watershed with a minimum parcel size of appriximately 2 - 5 hectares.
Pasture with Trees (grasses)			Usually minimal management activity with open-range grazing system in rainy season. Grasses dominate and trees with 20-25 m crowns provide shade for cattle. Living tree fences are also very common.	Often seen in the lower watershed where dry season is severe and trees are maintained on pasture to provide shade for cattle. Also occurs as a result of frequent fire where only fire-resistant woody species survive in the long-term.
(occasional woody species) *Enterolobium cyclocarpum* *Bursera simaruba* *Byrsonima crassifolia* *Gliricidia sepium*	Earpod Tree Gumbo-limbo	Guanacaste Indio desnudo		
Recent Fallow *Guazuma ulmifolia* *Dalbergia retusa*	Bastard cedar Cocobolo	Guacimo	Dominated by grasses and often characterized by compacted soils. Woody species may be dense in patches but growth rarely exceeds 2m and no canopy is present other than that of sparse trees. New woody growth are usually wind dispersed species.	Occurs throughout the watershed.

Table D-2. Continued

Vegetation Community *Dominant Species*	Common Name (English)	Common Name (Spanish)	Site Characteristics	Watershed Context
Poor Soil Grassland (grasses)			Sparse vegetation dominated by grasses and dotted with fire resistant woody growth. These tree species are small reaching heights no greater than 2.5 m.	Occurs in a particular zone of the middle watershed with poor soils, in pastures throughout the watershed where fire has long been used as a management tool, and along newer volcanic slopes in the eastern fringe of the watershed.
(occasional woody species)				
Byrsonima crassifolia		Nance		
Curatella americana		Raspaguacal		
Crescentia alata		Sacaguacal		

Table D-3. Major forest types and description of vegetation communities

Vegetation Community *Dominant Species*	Common Name (English)	Common Name (Spanish)	Site Characteristics	Watershed Context
Limestone Forest			Trees growing in small soil pockets of limestone outcrops that reach 100 - 250 m in elevation. Canopy reaches approximately 17 m and sparse hebaceous layer is found growing on limestone or in soil pockets.	Occurs in lower and middle watershed and usually serves as abrupt relief in a relatively flat local landscape.
Bursera simaruba	Gumbo-limbo	Indio desnudo		
Hemiangium excelsum		Guacharo		
Tabebuia ocharacea		Corteza amarillo		
Spondias mombin	Hog plum	Jocote de jobo		
Stenocereus aragonii		Candalabro		
Deciduous Lowland Forest			Characterized by two tree stories, one a discontinuous canopy of dry-season deciduous trees and an understory of shrubs and small trees, frequently spiny. Canopy reaches approximately 15 m in height.	
Bombacopsis quinata	Pochote	Pochote		
Calycophyllum candidissimum	Lemonwood	Salamo		
Albizzia caribaea	Tantakayo	Guanacaste blanco		
Caesalpinia eriostachys				
Guazuma ulmifolia				
Spondias mobin				
Evergreen Forest				Occurs along rivers throughout the watershed (riparian forest) as well as sites with adequately drained soils having a high water table.
Quercus oleoides		Roble encino		
Brosimum alicastrum		Ojoche		
Sapium thelocarpum				
Pithecelobium saman		Cenizaro		
Sideroxilon capiri		Tempisque		
Manilkara chicle		Zapotillo		
Plantation Forest (deciduous)			Homgenous forest with no understory and trees equidistant. Height and presence of canopy varies depending upon the age of the stand. Many plantations grow poorly due to soil compaction and lack of appropriate mycorrihzal associations in the soil.	Occur throughout the watershed in relatively small stands, having a mean size of approximately 1 hectare. There are several larger plantations in parts of the middle and upper watershed, however.
Gmelina arborea	Teak	Teca		
Bombacopsis quinata	Pochote	Pochote		
Eucalyptus deglupta	Rainbow gum			
(evergreen)				
Mangifera indica	Mango	Mango		

APPENDIX E
KAPPA CALCULATION

Equation E-1. Formula used in the accuracy assessment process to calculate KAPPA (K_{hat}) statistics.

$$K_{hat} = \frac{N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i+} * x_{+i})}{N^2 - \sum_{i=1}^{r} (x_{i+} * x_{+i})} \qquad \text{(E-1)}$$

where r is the number of rows in the error matrix, x_{ii} is the number of observations in row I and column I, and x_{i+} and x_{+i} are the marginal totals for row i and column i, respectively, and N is the total number of observations.

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BIOGRAPHICAL SKETCH

Amy Daniels grew up in Apalachicola, FL, graduating from Apalachicola High School in 1995. She went on to Wesleyan College to earn her B.A. in biology in 1999. In the two and one half years between college and graduate school, Amy worked for the Apalachicola National Estuarine Research Reserve (ANERR) in the area of resource management and she worked in New York as a counselor for a non-profit AIDS-care foundation. Amy also traveled extensively in Central America, learning Spanish and volunteering in various capacities for a Guatemalan conservation organization, along with working at several parks throughout the isthmus.

Amy began her M.S. degree in Interdisciplinary Ecology at the University of Florida in the fall of 2001 and graduated in August of 2004. During the Master's program (summer 2003), Amy worked in community development with the NGO Mercy Corps in El Salvador via a fellowship from Coca-Cola's World Citizenship Program. Amy plans to continue in the Interdisciplinary Ecology program to earn her PhD, using the tools and skills from her Master's work to focus explicitly on watershed management.