# SPATIAL AND TEMPORAL LAND-COVER TRANSFORMATION IN THE ANGKOR BASIN: A CHANGING LANDSCAPE IN CAMBODIA, 1989–2005

By

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To the women of the Martin family whose values, strength, and love guide me in life; to the rest of my family; and to Patrick Gaughan, who supports me no matter which direction I go

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The spatial and temporal transformation of land-use and land-cover change is an important component of global environmental change. This research examines land-cover change in a tropical watershed in Siem Reap Province, Cambodia from 1989–2005. The thesis addresses two research questions and two objectives. The two questions are (1) how has the overall land-cover changed throughout the basin from 1989 to 2005? (2) what are the spatial and temporal dynamics of vegetative cover decline and re-growth? The two objectives are (1) detect and quantitatively document forest and non-forest land-cover change patterns in the Angkor basin from 1989 to 2005, and (2) examine spatial and temporal dynamics of land-cover change in different topographic zones in the Angkor basin.

Geospatial methods were used to measure and detect landscape change in the Angkor basin. I used remote sensing to classify land-cover for 1989, 1995, 2002, and 2005 and then derived land-cover change trajectories to quantify the rate and extent of land-cover change in the basin. The watershed was divided into four elevation zones to examine the effects of topography and landscape position on land-cover change. A geographic information system was used to digitally delineate the watershed and create land-cover maps. In addition, I used Normalized

Difference Vegetation Index (NDVI) image differencing and principal components analysis (PCA) to compare changes in vegetation cover across time.

The dominant land-cover change in the Angkor basin has been upland forest to non-forest (bare and scrub land-cover) since 1995. The largest shift in upland forest cover occurred since 2002 which corresponds to the political stabilization and increasing development in Cambodia. The forest to non-forest change occurred in a transitional elevation zone between predominantly agricultural floodplains and protected upland forests. Results suggest that upland forest decline provides an indication of the extent and rate of human-induced land-cover change.

High land-cover variability in the flooded forests suggests change at different temporal scales. The floodplain zone was characterized by multiple change trajectories but the largest percent of change occurred from non-forest to forest since 2002. Floodplain dynamics are subject to more regional hydrologic processes of the larger Mekong basin than by anthropogenic forces. The different patterns of land-cover change for each elevation zone suggests further exploration is necessary to connect specific patterns of land-cover change to underlying processes.

This thesis contributes to the literature on land-use and land-cover change with a focus on a tropical watershed in Siem Reap, Cambodia. Specifically, topics within land-use/land-cover change studies (topography, tropical forest change, and protected areas) are identified as important actors in the changing landscape of the Angkor basin. The quantification of change is especially relevant in the context of the World Heritage Site of Angkor and the important biophysical characteristics of the Tonle Sap floodplains and upland forested region of Phnom Kulen National Park.

# CHAPTER 1
# GENERAL INTRODUCTION

## Tropical Land-Cover Change

Spatial and temporal transformations of land-use and land-cover are an important component of global environmental change (Moran, 2005; Rindfuss, Walsh, Turner II, Fox, and Mishra, 2005; Foley, DeFries, Asner, Barford, Bonon, Carpenter, et al., 2005). Changes in land-use and land-cover may be seen as indicators of environmental condition and a reflection of past human activities (Lambin and Geist, 2001; Moran, 2005). Human-environment interactions that occur with land-use decisions and subsequent land-cover changes represent a visible, physical manifestation of existing socio-ecological system.

Land-cover descriptions are the first step in understanding the dynamic process of land-use decisions (Turner II, Clark, Kates, Richards, Mathews, and Meyer, 1990; Brandt and Townsend, 2006). Studies of land-use and land-cover attempt to understand and identify the effects of human activities on land-cover transformation (forest clearing, agricultural expansion, pasture expansion, timber logging, infrastructure development, etc.) and the underlying relationships between social, economic, political, cultural, and biophysical drivers that cause the change (Lambin, Geist, and Leper, 2003; Geist and Lambin, 2002). Complex relations between socio-economic and biophysical factors often exist on different temporal and spatial scales (Turner, 1989) and are difficult to extrapolate from one case study to another.

Many land-use/land-cover studies focus on the landscape patterns in tropical, forested regions and study the complicated relations between the environment, socio-economic, and policy factors that drive the transformation and modification of tropical forest landscapes (Turner, Villar, Foster, Geoghegan, Keys, Klepeis, et al., 2001; Nagendra, Southworth, and

Tucker, 2003; Verburg, Overmars, and Witte, 2004; Etter, McAlpine, Wilson, Phinn, and Possingham, 2006). Tropical forested regions are among the most rapidly transforming areas on the globe (Walker 2004, Wright 2005). Changes in tropical forest cover may lead to or be caused by agricultural expansion that can have positive socio-economic effects such as increased food production, improved welfare and well-being, and better use of resources (Lepers, Lambin, Janetos, DeFries, Achard, Ramankutty, et al., 2005; Lambin et al., 2003). Tropical forest change has been shown to be associated with biophysical alterations such as climate change (Houghton, 1994), biodiversity decline (Skole and Tucker 1993), and altered hydrologic processes (soil erosion, flooding, runoff, etc.) (Giambelluca, 2002).

Often, studies in tropical forested regions involve one or more protected areas within the defined study boundary (Southworth, Munroe, and Nagendra, 2004). Changes in and around protected areas have become a popular topic of land-use/land-cover change studies (Bruner, Gullison, Rice, and da Fonseca, 2001; Child, 2004; DeFries, Hansen, Newton, and Hansen, 2005; Southworth, Nagendra, and Munroe, 2006; Verburg, Overmars, Huigen, de Groot, and Veldkamp, 2006). Parks, especially in tropical, developing regions, have been established as conservation measures to maintain ecological health and biodiversity in the presence of human population growth and expansion of agricultural lands (Sanchez-Azofeifa, Daily, Plaff, and Busch, 2003; Southworth et al., 2006). Studies have shown that the presence of park minimizes loss or maintains forest cover within parks but causes a high degree of fragmentation and land-cover change adjacent to park boundaries or within the surrounding landscape (Sanchez,-Azofeifa et al., 2003; Nagendra, Tucker, and Carlson, 2004). However, the processes and patterns of landscape change are dependant upon each individual park. Other studies emphasize the complex dynamics of socio-economic and biophysical factors that drive landscape changes in designated protected areas with the use of spatially-explicit models (Chowdhury, 2006a; Verburg et al., 2006).

Debate continues in the literature regarding the most effective management regime for maintaining the ecological and biological health of a protected area (Redford and Sanderson, 2000; Schwartzman, Napstad, and Moreira, 200; Agrawal and Ostrom, 2001; Bruner et al., 2001; Child, 2004). One way to measure the efficacy of park management strategies is with geo-spatial tools that provide a means to quantify and document land-cover changes within protected areas and the surrounding landscape (Southworth et al., 2006). Specifically**,** with the launch of the Earth Resources Technology Satellite (ERTS-1, now renamed Landsat 1) in 1972, remote sensing data has become a powerful tool to assist in the detection and interpretation of landscape changes over space and time. Remote sensing provides an important monitoring tool for identifying the extent and rate of land-cover change (Chowdhury, 2006b; Boyd and Danson, 2005) and is especially useful in tropical latitudes, as limited resources, accessibility, and lack of historical data may inhibit or prevent other forms of data collection and analysis (Brandt et al., 2006).

Many studies have identified the biophysical properties of landscape position and topography as important biophysical influences on land-use and land-cover change (Green and Sussman, 1990; Wilson, Newton, Echeverria, Weston, and Burgman, 2005; Brandt et al., 2006). These changes are not isolated from socio-economic forces. Trade-offs exist between the difficulty of harvesting or cultivating a piece of land and the economic incentives for such actions (Nagendra et al., 2003). However, variation in topography may strongly influence decisions in land-use and subsequent alteration of land-cover. For example, topographic influences, such as steep slopes, may impede a farmer's ability to cultivate a parcel of land

(Green and Sussman, 1990; Vagen, 2006). In addition, elevated regions may be more difficult to access and thus can be an initial deterrent to cultivation (Nagendra et al., 2003; Brandt et al., 2006). Wilson et al. (2005) used a spatially-explicit model to examine land-cover change in Chile and determined land conversion was less likely to occur on landscapes with steeper slopes. These studies show the importance of landscape position (elevation, slope, aspect) and their interactions with socio-economic factors (market influence, land-use policy, cultural values) that drive landscape change.

This research focuses on quantifying land-cover change in the tropical, forested Angkor basin in Siem Reap Province, Cambodia. I address how overall land-cover changed from 1989 to 2005 and focus on forest changes in the upland and lowland areas of the watershed. Three protected areas lie completely or partly within the watershed boundary. Landscape position is an important biophysical factor for understanding land-cover change, because the diverse landscape of the basin stretches from the forested uplands of Phnom Kulen, through the UNESCO World Heritage Site of Angkor, down into the floodplains of the Tonle Sap Lake.

**Tropical Forest Change**

Global measurements of recent forest loss show the highest rates occur in Southeast Asia (Lepers, et al., 2005) and result from multiple underlying factors such as weak governance, illegitimate timber practices, and large migration schemes (Lambin et al., 2003). In contrast to the economic development of other ASEAN (Association of Southeast Asian Nations) nations, the turbulent and politically unstable history of Cambodia over the last few decades limited the amount of natural resource exploitation that occurred in the country (Le Billon, 2000). However, with the reestablishment of Cambodia as a capitalist state (1989), the rate and extent of forest exploitation has increased (Le Billon, 2002; de Lopez, 2002). Few studies have documented quantitatively the forest-cover change in Cambodia. Southeast Asian regional land-cover analyses include minimal data on land-cover in Cambodia (Stibig, Achard, and Fritz, 2004; Giri, Defourny, and Shrestha, 2003). In addition, large regional-scale studies commonly use coarse spatial resolution which limits the ability of such data in local applications. Quantitative scientific evidence is needed to support statements about wide-spread exploitation of forests in Cambodia and local-scale measurements are needed for case-specific studies.

One important area in Cambodia that needs more attention on land-use and land-cover patterns is the Angkor basin in Siem Reap Province. This area will continue to be a key economic area in Cambodia because of tourism generated by the World Heritage Site of Angkor, large expanses of paddy cultivation, and the important fishery of the Tonle Sap Lake. In addition, the forested lands of the Angkor basin are important functionally (water supply and regulation, soil stability, biodiversity, etc.) and well as aesthetically (tourism). Thus, there is a need to understand the extent of land-cover in the basin and its rate of change. This study uses multiple remote sensing methods to document and identify the change quantitatively.

**Landscape Position**

Landscape position and topography affect land-use/land-cover change in this watershed that is part of the larger Mekong basin in Southeast Asia. Changes in land-cover often depend on biophysical characteristics of a landscape such as elevation, soil productivity, and precipitation regimes (Sanchez-Azofeifa et al., 2003; Chowdhury, 2006a) which change according to regional topography. The topographic profile of the Angkor basin extends from the floodplains of Tonle Sap Lake, through the Angkor World Heritage site, into the mountainous area of Phnom Kulen National Park. This variable landscape displays multiple processes that are influenced by landscape position and subsequently affect land-use decisions. For example, a biophysical factor such as precipitation may have more influence in one part of the basin but not in another part due to landscape position.  I divide the watershed into elevation zones and quantify change to determine the effect of landscape position on land-use/land-cover changes.

**Protected Areas**

This work contributes to protected area literature by describing quantitatively land-cover changes that existed before and after the re-establishment of protected areas in Cambodia. Forests surrounding Angkor Wat were designated as the first protected area in Southeast Asia in 1925, but the whole protected-area system collapsed during past several decades of civil strife and war (ICEM, 2003).  With the end of conflict and the acceptance of a new Cambodian constitution in 1993, twenty-three protected areas were created comprising ~21% of the total area in Cambodia. Protected areas in Cambodia consist of National Parks, Wildlife Sanctuaries, Protected Landscapes, and Multiple Use Management Areas. Three of these protected areas are situated partly or wholly within the study region and are characterized by mostly forested land-cover.   Located in the upland region of the Angkor Basin and forming the northern boundary is part of Phnom Kulen National Park (IUCN category II, 37,500 ha).  The southern boundary of the basin contains part of the Multiple-Use Management Area of the Tonle Sap Lake and surrounding floodplains (316,250 ha), all of which is part of a UNESCO Biosphere Reserve. The protected landscape of the UNESCO World Heritage Site of Angkor Wat and surrounding temples (10,800 ha) is centrally located within the basin.

The protected area designated in 1925 and the recently established parks (1993) were created in a landscape dominated by human use for thousands of years (Coe, 2004). Similar to protected areas in other developing nations, these designated areas are surrounded by continually growing human populations (Child, 2004).  There is a need to quantify changes in spatial and temporal landscape patterns of the Angkor Basin as a first step in understanding how the re-establishment of protected areas affected land-use decisions of the largely rural population.

## Research Objectives

This study is one component of a larger NSF funded project entitled *Economic Growth, Social Inequality, and Environmental Change in Thailand and Cambodia.* I focused on a watershed in Siem Reap province, Cambodia, and used Landsat imagery to analyze land-cover changes over a sixteen year period (1989-2005). The thesis is divided into two separate research papers (Chapters 2 and 3) which analyze spatial and temporal land-cover transformations by using a combination of geo-spatial techniques to quantify landscape change in the basin. Methods include digital delineation of the watershed, categorical classification maps, land-cover trajectories, Normalized Difference Vegetation Index (NDVI) image differencing, and principal components analysis (PCA). These methods, combined with datasets collected from various agencies, are used to examine the relations between land-cover change and the socio-economic and biophysical changes at a local and regional scale that may influence landscape dynamics in the Angkor basin.

Chapter 2 describes the changes of six different land-covers with an emphasis on the different vegetation dynamics of upland and flooded forests. The biophysically defined watershed was designated as the study region because of the well recognized relationship between land-use/land-cover change and water resources, and the growing scarcity of water availability in the Southeast Asia (Chuan, 2003). Changes in tropical forested land cover influence the hydrologic functions of watersheds as forested land-cover generates higher rates of evapotranspiration and rainwater infiltrates into undisturbed soils more rapidly than it does in compacted soils (Giambelluca, 2002). Two questions addressed in the Chapter 2 are (1) how has the overall land-cover changed throughout the basin from 1989 to 2005? (2) what are the spatial and temporal dynamics of vegetative cover decline and re-growth?

Chapter 3 addresses possible biophysical influences in the Angkor basin in relation to spatial landscape position and topography of the basin. In Chapter 3, I narrow the focus to a binary classification of forest dynamics and address spatial and temporal patterns of forest-cover change as a function of landscape position and topography. The Angkor basin is divided into different elevation zones and multiple change detection techniques are utilized to document quantitatively the amount of change across the sixteen year period. Chapter three highlights the three protected areas within the basin and considers the importance of the land-cover changes as they relate to these areas. Specifically, I address the following objectives (1) detect and document quantitatively forest and non-forest land-cover changes in the Angkor basin from 1989 to 2005 and (2) analyze how topography affects spatial and temporal dynamics of land-cover change in the Angkor basin. Journals targeted for the stand alone papers are Applied Geography and Agriculture, Ecosystems, and Environment for Chapters 2 and 3 respectively. As a result, some information may be repeated such as study area descriptions in each Chapter.

## Study Rationale

There exists a continual demand for accurate and precise measurements of the rate and change of land-cover transformation across the globe. This thesis contributes to the literature on land-use/land-cover changes with a focus on a tropical watershed in Siem Reap province, Cambodia. Specifically, topics within land-use/land-change studies (topography, tropical forest change, and protected areas) are identified as important actors in the changing landscape of the Angkor basin. This thesis also documents land-cover change for an area that has been isolated from intense scientific research for much of the past thirty years. The changes documented are especially relevant in the context of the World Heritage Site of Angkor and the important biophysical characteristics of the Tonle Sap floodplains and upland forested region of Phnom Kulen National Park.

## CHAPTER 2
## FOREST CONVERSIONS AND LAND TRANSFORMATIONS IN THE ANGKOR BASIN: A CHANGING LANDSCAPE IN CAMBODIA

### Introduction

Within the past fifty years tropical, forested landscapes in developing countries have undergone extensive transformations as a result of economic and social development (Lambin et al., 2003; Walker, 2004; Wright, 2005). The most rapid and significant of these transformations include deforestation, reforestation, urbanization, agricultural expansion, and pastoral expansion (Lambin et al., 2003). Environmental changes such as decreased biodiversity, degraded soil resources, and increased greenhouse gas emissions continue to occur at all geographic scales as a consequence of these land-cover transformations (Kummer and Turner, 1994). Although most of these factors have influenced landscape change in the tropics, deforestation remains the most prominent mode of land-cover transformation in tropical, developing countries (Geist and Lambin, 2002; Lambin and Geist, 2003; Carr, 2004; Walker, 2004).

The productive forested ecosystems in Southeast Asia are valued for their high biodiversity and commercially important *Dipterocarpus* hardwoods (Kummer and Turner, 1994). In the past decades, illegitimate private and state-run commercial timber harvesting practices, large transmigration schemes, and weak governance have all contributed to large losses of Southeast Asian forest cover (Lambin and Geist, 2003). Globally, projections of forest loss are highest in Southeast Asia and there is a close association between the forest loss and the expansion of agricultural lands (Lambin et al., 2003; Lepers, at al., 2005).

Deforestation affects upland regions as well as the floodplain regions within the Mekong basin. The Mekong River, the 9$^{th}$ largest river in the world when measured by runoff (Varis and Keskinen, 2003), flows through portions of Burma, Thailand, Laos, Cambodia, and Vietnam. The entire Mekong Basin provides both socio-economic (food, drinking water, transportation) and biophysical (sediment transport and deposition, temperature modification, aquatic life support) benefits to the region (Kite, 2001; Fujii, Garsdal, Ward, Ishii, Morishita, and Boivin, 2003). The lower portion of the Mekong basin has different hydrologic characteristics from the upper portion. The lower Mekong displays flat topography, inundation of large floodplains during the wet season, and a strong relationship between with Tonle Sap Lake (Fujii et al., 2003). During the rainy season (May–November), Tonle Sap Lake acts as a natural reservoir for the larger Mekong Basin. When the discharge from the Mekong River reaches a certain level, outflow water from the Tonle Sap River reverses direction, flows into the lake, and subsequently floods the landscape surrounding the lake. Between the end of the dry season and the height of a very rainy season in the Mekong basin, the mean surface area of Tonle Sap Lake can vary from 2,500 $km^2$ to over 15,000 $km^2$ (Fujii et al., 2003). The variability associated with these dynamic fluctuations of lake level has important implications (levels of fish production, timing of harvests, etc.) for rural Cambodians whose livelihoods depend on the natural resources of the Tonle Sap floodplain.

Since 1989, Siem Reap province (one of six provinces surrounding Tonle Sap Lake) has been one of the most rapidly changing areas in Cambodia with increasing population, a growing tourism industry, and important fisheries and forests. Vietnamese forces exited Cambodia in 1989 and since then, dynamic policy initiatives have contributed to the increasingly rapid land-cover transformations both at a national scale and within the study area. Situated within the province of Siem Reap, the Angkor basin (2,986 $km^2$) extends from the Tonle Sap Lake floodplains northward into the upland forested area of Phnom Kulen. Observation of Landsat images acquired from 1989 to 2005 reveals the expansion of bare land in the upland portion of the basin. Upland deforestation influences predominantly agricultural floodplains through increased erosion and nutrient inputs as well as increased water runoff to agricultural fields. The floodplains are also affected by annual lake stage excursions of the Tonle Sap and land-use decisions on flooded paddy cultivation. There are also conflicts of interest between agricultural production and tourism development as water scarcity becomes more of an impediment to growth in the basin. Therefore, there is a need to describe and explain the rate and extent of land-cover change as a first step to understand better the forces driving landscape transformation in the Angkor basin. The trend of land-cover change within the Angkor basin is especially important because the basin includes the World Heritage Site of Angkor Wat (est. 1992), part of Phnom Kulen National Park, and the Tonle Sap Lake Biosphere Reserve, which together draw millions of tourists each year.

The objective of this study is to describe land-cover change in the Angkor basin from 1989 to 2005 by determining the spatial and temporal land-cover dynamics of the basin, and by examining possible biophysical drivers of the changes at both local and regional scales. Specifically, this study addresses the following research questions: (1) How has the overall land-cover changed throughout the basin from 1989 to 2005? and (2) What are the spatial and temporal dynamics of vegetative-cover decline and re-growth? I used satellite remote sensing methods to describe quantitatively the spatially-explicit patterns and trajectories of land-cover change. Classification maps consisting of six different land covers were derived for each of the four image dates and a change trajectory was created to analyze from-to land-cover changes. In addition, the description of vegetation change through the use of the standardized Normalized Difference Vegetation Index ((NDVI: (IR reflectance-Red reflectance)/ (IR + R)) provided useful information about vegetation change across time and space. These methods provide a synoptic and multi-temporal perspective on dynamic landscape changes in the study area.

## Study Area

### Physical Characteristics

The Angkor basin (2,986km$^2$) is at the northern end of the Tonle Sap Lake and lies completely within the Siem Reap province of Cambodia (Figure 2-1). Elevation, collected from a 50-m spatial resolution digital elevation model (DEM), ranges from 6 meters above sea level at the southern boundary of the basin (located in Tonle Sap Lake) up to 469 m above sea level. The Angkor basin includes three main rivers (Puok, Siem Reap, and Rolous) which flow into Tonle Sap Lake. The diverse landscape is a mosaic of different land covers and land uses such as flooded forest, rice paddies, scrub land, shifting cultivation and designated protected areas. The vast majority of farmers grow rice although the type of rice varies depending on topographic location relative to Tonle Sap Lake. In the floodplain of Tonle Sap both floating and recession rice varieties are cultivated while dry season irrigated rice and rainfed rice are grown on land farther away from the lake (Varis, 2003). Land mines were scattered throughout the uplands until recently and were not completely cleared until 2002, making cultivation in some areas dangerous. The small city of Siem Reap and the Angkor complex, which was named a UNESCO World Heritage Site in 1992, are located within this predominantly flat landscape.

The northern boundary of the basin includes part of Phnom Kulen National Park and contains large forested tracts of land while the southern boundary contains a portion of Tonle Sap Lake and its surrounding floodplains. The largest fresh water lake in Southeast Asia, Tonle Sap (also known as the Great Lake) was given UNESCO's Biosphere Reserve status in 1997. Annually flooded, nutrient-enriched floodplains surround the lake and sustain traditional livelihoods through paddy cultivation and fish harvesting. A biologically diverse wetland ecosystem, the perimeter of the lake also includes a vast expanse of flooded forests (Varis and Keskinen, 2003).

Forests within the basin are comprised of both deciduous and evergreen trees. Several species of the dominant genus *Dipterocarpus* offer valuable timber resources both for local, subsistence farmers and more broad-scale commercial timber harvesting companies. Inter- and intra-annual precipitation patterns, regardless of location, influence vegetation phenology and are recognized as an important factor in changing landscape patterns (Green, Schweik, and Randolf, 2005; Jensen, 2005). Rainfall is variable across the region and the majority of rice farmers in the floodplains and uplands depend on the seasonal water flows of the monsoon wet season. In Siem Reap, these seasonal monsoons bring wet, moisture-rich air from the southwest from May-November while December-April is characterized by drier, cooler air that flows from the northeast. The majority of rainfall occurs during the wet season with an annual precipitation range from 1050-1800 mm.

**Historical Characteristics**

The Khmer dynasty ($9^{th}$–mid $15^{th}$ century A.D.), centered in the Angkor region, ruled an area that extended into present-day Thailand, Laos, Vietnam,and all of Cambodia and had a population that may have exceeded one million, mostly supported through extensive rice cultivation (Chandler, 2000; Coe, 2004). In 1953, Cambodia gained its independence from French colonial rule but after a period of trying to balance between communist and capitalist powers, the existing Cambodian government was overthrown by the communist Khmer Rouge in 1975. After the invasion by Vietnam in 1978 the rest of the world learned about the genocide that killed an estimated two million Cambodians during the Khmer Rouge reign **(**Chandler, 2000**).** Cambodia continued under Vietnamese control until 1989 and since then has worked towards the establishment of a stable, democratic government. Since 1998 and the death of Pol

Pot, the most well-known of the Khmer Rouge leaders, the country has been reasonably stable politically. Today, the complex design and restored grandeur of Angkor Wat and the surrounding temples draws international attention and tourism to the country and specifically Siem Reap province.

## Methods

### Field Data Collection

Field work was conducted in May 2005 at the end of the dry season. Training samples were collected for land-cover classification and accuracy assessment of the 2005 land-cover classification map. Randomly placed field locations were selected to represent various land-cover classes (i.e., bare, water, built, forest, and scrub). Land-cover classes represent multiple land-uses as described in Table 2-1. Field data were collected according to the CIPEC protocol (Green et al., 2005). Forest training samples were determined according to the Food and Agriculture Organization's definition of >10% canopy closure with trees higher than 5 meters.

### Data and Sources

I used various geographical information datasets from multiple sources (Table 2-2). Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) images were acquired from the U.S. Geological Survey's EROS Data Center (February 7, 1989, January 31, 1995) and the Global Land-cover Facility at the University of Maryland (January 10, 2002). The February 27, 2005 Landsat TM image was acquired through the Geo-Informatics and Space Technology Development Agency (GISTDA) to avoid the SLC-off problems that the Landsat ETM+ has had since May 2003. Software used was ERDAS IMAGINE 8.6 and ESRI ArcGIS version 9.1.

### Pre-Processing

All Landsat images were acquired within an eight-week window during the dry season. The time frame of the study (1989-2005) encompasses the time of emergence of Cambodia as a capitalist state and the year in which field work was conducted. The 2002 ETM+ scene served as the base image and was registered to the Food and Agricultural Organization (FAO) digital national roads layer for Cambodia. The 2002 ETM+ image was the reference image used in the field and was already in the best format for immediate registration. A root mean square error (RMSE) of less than 0.5 pixels (or <15m) was achieved using the nearest neighbor resampling algorithm. Image-to-image geometric rectification was performed on the other images and I used the overlay function in ERDAS Imagine to verify the accuracy of visual overlap for each image to the 2002 base image. After completing the rectification, each image was radiometrically calibrated to account for sensor drift, error caused by non-anniversary dates and changing atmospheric conditions (Green et al., 2005).

The delineation of the Angkor basin used multiple resources, including the JICA topographic maps (scale: 1:100,000), the 50-m spatial resolution digital elevation model (DEM), and an FAO vector file of both the natural and man-made waterways within Siem Reap province. The DEM was georectified to the 2002 Landsat image with an error of less than 0.5 pixels (25 m) and was overlaid to the 2002 image to ensure correct alignment.

**Precipitation Data and Normalized Difference Vegetation Index (NDVI)**

Precipitation has a profound effect on vegetation growth, thereby influencing vegetation indices. If there has been high rainfall prior to an image acquisition date, there may be a positive response for indices of vegetation, which could skew change-detection results (Jensen, 2005). I examined the relationship between antecedent precipitation and the Normalized Difference Vegetation Index (NDVI) by using data collected by the meteorological station in Siem Reap, Cambodia. The Normalized Difference Vegetation Index (NDVI: (IR reflectance-Red reflectance)/ (IR + R)), is a measure strongly correlated with primary production and somewhat correlated with vegetation biomass, and is used to measure vegetation change between image years as well as overall change between 1989 and 2005. The time series of annual precipitation values from 1980 to 2004 is shown in Figure 2-2. Exceedance probability was calculated using the Weibull distribution to determine the probability of the range of magnitudes being exceeded in a given year (Cunnane, 1978). Next, the mean and standard deviation for NDVI forest values were extracted and plotted against precipitation for annual, six-month, three-month, and one-month prior times. Only forest NDVI values were calculated to examine the relationship between vegetation growth and precipitation values. While scrub is a type of vegetation, the scrub land cover was excluded from analysis as it comprises multiple land-uses with minimal canopy cover by the vegetation. Intact forest canopy cover defined the spectral characteristics of forest cover in the basin.

**NDVI Calculation**

Precipitation values were compared to NDVI forest mean values to observe what type of relationship, if any, existed between the two datasets. Based on results, I chose to calculate the standard normal deviate (Z-score) for each NDVI image to minimize the influence of seasonal variation and inter-annual differences. Image differencing was performed between two standardized NDVI images for multiple time steps to detect variation of biophysical change. Image differencing is useful for continuous data because the image output results in a range of positive and negative values that represent change, with no-change values close to zero (Guild, Cohen, and Kauffman, 2004). Next, a threshold of ±1 standard deviations was determined from the standard NDVI differenced images to define change in the landscape. Creating a threshold that highlights 33% of pixel values that fall outside ±1 standard deviations from the mean emphasizes more extreme biophysical change in the differenced images. Applications of thresholds to highlight areas of change from no change have been applied in previous studies (Southworth et al., 2004; DeFries et al., 2005).

### Image Classification

For each of the four multi-spectral images, five initial land-cover classes were defined by independent supervised classifications using a minimum distance algorithm. Training samples collected in the field were used to establish land-cover classes on the ground and then used to train the 2005 satellite image to recognize the land covers. Other images were classified based on the interpretation of the 2005 image for which I had ground truth data. Initial supervised classifications involved ~ 20 spectrally separable land-cover classes and then these land covers were aggregated into the five overall land classes specific to the study. Post-classification sorting is a common approach used to discriminate misclassified pixels (Janssen, Jaarsma, and Vanderlinden, 1990, Loveland, Reed, Brown, Ohlen, Zhu, Yang, et al., 2000). For this analysis, post-classification sorting incorporated on-screen digitizing to correct systematic classification errors in which correct classes were verified through field work. The MLMUPC digital elevation model was used to separate upland forest (UF) from flooded forest (FF), using a 9 m maximum elevation threshold for FF. Field work, image analysis (specifically, inspection of the flood extent in 2002), and spectral signatures determined that 9 m was the appropriate upper elevation limit for FF. With the creation of the FF class, the change-trajectory analysis used six classes in determining land-cover change across the four images.

### Change-Trajectory Analysis

A post-classification change analysis for the four image dates was performed to map the patterns of spatial and temporal changes in the landscape. Forest was divided into upland and flooded forest using the DEM because different mechanisms may drive the changes for each area. In the lower floodplains, lake-level fluctuation and regional scale (Mekong River drainage basin) dynamics may have a major influence on land-cover change while upland forest covers are more likely to be altered by local hydrologic factors and anthropogenic land-use decisions such as agricultural clearing, logging operations, and subsistence farming patterns. Of the possible 1,296 trajectories derived from a four-date, six-class change trajectory, only those trajectories that covered greater than 1% of the landscape were used for further overall basin analysis.

## Results

### Precipitation and NDVI Change

The Weibull Plotting Position was used to estimate simple probabilities of annual precipitation in the years prior to each image date. Figure 2-3 compares observed probabilities of annual rainfall and the estimated normal probability distribution (years prior to an image date highlighted in gray). The cumulative probability conveys the percentage of the years expected to have rainfall less than or equal to that value. Observing the pattern on Figure 2-3**,** the year prior to an image date with the highest cumulative rank is 2001. The four image years provide an objective measure of precipitation prior to an image year. Figure 2-3 also shows the wide variation in antecedent precipitation relative to each image year. Thus, the next section addresses how NDVI varies with precipitation across time.

To determine the relation between NDVI values and precipitation values, I applied a simple masking procedure based on independent classifications of each year to extract NDVI forest values only and subsequently compared the mean to four time periods of precipitation. The NDVI forest images have values that range from -.0.35 to +.96 with higher pixel values indicating higher vegetation productivity. While the sample size (four years) for comparison is too small for statistical hypothesis testing, the pattern shown for annual, six-month, three-month, and one-month antecedent precipitation actually shows a negative relationship between precipitation and mean NDVI (Figure 2-4). The annual antecedent time period includes all of the previous rainy season as does the six-month time series. However, each image was acquired in the early-mid part of the dry season; thus, three-month and one-month accumulations (Figure 2-4c, d) of precipitation were necessarily lower than the annual and six month amounts. At the annual scale, a positive relationship with NDVI mean values is shown from 1989-1995. However, for the other three time periods (six-month, three-month, and one-month) there appears to be a slightly negative relationship between precipitation and NDVI mean forest values. The negative relationship is emphasized from 1995 onwards between all four precipitation time periods and the NDVI forest means. The negative correlation observed from 1995 to 2002 (Figure 2-4) illustrates the possible effect of saturated vegetation in the floodplains that is included in NDVI forest mean values. While precipitation increased by ~400 mm for each time period, NDVI mean forest values decreased for each image year. During the next time period (2002-2005), precipitation values were lower but there is a slight increase in forest NDVI. The increase in forest NDVI is related to the possible drainage of FF whose surface reflectance increases with less inundation of the forests.

The inverse relationship between precipitation and NDVI forest values may be influenced by the inclusion of flooded forest values in the analysis. Thus, the mean NDVI values were separated for upland and flooded forests and subsequently compared to the precipitation values for each time segment (Figures 2-5 and 2-6). The main difference between the two figures is a much lower flooded forest mean NDVI value in 2002 (0.144) than upland forest (0.410). The lower flooded forest NDVI value suggests less forest reflectance in 2002 due to higher water levels.

The spatial patterns that result from the NDVI image differencing and the comparison of NDVI mean values vs. precipitation indicates that the two different forests, upland and flooded, behave differently over time and are probably subject to different factors influencing the dynamic land-cover changes from 1989-2005 in the Angkor basin. Separation of the two forests is important due to the different mechanisms driving the changes occurring on annual and inter-annual time scales. Thus, UF and FF cover is separated from the overall region to highlight the importance of NDVI change in each respected area.

**NDVI Change**

Spatial patterns of vegetation change are shown by multi-temporal NDVI scenes (Figure 2-7). Overall there was a decrease in standardized NDVI throughout the Angkor basin from 1989 to 2005 of ~9% and an increase of NDVI values of almost 6% (Figure 2-8a). Standard deviations greater than 1 refer to increases in NDVI while standard deviations less than one are decreases in NDVI. There was a larger area of increased NDVI values from 2002 to 2005 than earlier time periods (1989–1995 and 1995–2002). In addition, the difference between increased NDVI and decreased NDVI from 1995 to 2002 was ~6% with a much larger percentage of area with NDVI decrease. The complex patterns of increasing and decreasing NDVI values are clearer by the separation of upland and flooded forest (Figure 2-8b and 2-8c). Opposite trends are detected between the two different forests with the most significant difference between 2002 and 2005.

Flooded forest NDVI values (Figure 2-8c) indicate initial decrease in NDVI values up until 1995 while the time between 2002 and 2005 indicates a much greater increase in NDVI values. The large increase in FF NDVI (~11%) from 2002–2005 suggests the FFs were inundated due to high water levels in the 2002 image which makes it difficult to spectrally separate forest pixels from water (inherently low NDVI because IR light is absorbed in water) in the floodplain region.

By extracting the upland vegetation (Figure 2-8b) a better indication of the spatial distribution of NDVI decrease is evident. The largest percent of upland NDVI decline occurs within the last three years of the study (2002–2005). From 1995-2002, there is not a substantial difference between increases and decreases of vegetation change. Comparing these relatively equal values in the upland basin to the same time period for the overall basin (Figure 2-8a) illustrates the NDVI decrease is more influenced by the changes in annual surface flooding of Tonle Sap rather than upland clearing although both processes contribute to the decrease. This is supported by the decreased NDVI values in the flooded forest from 1995–2002. However, the large percent of decrease in NDVI values from 2002–2005 (Figure 2-8b) indicates that much of the vegetation decrease is connected more to land clearing in the uplands than lake level fluctuations.

**Land-Cover Change**

The supervised classification maps of five land-cover classes for each of the four image years is shown in Figure 2-9, with a time-series of the classification given in Figure 2-10. An error assessment of the land-cover classification based on the 2005 image showed an overall accuracy of 83% and a kappa statistic of 0.75 (Table 2-3). An accuracy assessment was performed only on the 2005 classification because land-cover data for previous years of interest do not exist. The most misclassified land-cover was built areas because of confusion with bare and scrub land-covers. While the town of Siem Reap continues to develop rapidly, much of the urbanized areas are still constructed of natural materials that are spectrally similar to scrub and bare land covers. In 1989, both bare and forest land comprise approximately 40% of the study area. The next largest land cover, scrub, made up ~15% of the basin and water made up ~3%. Built land cover was less than 2% of the basin and clusters around the town of Siem Reap. Between 1989 and 1995, forest cover increased by 4.12% while bare areas decreased 4.87%. Bare land covers continued to decline, although at a slower rate of 1.58% from 1995 to 2002. Total forest cover also declined at a rate of 2.3% during the same period. However, within the last three years (2002–2005) of the study, bare land-covers have increased almost 13%

throughout the basin covering almost 47% of the total landscape while forest cover decreased by over 10% and makes up 32% of total land-cover. Water steadily increased from 1989 to 2002, covering ~8.5% of the basin by 2002 but dropped sharply by 2005 to only 3% of the total land-cover. This fluctuation is a function of the level of Tonle Sap and not of land-cover change caused by other factors. Built land-cover fluctuated minimally and never rose above 2% of the basin. These numbers indicate a general trend in recent deforestation (2002–2005) but are misleading because flooded and upland forests remain as one entity. For the change trajectory, these two classes of forest are separated for independent analysis.

**Overall Change Trajectory**

The classification maps for 1989, 1995, 2002, and 2005 were compared on a pixel-by-pixel basis to examine six land-cover trajectories (Figure 2-11). Basin forest cover was split into UF and FF and land-cover trajectories that covered >1% of the landscape for the four time steps identified. The large expanse of white in the figure (represents land-cover change trajectories that individually cover <1% of the basin, but collectively amount to ~37% of the basin) emphasizes the magnitude and complexity of different possible trajectories in the flooded area of the basin. Forty-five percent of the landscape remained in the same land-cover class from 1989–2005. The most extensive stable land-cover was bare (comprised of paddy fields and dry fields) covering 22.8% of the basin followed by UF with 14%, FF with 4.9%, scrub with 1%, and water with 2.3%. The four-year trajectory of built land-cover was less than 0.01% of the landscape. If UF change across all four dates is compared for trajectories >1%, then there is a 9.2% change in UF to scrub or bare land covers from original forest cover in 1989. Since 1995, the most concentrated area of forest-cover decline is directly south of Phnom Kulen. All possible trajectories involving land-cover change between bare and scrub classes represent 5% of the overall landscape changes in the basin. There was also > 1% change in the trajectory of FF to water in 2002, and back to FF in 2005, related to the regional heavy rainfall and flooding of 2000, 2001, and 2002 monsoon seasons. No built trajectories for the four time steps had greater than 1% change throughout the entire time period.

### Upland Forest Change

To assess the changes occurring in the upland portion of the basin (UF), I focused on forest-cover change at elevations greater than 9 m. Table 2-4 shows the percent change from UF to bare lands, UF to scrub lands, and overall changes from UF to non-forest. While forest cover moderately increased from 1989 to 1995, it declined since then as both scrub and bare land-covers expanded. The two-date deforestation trajectory almost doubles in each time period with losses of 11%, 20%, and 38%, respectively. For clearing and re-growth patterns, scrub and forest dynamics have a higher percentage of change than bare and forest patterns throughout the time series. All values related to forest/water dynamics were less than 1%.

### Flooded Forest Change

Table 2-4 also shows the percent of land-cover change related to FF and the land-covers bare, scrub, and water. For the first two time periods (1989-1995, and 1995-2002), more forest regeneration occurred than declined. From 2002-2005, though, there is much more decrease in forest cover as a result of land-cover changes related to bare and scrub lands. Again, similar to the UF patterns, a larger percent of change is related to forest and scrub dynamics rather than forest and bare interactions.

FF inundated by water in the first two time periods was much greater than flooded waters that reverted back to forest cover. However, from 2002 to 2005, 20% of inundated land reverted back to forests while only 1% of the forested land cover was covered in water. Differences in trajectories between FF and UF suggest a different set of drivers of land-cover change, which may suggest that there is a more regional influence on land-cover changes at elevations less than 9 m in the basin

## Discussion

The contradicting results between the two different remote sensing methods of change analysis (NDVI and post-classification) emphasize the complex nature of land-cover changes in the basin. Variation in NDVI patterns suggests different drivers of change more heavily influence land-cover change in each part of the basin. Regional climatic patterns may drive the water-forest interaction within the floodplain which subsequently distorts the results of forested land-cover change when examined at the whole-basin level. Separation of these two distinct forest covers in the change trajectory analysis provides a clearer landscape pattern of the different mechanisms which drive the rate and extent of land-cover change in each part of the basin. The spatial patterns of NDVI change indicate the increase in NDVI values between 2002 and 2005 occur predominantly in the FF portion of the basin because there is less flooding in the 2005 image. The separation of the two forests also provides complementary results between the NDVI and post-classification change detection methods in highlighting the forest decline in the upland area.

The six land-covers in the basin make up 1,296 potential trajectories. All bare and scrub land-cover change trajectories comprised 5% of the landscape. These shifts from and to bare and scrub are probably due to the strong seasonal influences of local precipitation regimes combined with subsistence agriculture prevalent in the basin. Despite development and infrastructure growth in Siem Reap over the past few years, the built land-cover trajectories made up less than 1% of overall change in the basin. However, continued interest in the region due to the World Heritage Site of Angkor may accelerate infrastructure and urban development in coming years.

While a large percent of the basin remained in the same land cover across all image dates as either bare or forested lands (41.7%), the most prominent change in the basin was the decline in UF cover. Aggregated together the four image-date trajectories show that forest change to either bare or scrub land-covers makes up almost 10% of the total UF decline. The change trajectory initially (1989-1995) shows slightly more UF re-growth than decline from the regeneration of bare and scrub land-covers. These results, though, probably relate to the shifting cultivation patterns that occur in the upland area, especially within the higher elevated region of Phnom Kulen where indigenous communities continue to practice subsistence farming. A two-date trajectory of more recent image dates (2002-2005) shows dramatic forest change with a ~38% conversion rate of upland forest area to bare or scrub compared to only 5% re-growth. The majority of the forest loss occurred between Angkor Wat and Phnom Kulen with large, contiguous patterns that suggest the area is being cleared for permanent cultivation rather than regeneration that is part of a cyclic, shifting pattern. While more studies must be conducted to determine whether the land-use decisions relate more to local, subsistence farming or are the result of large-scale agriculture being developed in the region, the change trajectory shows a distinct decline in forest cover within the last three years of the study.

On a regional scale, much of Southeast Asia was affected by floods during the 2000 monsoon season (Zhan, Sohlberg, Townshend, DiMiceli, Carroll, Eastman, et al., 2002), and Cambodia was again subject to extensive flooding during 2001. High precipitation that occurred throughout the Mekong Basin, and consequent Mekong River discharge and stage, directly influenced lake-level of the Tonle Sap, and in turn, landscape dynamics in the lower portion of the Angkor Basin. Natural flooding can cause significant alterations in vegetation cover within the floodplain region (Zhan et al., 2002). Greater than 1% of the entire basin was altered due to fluctuations in lake level that caused a pattern of forest-water-forest for the last three image years (1995, 2002, 2005). The first two time periods (1989–1995, 1995–2002) show more forest-to-water conversion while the last three years (2002–2005) show 20% of the floodplain area reverted from water back to forest (Table 2-4). The temporal patterns of forest-water interaction match the timing of floods that affected the larger region in 2000 and 2001. This correspondence suggests that land-cover changes in the floodplains are tied to annual lake-level fluctuations and are influenced directly by the amount of surface area covered by the annual expansion of Tonle Sap. Moreover, while 2000 is said to have been the highest lake stand, higher local precipitation was recorded in 2001 (Figure 3) which also indicates a difference between local rainfall and regional Mekong basin influences on the lake level and subsequent land-use decisions made in the floodplain area. Recognition must also be made for human influences that contribute to the FF trajectories linked to bare and scrub land-covers. From 2002–2005, the percent of water to FF transition (20%) is almost balanced by the 24% decrease in FF that changed to either bare or scrub land covers. The two very different trajectories predominantly occur in different parts of the floodplain area (Figure 2-10). If loss of forest cover becomes permanent (upland or lowland) there may be important ramifications for hydrologic functions in the basin. In addition to local alterations in land-cover, the Angkor basin and the Tonle Sap ecosystem may be further affected by regional upstream modifications in the Mekong Basin as the collective impact from upstream neighboring countries could adversely affect important environmental components of the Tonle Sap ecosystem (Lebel, Garden, and Imamura, 2005; de Lopez, 2002).

Similar to other findings in the region, the change in forest cover also may be connected to any number of interrelated socio-economic factors such as shifts in policy, market integration, accessibility, and human population growth (Kummer and Turner, 1994; Carr, 2004; Verburg et al., 2004; Castella, Manh, Kam, Villano, and Tronche., 2005; Fujita and Fox, 2005). In the Angkor basin, forest decline coincides with policy changes at both the national and regional scale. While forests were exploited during the 1980s as a means of economic revenue, it was not until the U.N. sanctioned a provisional government for Cambodia in 1991 that there was a means to conduct legitimate business with international timber companies. These relationships may have accelerated the exploitation of Cambodia's natural resources, especially forests. In addition, a ban on logging implemented in Thailand (1989) and Vietnam (1991) coincides with increased logging in Cambodia, Laos, and Myanmar (Hirch, 2001). Results show that the Angkor basin experienced an initial increase in forest cover but since 1995 has followed the larger regional pattern of decreasing forest cover. The connection to these policy shifts and the land-cover changes in the Angkor basin remain unclear and further investigation is necessary to determine the influence that policy changes may have had on a shift from traditional shifting cultivation to the establishment of more permanent cultivation plots.

The fact remains that changes in national policies have made international markets more accessible and, in turn, accelerated development within Cambodia, especially Siem Reap Province. Large decreases in forest cover have occurred in the basin and despite the quick income generated from forest cutting, the actions may dramatically alter the landscape patterns and processes in the basin. Angkor was established as a World Heritage Site in 1992 but most of the deforestation in the Angkor Basin has occurred in the latter half of the study period (1995–2005), with the most dramatic decreases occurring since 2002. However, varying spatial and temporal patterns of land-cover transformation were detected with different remote sensing techniques which suggest the recent changes in land-cover are a result of complex, multi-scalar relationships that drive land-cover change in the Angkor basin.

## Conclusion

The post-classification change analysis indicates distinct forest decline in the upland area of the Angkor basin, with a high percent of deforestation since 2002. While the standardized NDVI image differencing also shows a more recent decrease in NDVI values, there is a large increase in NDVI values since 2002 that are connected to the floodplain dynamics of Tonle Sap Lake. The floodplain variability shown in the NDVI analysis generates a hypothesis that processes which drive land-cover change occur at multiple temporal and spatial scales. Direction for future study is to improve the land cover classification of the flooded area around Tonle Sap Lake and further investigate local and regional hydrologic influences on the vegetation productivity of the area.

My results suggest strong influences due to biophysical characteristics on land-cover change patterns as well as distinct socio-economic influenced changes that may relate to policy shifts and market dynamics on multiple scales. The most significant changes in the Angkor basin have been patterns of vegetation increase and decline. With the use of multiple change detection methods, this baseline study sets the context for future work to explicitly determine the interactions of multiple biophysical and socio-economic drivers of land-cover in the Angkor basin.

Table 2-1. Description of land-cover classes in classification scheme. Each land-cover class incorporates multiple land-uses.

| Land Cover Class | Description |
|---|---|
| Bare and Rice | Land cover that includes paddy fields as well as vegetation fields. While these areas seasonally change with cultivation periods, the spectral signatures across dates remain similar due to dry season acquisition. |
| Scrub | Incorporates land uses of pasture, and mixed scrub/agriculture and the land covers grass and secondary growth areas. The class is intermediate between areas of pure bare land cover and completely forested land cover. |
| Forest | Land cover class that contains evergreen and deciduous forests predominantly in the upland portion of the watershed (an exception being within the walls of Angkor Thom), and flooded forest predominantly in the lowland areas annually inundated by the expansion of the Tonle Sap Lake. |
| Water | Land cover class incorporates open water, completely saturated rice paddies (due to irrigation), and saturated vegetation (floodplain area). Spectrally, inundated flooded vegetation and irrigated rice paddies were not separable from open water. |
| Built | Land cover that separates paved roads as well as the main population center of Siem Reap. Separates rural urban from scrub and bare, which includes villages along main roads throughout the basin. |

Table 2-2. Datasets comprising information used in creating study region and analyses of changes

| Organization | Ancillary Data Description |
|---|---|
| Food and Agriculture Administration (FAO) | FAO datasets include National level data for roads, topography, political boundaries, and protected areas were all collected in WGS84 UTM 48N projections. The national roads dataset is used for the base rectification of the 2002 image, while the rivers vector layer aids in the delineation of the Angkor basin |
| Japanese International Cooperation Agency (JICA) | JICA digital topographic maps at the 1:100,000 scale aided in the watershed delineation. Each topographic map was re-projected into WGS84 UTM 48N to match satellite projections |
| Ministry Land Management, Urban Planning, and Construction (MLMUPC) | The MLMUPC provided a 50-meter digital elevation model that was used both in delineating the Angkor watershed as well as post classification separation of information classes of interest. |
| Meteorology Station Siem Reap, Cambodia | Provided precipitation data for Siem Reap station between 1981-2004 |

Table 2-3. Error matrix of 2005 Landsat TM classification.

| Error Matrix | | | | | | |
|---|---|---|---|---|---|---|
| Class | Bare | Scrub | Forest | Water | Built | Total |
| Bare | 67 | 2 | 3 | | | 72 |
| Scrub | 13 | 33 | 2 | | 1 | 49 |
| Forest | | 2 | 21 | | | 23 |
| Water | | | | 7 | | 7 |
| Built | 2 | 2 | | | 5 | 9 |
| Total | 82 | 39 | 25 | 7 | 6 | 160 |
| | | | | | | |
| Producer's Accuracy | 82% | 85% | 81% | 100% | 83% | |
| User's Accuracy | 93% | 67% | 91% | 100% | 56% | |
| | | | | | | |
| Overall Accuracy 83% | | | | | | |

Table 2-3 continued

| Kappa Statistic 0.75 |
|---|

Table 2-4. UF clearing and re-growth changes related to bare and scrub land-covers. Numbers were derived from taking the total area (ha) of each conversion and dividing by the total area of forest conversion between two time periods in the upland or flooded area respectively. The total of all UF trajectories was 29.4%, 30.8%, and 28.3% for 1989 - 1995, 1995-2002, and 2002-2005 respectively.

| Land Conversions of UF (> 9 meters) | | | |
|---|---|---|---|
| | 1989-1995 | 1995-2002 | 2002-2005 |
| Clearing → | | | |
| Forest to Bare | 3% | 7% | 17% |
| Forest to Scrub | 8% | 13% | 21% |
| Forest to Bare/Scrub | 11% | 20% | 38% |
| Re-growth → | | | |
| Bare to Forest | 6% | 3% | 1% |
| Scrub to Forest | 9% | 9% | 4% |
| Bare/Scrub to Forest | 15% | 13% | 5% |
| **Land Conversions of FF (< 9 meters)** | | | |
| | 1989-1995 | 1995-2002 | 2002-2005 |
| Clearing → | | | |
| FF to Bare | 3% | 2% | 7% |
| FF to Scrub | 6% | 3% | 17% |
| FF to Bare/Scrub | 8% | 5% | 24% |
| Re-growth → | | | |
| Bare to FF | 18% | 7% | 1% |
| Scrub to FF | 14% | 11% | 2% |
| Bare/Scrub to FF | 32% | 18% | 3% |
| Flood Increase → | | | |
| FF to Water | 8% | 16% | 1% |
| Flood Decrease → | | | |
| Water to FF | 1% | 5% | 20% |

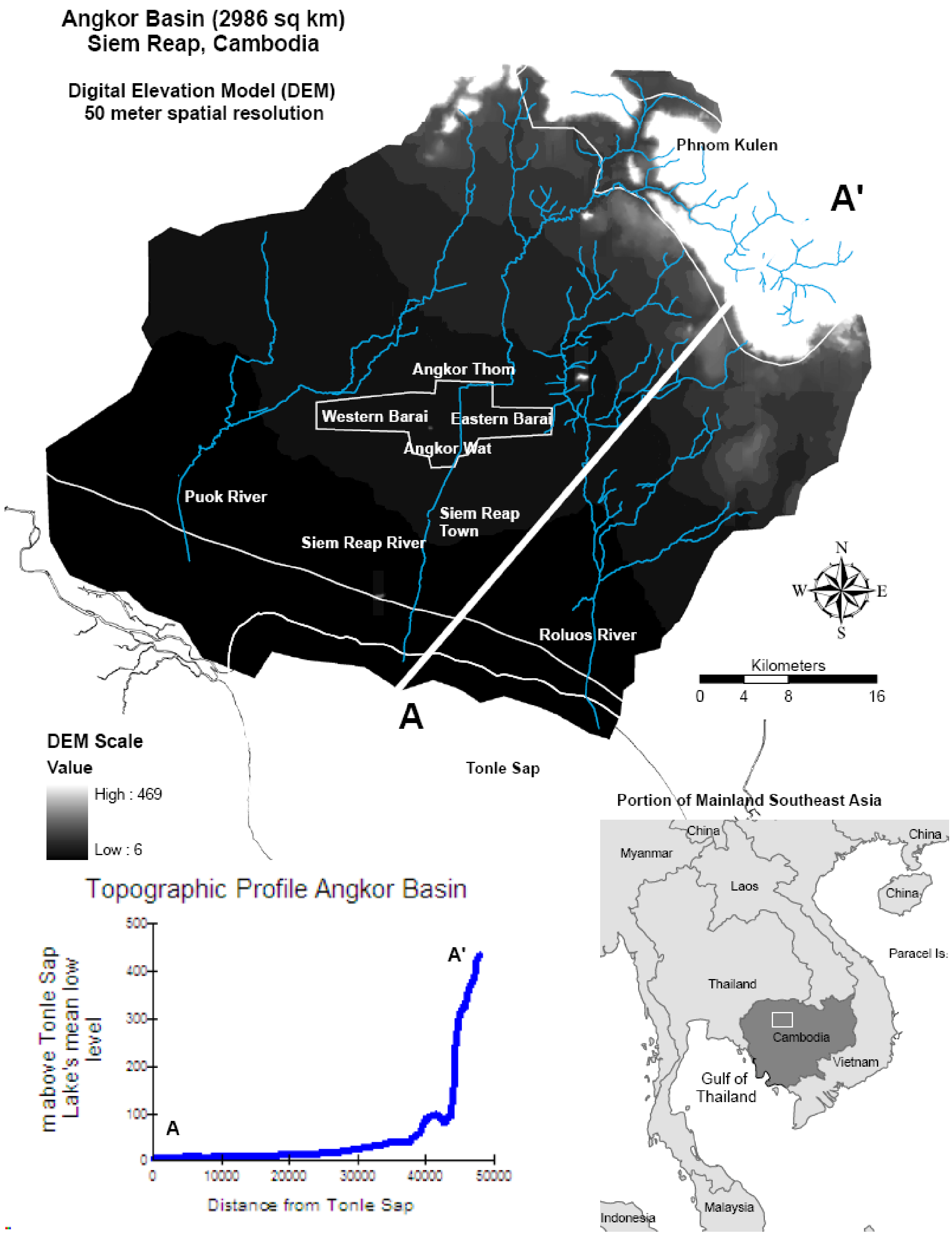


Figure 2-1. Study region of the Angkor basin in Siem Reap, Cambodia.

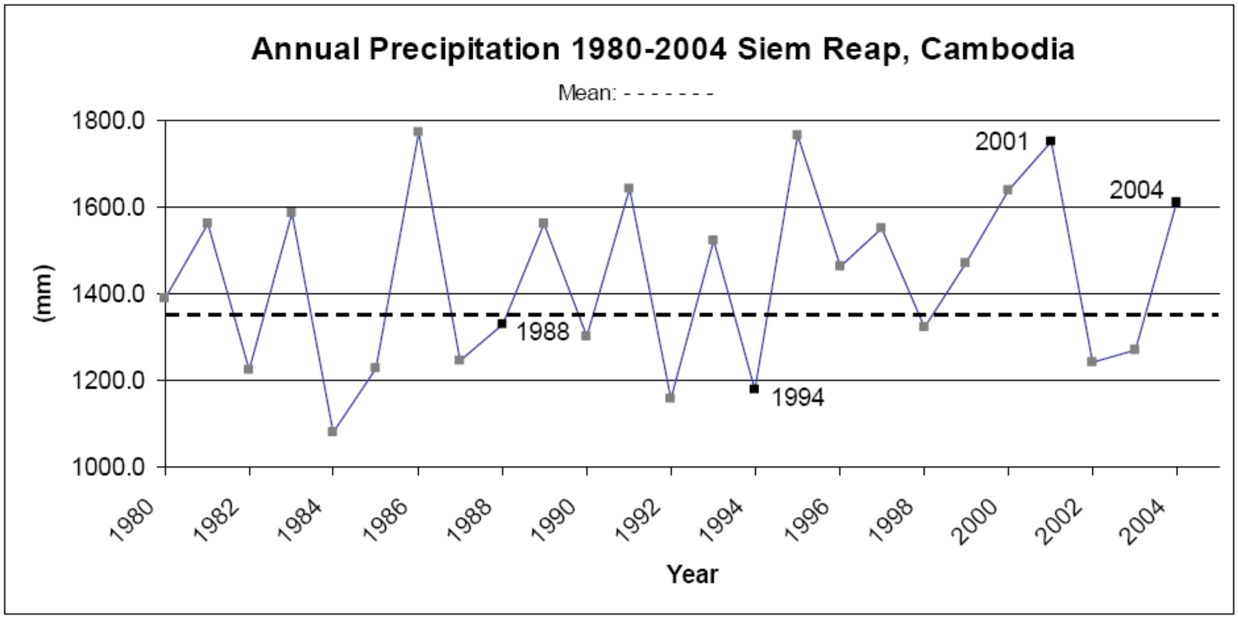


Figure 2-2. Annual precipitation values from 1980–2004 in Siem Reap, Cambodia from the meteorology station in Siem Reap, Cambodia. The dotted line is the mean annual precipitation and the dates indicate years immediately prior to the acquired satellite images.

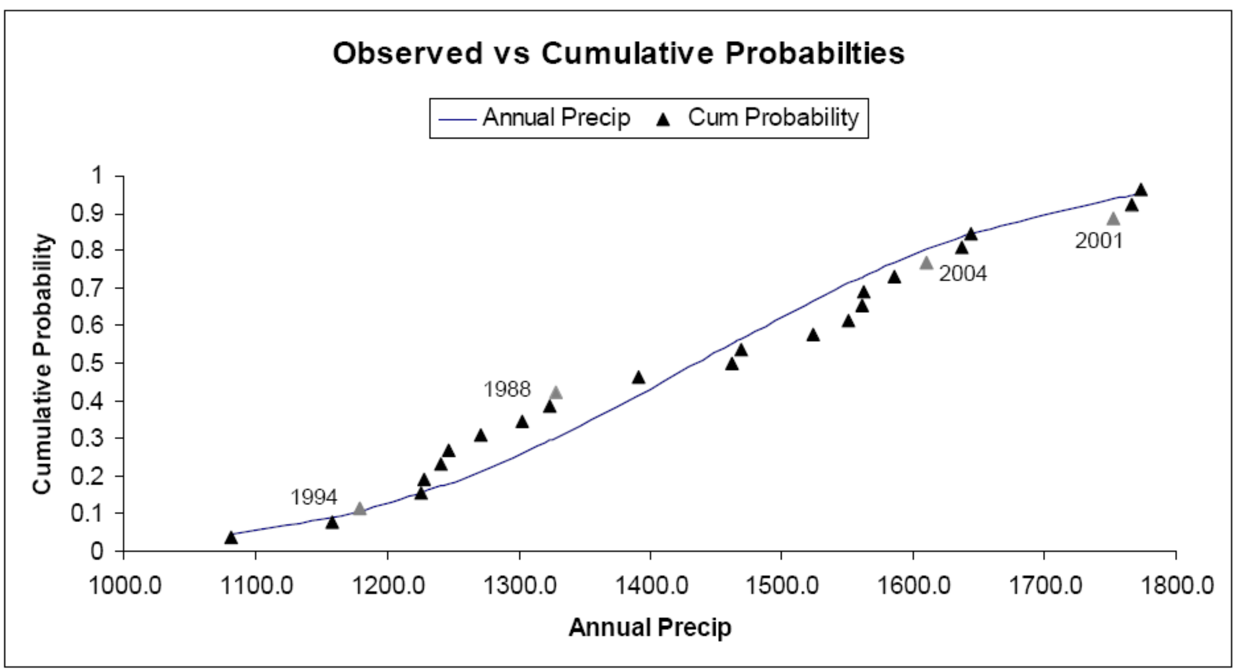


Figure 2-3. Cumulative probability compared to observed probabilities of annual rainfall from 1981–2004. Years highlighted represent rainfall prior to each image year.

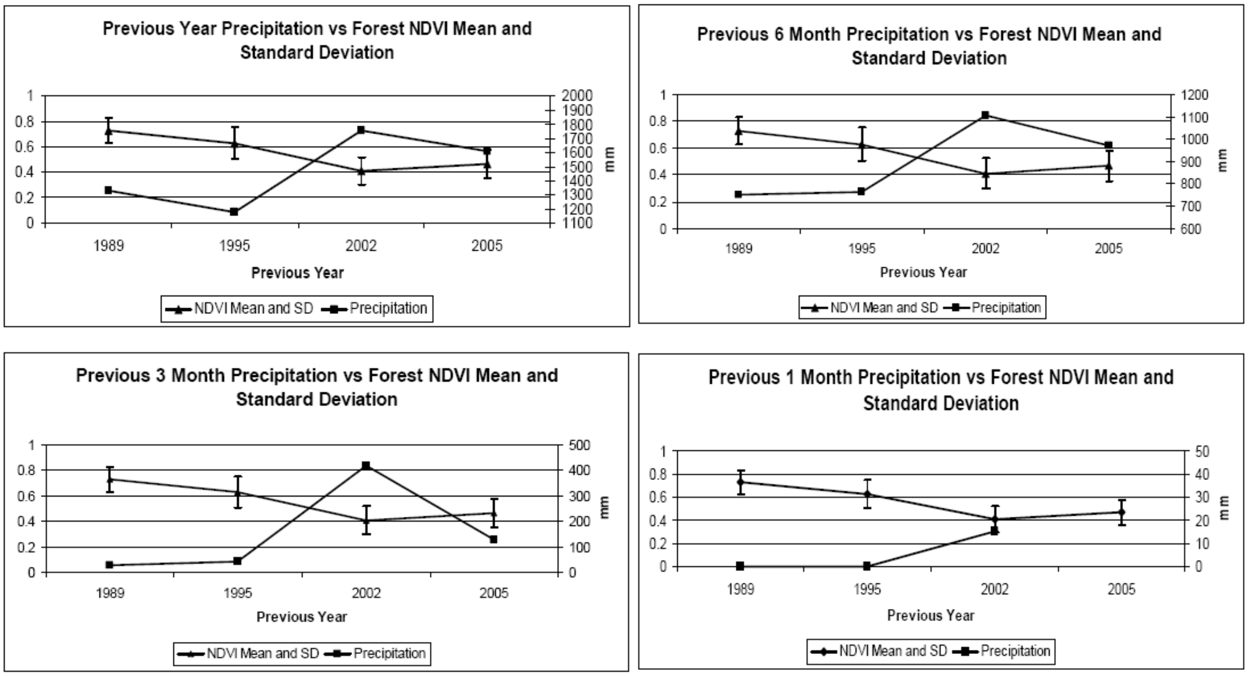


Figure 2-4. Comparison of precipitation values to relative forest NDVI mean values for annual, six month, three month, and one month time scales.

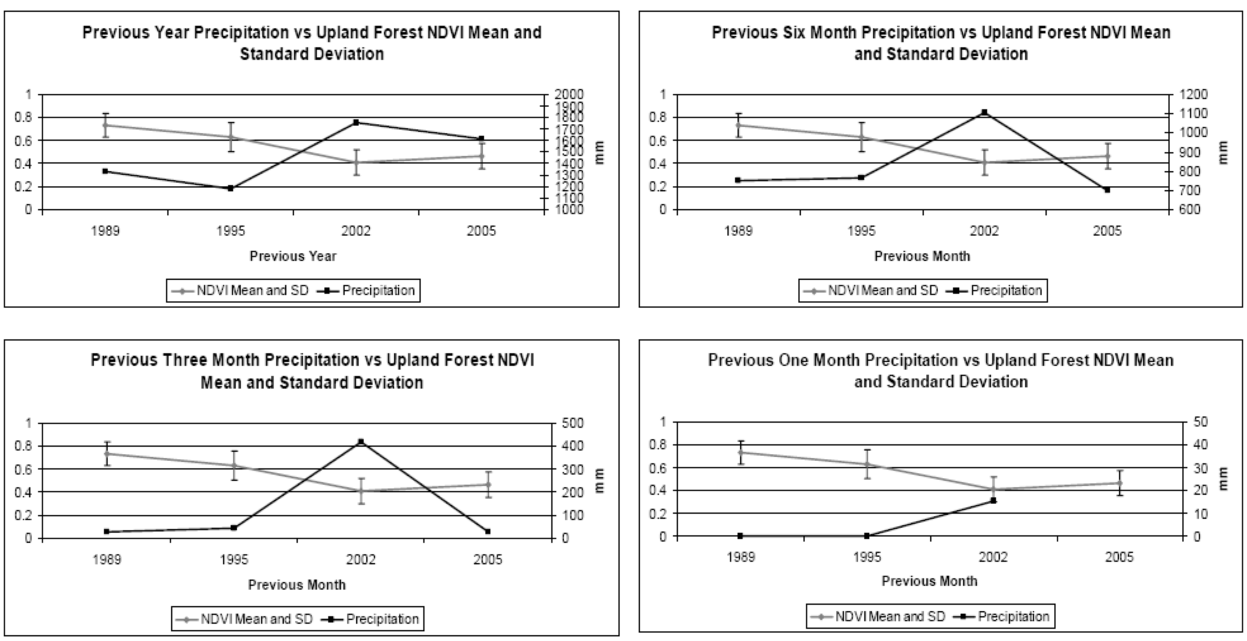


Figure 2- 5. Comparison of precipitation values to relative upland forest NDVI mean values for annual, six month, three month, and one month time scales.

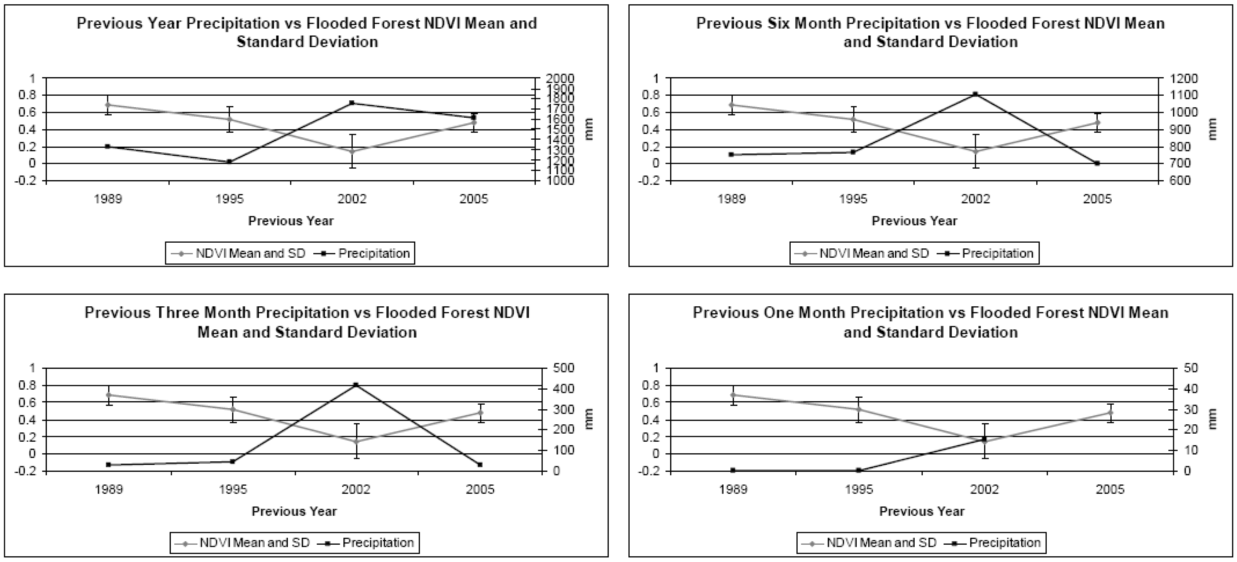


Figure 2-6. Comparison of precipitation values to relative flooded forest NDVI mean values for annual, six month, three month, and one month time scales.

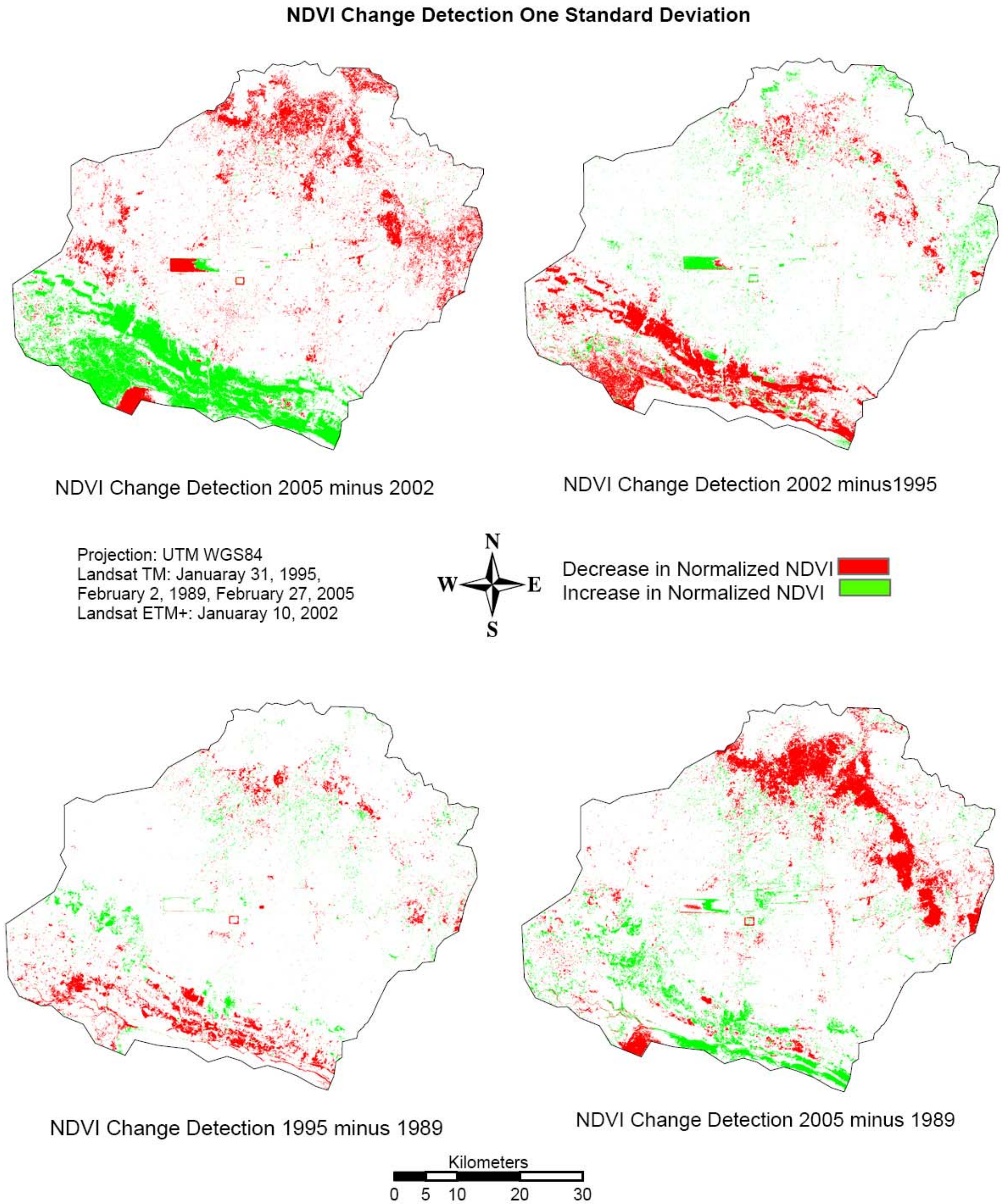


Figure 2-7. Standardized NDVI change detection within the Angkor basin. One standard deviation away from the mean was calculated for each change detection (2005–2002, 2002–1995, 1995–1989, and 2005–1989).

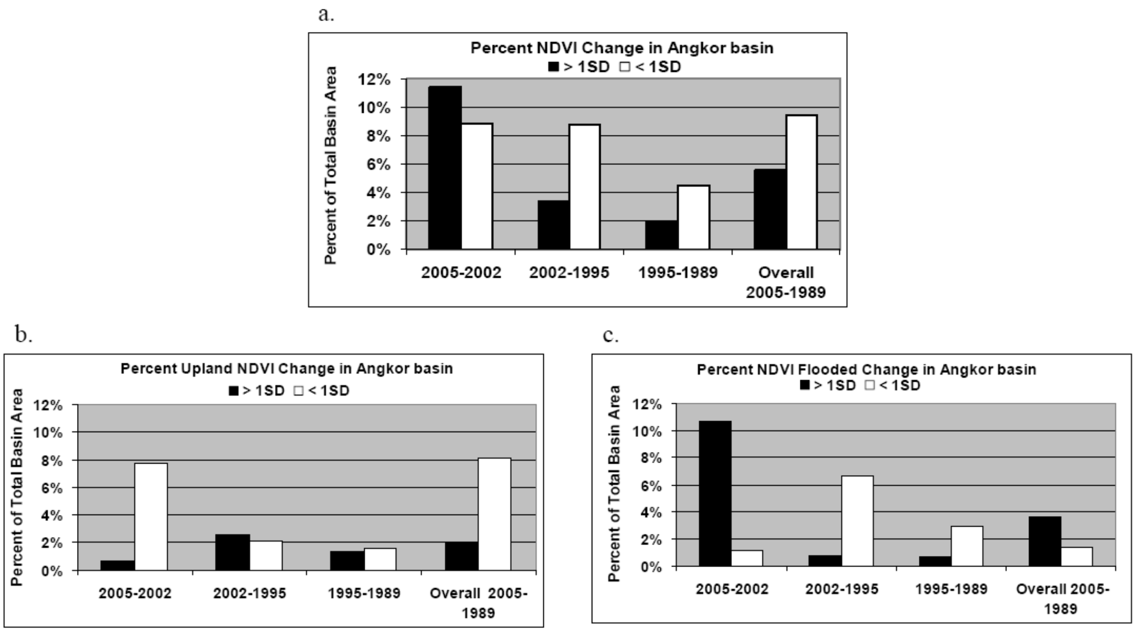


Figure 2-8. Percent of NDVI change for overall, upland, and flooded forest area in the Angkor basin for 1989–1995, 1995–2002, 2002–2005, and 1989–2005.

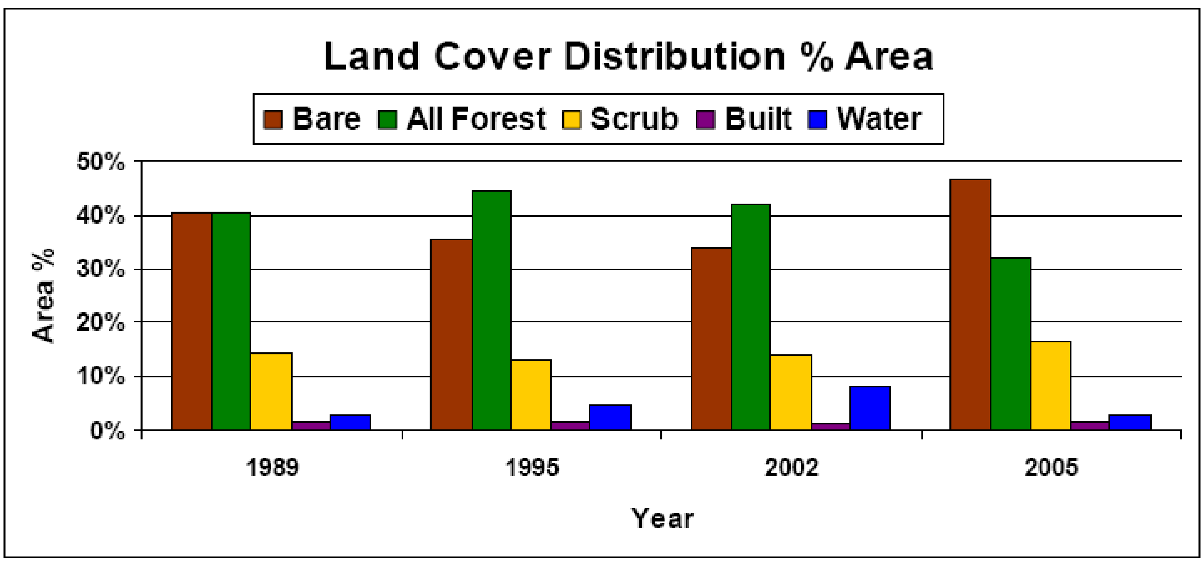


Figure 2-9. Land-cover classification for five land covers in the Angkor basin, Siem Reap Cambodia.

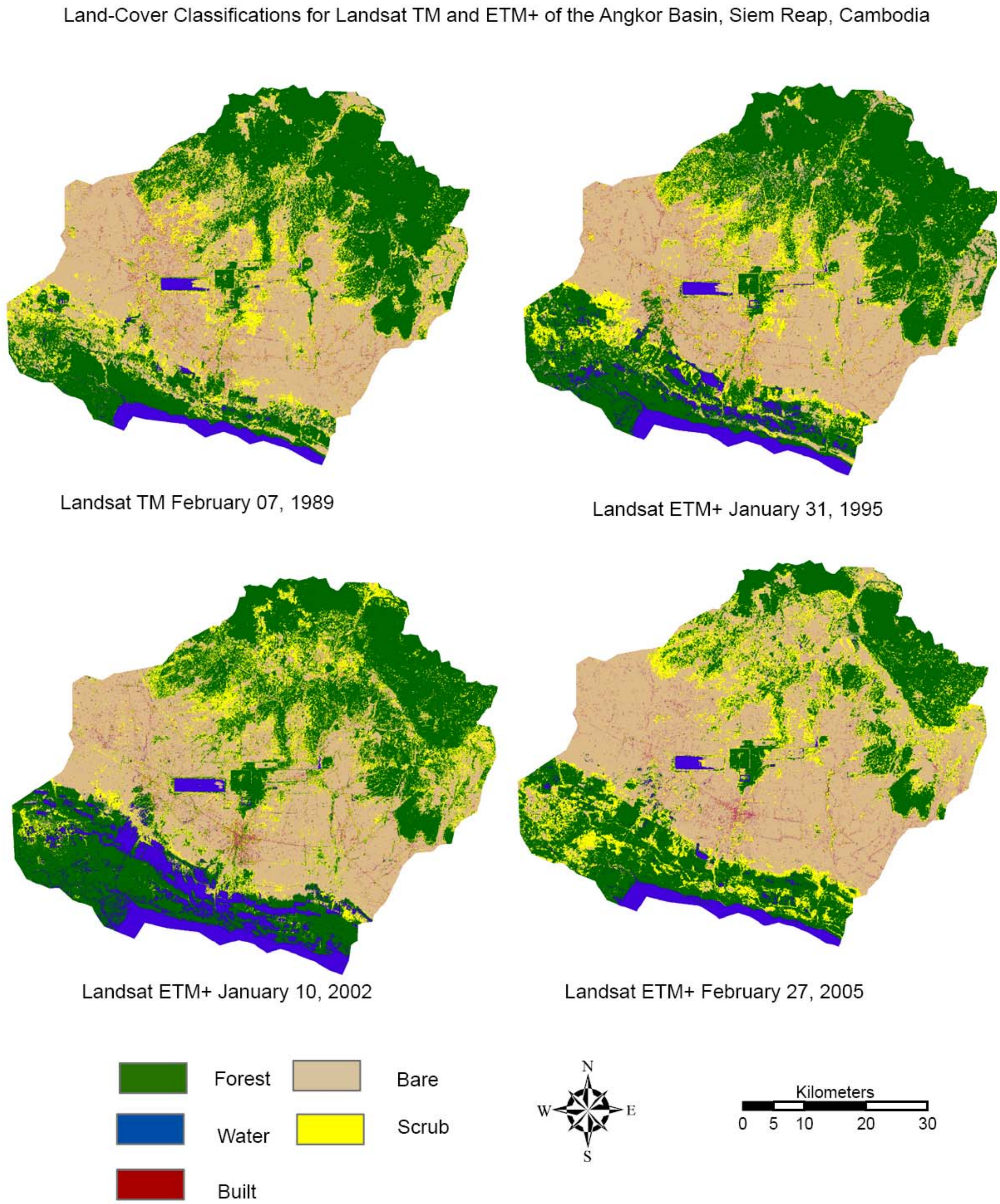


Figure 2-10. Land -cover changes by year for entire Angkor basin, with flooded and upland forests aggregated together.

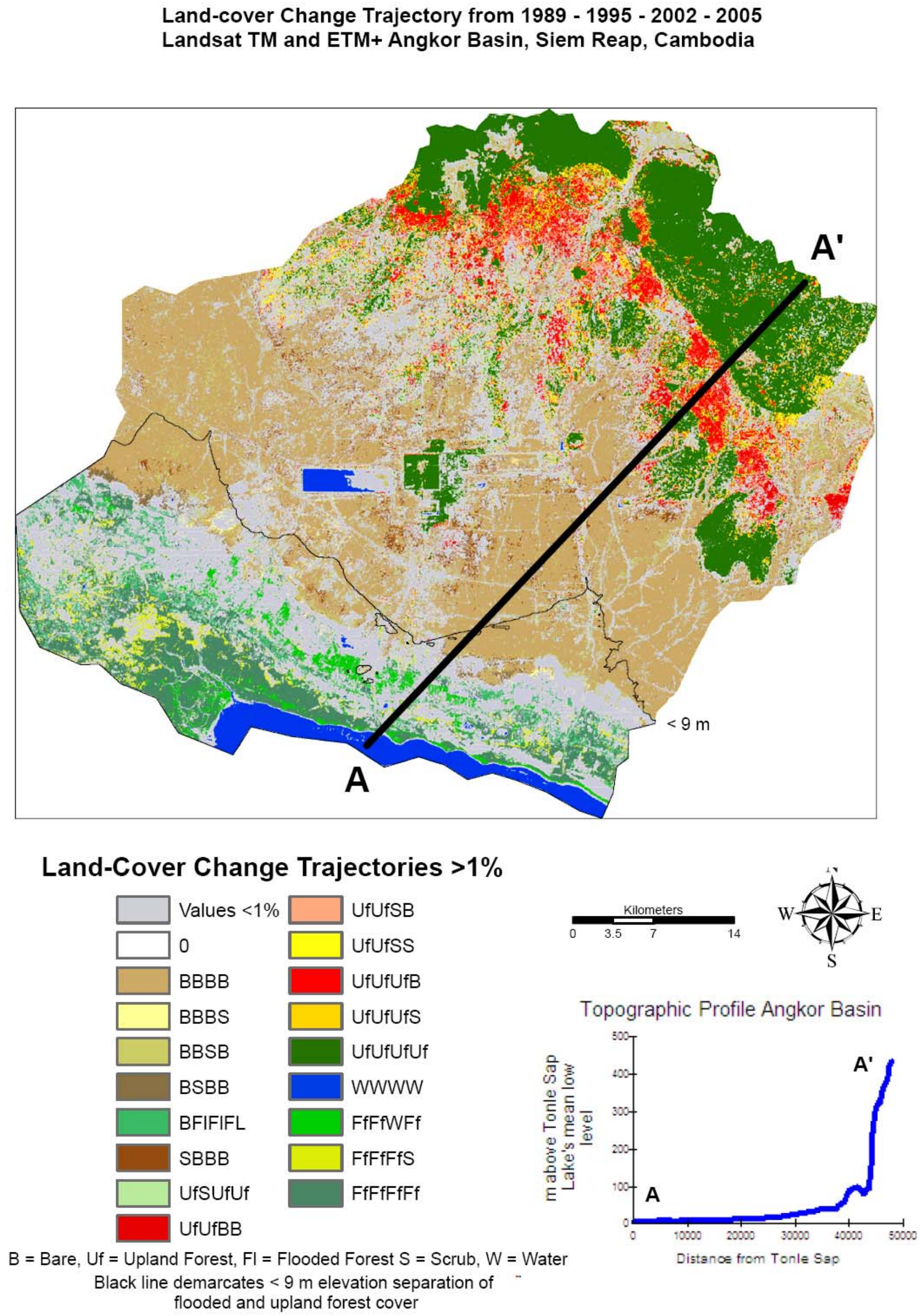


Figure 2-11. Land-cover classification trajectory for six land covers in the Angkor basin, Siem Reap, Cambodia. Only trajectories >1% are highlighted while trajectories <1% of the land-cover are aggregated together. Trajectories that showed forest loss over the time period were highlighted in shades of red for forest-bare change and shades of orange for forest-shrub change. Stable forests (both upland and flooded) as well as trajectories that ended in forest (2005) are shades of green. Water is shown in blue.

# CHAPTER 3
# IMPORTANCE OF LANDSCAPE POSITION IN THE ANGKOR BASIN, SIEM REAP, CAMBODIA: SPATIAL AND TEMPORAL FOREST CHANGE IN A TROPICAL WATERSHED

## Introduction

Landscape position and topographic effects are important biophysical factors that contribute to land-use/land-cover changes (Green and Sussman, 1990; Brandt et al., 2006). Variation in topography will influence land-use decisions and subsequent alterations of land-cover. These changes are especially relevant within a watershed boundary because change in the upland forested regions can directly modify the biophysical properties of the lowland floodplains (Giambelluca, 2002).

The position of a landscape affects and is affected by both socio-economic changes and other biophysical processes. In tropical developing regions, research has focused on the complicated relations between the environment, socio-economic, and policy factors that drive the transformation and modification of tropical forest landscapes (Turner et al., 2001; Nagendra et al., 2003; Verburg et al., 2004; Etter et al., 2006). Interactions of biophysical and socio-economic factors across scales must be understood to understand the local-level landscape patterns (Turner, 1989).

Comparison of global deforestation rates shows that Southeast Asia has the highest rate of forest loss, often associated with cropland expansion (Achard, Eva, Stibig, Mayaux, Gallego, Richards, et al., 2002; Lambin et al., 2003; Leper et al., 2005). The forests in Southeast Asia are very productive, biologically diverse ecosystems and are highly valued for commercially important *Dipterocarpus* hardwoods. Large decreases in forest cover have occurred mainly due to aggressive logging practices (private and state-run commercial timber harvesting), large transmigration schemes, and weak government infrastructure (Lambin and Geist, 2003).

Although human influences (population growth, market activity, socio-economic development, etc.) play a large role in land transformation, it is also important to recognize the influence of landscape position and topographic influences on land-use decisions and land-cover changes. Literature on other tropical forested regions shows the importance of landscape position (elevation, slope, aspect) and their interactions with socio-economic factors (market influence, policy changes, cultural values) that drive landscape change (Green and Sussman, 1990; Nagendra et al., 2003; Vagen, 2006). Green and Sussman (1990) and Vagen (2006) found elevation to be a prominent factor in decisions to clear land when accessibility due to topography and infrastructure made certain areas difficult to farm. Thus, elevation can be an initial deterrent to forest clearing, but as shown in Nagendra et al. (2003), policy shifts may make accessibility and topographic constraints less important in the decision to deforest an area. Different results for each case study stress the importance of spatial and temporal land-cover change and the fluctuations of a specific system.

This study used multiple change-detection methods to describe region-specific landscape dynamics from 1989 to 2005 in the Angkor basin in Siem Reap Province, Cambodia. The watershed, (also called drainage basin or catchment) provides a biophysically-defined landscape within which the spatial and temporal variability of natural resources affects socio-economic conditions and activities (Gautam, Webb, Shivakoti, and Zoebisch, 2003). The Angkor basin is important because within its boundaries are diverse land-uses (paddy cultivation, fisheries, World Heritage Site, protected areas, etc) important to local livelihoods as well as national economic growth. The topographic profile of the Angkor basin extends from the floodplains of Tonle Sap Lake, through the Angkor world heritage site, into the mountainous area of the Phnom

Kulen National Park and presents a variable landscape with multiple processes that are directly influenced by landscape position that ultimately affects land-use decisions.

The forests surrounding Angkor Wat were designated as the first protected area in Southeast Asia in 1925. The whole protected-area system collapsed during the recent decades of civil strife and disruption (ICEM, 2003). With the end of conflict and the establishment of a new Cambodian constitution in 1993, twenty-three protected areas[1] were created comprising ~21% of the total area in Cambodia.

Three of these protected areas are situated partly or wholly within the Angkor Basin. Phnom Kulen National Park is located in the upland region of the Angkor Basin and forms the northern boundary (IUCN category II). The southern boundary of the basin is made up of part of Tonle Sap Lake and the surrounding floodplains, all of which is part of a UNESCO Biosphere Reserve. This area is also designated as a protected multiple use area under the Cambodian constitution. The UNESCO World Heritage Site of Angkor Wat and surrounding temples is centrally located within the basin. These protected areas were created in a landscape that has been dominated by humans for thousands of years (Coe, 2004) and, as with many protected areas in developing countries, is surrounded by continually growing human populations (Child, 2004). Within the predominantly agricultural landscape of the Angkor Basin, protected forested areas provide important services for water supply and regulation, soil stability, control of sediment runoff, and higher biodiversity and species habitats (Giambelluca 2002; Pattanayak, 2004). The majority of densely forested area in the uplands is protected within the boundaries of the national park, although indigenous communities live within the boundaries and actively practice swidden

[1] Protected areas in Cambodia consist of National Parks, Wildlife Sanctuaries, Protected Landscapes, and Multiple Use Management Areas. Phnom Kulen is a national park (37,500 ha), Angkor is a protected landscape (10,800 ha) and Tonle Sap is a multiple use management area (316,250 ha). Only part of Tonle Sap resides within the Angkor Basin while the entire Angkor complex and most of Phnom Kulen resides within the boundaries of the watershed.

cultivation. There has also been much recent activity and development along the base of Phnom Kulen, which may have important environmental, social, and economic implications for both the lowland and upland areas of the basin.

Quantifying land-cover change with remote sensing techniques provides a spatial and temporal representation of the Angkor basin and is a robust tool to detect patterns of landscape change. I used a three-fold approach with different remote sensing techniques that analyze and document the land-cover change to analyze effects of landscape formation on land-cover change in the Angkor basin. First, traditional supervised classifications of forest/non-forest land-cover were created for each of three Landsat TM images, acquired in 2005, 1995, and 1989. I divided the Angkor basin into four elevation zones (less 9 m, 10 to 42 m, 43 to 110 m, and 111 to 469 m) and calculated forest-non-forest change trajectories across all dates to quantify topographic influence on landscape change. Next, I conducted a principal components analysis (PCA), which transformed the original, TM multi-spectral and multi-temporal data into a reduced format by minimizing redundancy in the dataset (i.e. reducing correlation between bands) (Fung and LeDrew, 1987; Mas, 1999). The PCA transformation loads the majority of the overall variance of the original three-scene dataset onto the first axis (known as the first principal component) with subsequent axes (second, third, etc. components), each accounting to a lesser degree for the remaining unexplained variance (Fung and LeDrew, 1987). The ability to compress data variability reduces correlation between bands, but another important function of PCA is its usefulness as a change detection method when applied to multi-temporal data. Minor components hold valuable change detection information while major components explain a larger percentage of landscape spatial variance (Richards, 1984; Fung and LeDrew, 1987; Lu, Mausel, Brondizio, and Moran, 2004). Thirdly, Normalized Difference Vegetation Index

(NDVI= (IR reflectance-Red reflectance)/(IR + R)) images were created to compare vegetation change with the principle components. NDVI, a standard measure strongly correlated with vegetation productivity, is an index of the amount of photosynthetic activity derived by measuring the difference between the absorption of red light and the reflectance of infrared light (Xiuwan, 2002; Jensen, 2005). Thus, the strength of photosynthetic activity measured by NDVI is compared to results shown in each principal component.

Objectives for this study were: (1) detect and document quantitative forest and non-forest land-cover change patterns in the Angkor basin from 1989 to 2005 and (2) examine spatial and temporal dynamics of land-cover change in different topographic zones in the Angkor basin.

## Materials and Methods

### Site Description

The Angkor basin covers 2,986 $km^2$ and is located in Siem Reap province, Cambodia (Figure 3-1). The Angkor basin has three main rivers (Puok, Siem Reap, and Rolous) that flow through the watershed and drain into Tonle Sap Lake. Semi-deciduous and semi-evergreen trees cover much of the forested areas. Several species of the genus *Dipterocarpus* are prevalent in the study area, and have high value for both local subsistence farming and more regional timber harvesting. The floodplains that form the perimeter of Tonle Sap Lake are predominantly forested and form a biologically diverse wetland ecosystem (Varis and Keskinen, 2003). These floodplains, enriched by nutrients from annual flooding, also sustain traditional livelihoods through paddy cultivation and fish harvesting.

Inter and intra-annual precipitation patterns influence the vegetation phenology and are recognized as important in changing landscape cover. The seasonal monsoons bring moisture-rich air from the southwest from May-November and dry, cooler air from the northeast from December-April. The majority of rainfall (~94% of the annual average) occurs during the wet season with total annual range of 1050-1800 mm. Rainfall is variable across the region and the majority of rice farmers in the floodplains and uplands are dependant on the seasonal water flows. While the uplands of the Angkor basin are influenced largely by the local precipitation patterns, lowland floodplains are subject to more regional influence as a result of the relation between the Mekong River and Tonle Sap Lake. Tonle Sap Lake acts as a natural reservoir for the greater Mekong basin. During the monsoon wet season, water from the Mekong River flows up the Tonle Sap River and subsequently floods Tonle Sap Lake and surrounding floodplains. As a result, the surface area of the lake varies as much as 12,500 $km^2$ between the end of the dry season and the height of very wet seasons (Fujii et al., 2003).

The majority of the landscape is very flat (Figure 3-1 – topographic profile), making it ideal for flooded rice cultivation. Elevation rises sharply in the upper third of the study area to the highest point at 469 meters along a plateau in Phnom Kulen. Measurements of elevation were collected from a digital elevation model (DEM) with a 50-m spatial resolution at the Ministry Land Management, Urban Planning, and Construction (MLMUPC). The higher elevation areas of Phnom Kulen are protected within the park boundaries. Between the protected upland and lowland forests there are paddy fields and scrublands. The town of Siem Reap and the ancient Khmer ruins are centrally located within this area, with approximately 6 km separating Siem Reap from Angkor Wat.

The rich history of the Angkor region dates back to the Khmer dynasty ($9^{th}$-mid-$15^{th}$ century A.D.) which encompassed surrounding areas of Thailand, Laos, Vietnam, and all of Cambodia (Chandler, 2000; Coe, 2004). Cambodia became a protectorate under the French crown in 1863 and did not become an independent state until 1953 (Coe, 2004). In 1975, the Khmer Rouge overthrew the Cambodian government, severing international ties and imposing a communist agrarian society on the people of Cambodia. The Vietnamese ousted the Khmer regime in 1979 and remained until 1989. Since then, Cambodia has worked towards stable, democratic rule and to rebuild the physical and educational infrastructure that was destroyed by the Khmer Rouge. Restoration of the monarchy and national elections took place in 1993 resulting in a coalition government ruled by FUNCINPEC (royalist party) and CPP (incumbent party) (Chandler, 2000). With the collapse of the Khmer Rouge, which culminated with the death of Pol Pot in 1998, and democratic elections in the same year, there has been relative stability within Cambodia. Weakness and corruption still exist within government institutions, but with continual stability, development continues throughout the country with a major focus on the rich history and restored Khmer ruins of the UNESCO World Heritage Site of Angkor.

**Data Preparation**

Landsat Thematic Mapper (TM) images were acquired from U.S. Geological Survey's EROS Data Center (originally acquired February 7, 1989, January 31, 1995), and the Thailand Geo-Informatics and Space Technology Development Agency (GISTDA) (February 27, 2005). I used ERDAS IMAGINE 8.6 and ESRI ArcGIS version 9.1 for imagery calibration, geo-referencing and all change-detection analyses. A 1:100,000 digital topographic map was obtained from the Japanese International Cooperation Agency (JICA) and a 50-meter spatial digital elevation model (DEM) was obtained from the Ministry of Land Management, Urban Planning, and Construction (MLMUPC) in Cambodia.

The initial satellite image corresponds to 1989, the year that Vietnamese troops left Cambodia. Acquisition of exclusively dry season images was important because of the seasonally dynamic landscape. During the dry season, the majority of paddy fields lie fallow and their spectral signature show high reflectance values in the mid-infrared bands. Because dates for all acquired images fall between 31st January and 27th February, the dry season images also make it easier to separate the bare agricultural and urban lands from dense forested vegetation.

Pre-processing included georectification and calibration procedures for each individual satellite image. Sixty ground control points were used for image-to-image rectification for each scene and used a first-order geometric transformation (the base image, a 2002 Landsat ETM image, was registered to a Food and Agricultural Organization [FAO] national digital roads layer for Cambodia). Using a nearest-neighbor resampling algorithm, each rectification achieved a root mean square error (RMSE) of <0.5 pixels (less than 15 m). The accuracy of the rectifications was visually verified by overlaying two images and using the swipe function in ERDAS Imagine. Radiometric calibration (Schweik and Green, 1999) was performed to convert the digital numbers to at-sensor radiance and also to surface reflectance to correct for atmospheric absorption and scatter as well as sensor drift (Jensen, 2005).

**Classification**

Training samples were collected in the field during May 2005 according to protocols developed by the Indiana University Center for the Study of Institutions, Populations, and Environmental Change (CIPEC) (Green et al., 2005). Forest training samples were defined according to the FAO's definition of > 10% canopy closure with trees higher than 5 meters (FAO, 2005). The abrupt change across the landscape between scrub lands and mature forests in the Angkor basin provides a basis to separate natural, dense forest from more fragmented and secondary re-growth that is typical of shifting cultivation or mixed land uses. Other classes (see Gaughan and Binford in prep for the definition of land-cover classes) such as bare, built, water, and scrublands were subsequently aggregated into a non-forest class to simplify the change trajectory analyses and highlight distinct changes in forest cover. For each year (2005, 1995, and 1989) a land-cover classification was generated using a supervised classification technique and a minimum distance algorithm.  Post-classification sorting incorporated on-screen digitizing and a digital elevation model to recode systematic errors detected in the supervised classification (Janssen et al., 1990; Loveland et al., 2000).  For example, pixels in the 8 x 2 km, rectangular reservoir adjacent to Angkor Wat called the Western Barai ("Barai" is Khmer for reservoir) were misclassified as forest at the receding water line so these pixels were re-coded to reflect the correct land-cover (bare), on the basis of field observations.

**Elevation Subsets**

Delineation of the Angkor basin used the 1:100,000 topographic maps and the georectified digital elevation model (DEM) with a grid size of 50 x 50 m.  Elevation of the basin ranges from 6 m above sea level which separates complete water coverage of the Tonle Sap from flooded forests in the 2002 Landsat image up to 469 m which is the highest point in Phnom Kulen. Georectification and re-sampling of the DEM was conducted to match the 30 x 30 m scale of the 2002 Landsat ETM base image, although the resampling did not provide a greater resolution to the DEM image.  After processing, the DEM was used to subset the watershed into four elevation zones (shown on Figures 3-1, 3-2, and 3-3).  Relationships between the spatial topographic characteristics of the basin and resulting land-uses may be illustrated by creating separate elevation zones with the study area,. Zones were created using knowledge of the area and natural breaks determined from the DEM histogram.  Zone one (6-9 m) represents the floodplain region of the watershed with lake level fluctuation that varies on an annual scale. Zone two (10-42 m) represents a mostly flat but gradually upward sloping, predominantly agricultural landscape with built areas clustered around Siem Reap town and the ancient Khmer temples (802 -1400 A.D.).  A transitional area defines Zone three (43-110 m), with a low slope up to the foothills of Phnom Kulen, separating traditional paddy fields and the more densely forested region.  Zone four (111-469 m), with a steep slope to the top of the high area, represents the largest range in elevation and encompasses a large portion of the protected area of Phnom Kulen.

### Principal Components Analysis (PCA) and NDVI

Standardized principal component analysis was performed on the original Landsat TM three-date (2005, 1995, and 1989) stacked image of eighteen bands, TM reflective bands 1-5, and band 7 for each year. Band six (thermal) was excluded from the analysis because of its different spatial resolution and retained as a separate dataset to be used in future research. A zonal analysis of the PC scores, using the areas of each of the eight possible land-cover trajectories as zones, was conducted. The zonal analysis takes each individual cell value for all cells belonging to the same trajectory and calculates descriptive statistics for each PC. The values are then compared within each of the first four principal components for the set of forest/non-forest trajectories. In addition, the correlation between Normalized Difference Vegetation Index (NDVI) and the PC scores was also calculated to examine the relationship between the first four PCs and the amount of photosynthetic activity measured in each scene.

## Results

### Overall Land-Cover Change

Land-cover classification maps for each of the years of forest/non-forest are shown in Figure 3-2. While an initial increase in forest cover occurred from 1989 to 1995, there has been a noticeable decrease in forest cover within the past ten years. The percent of forest and non-forest cover by year (1989, 1995, and 2005) was: 40%, 45%, 32% and 60%, 55%, and 68% respectively. Accuracy assessment for the land-cover classification of the 2005 Landsat TM image includes an overall accuracy of 96% and a kappa statistic of 0.91 (Table 3-1). Accuracy assessment was conducted only for the 2005 image as there are no long-term land-cover datasets with which to compare the earlier classifications. Earlier images were classified based on the interpretation of the 2005 image for which I had conducted field work to ground truth the different land covers. In addition, I believe that because all three images use TM5 data, the accuracies of the 1989 and 1995 land-cover classifications are equivalent to the 2005 image.

### Change Trajectory for 1989, 1995, and 2005

To derive from-to changes rather than overall change from 1989 to 2005, a three time-step change trajectory shows when and what type of land-cover changed across the study area (Figure 3-3). A three-digit code is the sequence of land cover for each pixel where F means forest and N means non-forest for 1989, 1995, and 2005. Trajectories of land-cover change for the Landsat TM classification maps were compared on a pixel-by-pixel basis to determine from-to changes of forest and non-forest land covers. The forest increased in the flooded region and around Angkor Wat from 1989-1995. The increase in forest within the low-lying areas may be a consequence of the lower water level in 1995, resulting in less open water and more vegetation cover in each pixel. In contrast, deforestation in upland forest increased during the latter half of the study period (1995-2005). Stable land covers of non-forest (N) and forest (F) remained the largest areas of land-cover in the basin at 45.4% and 21.2% respectively (Table 3.2). Continuous non-forest is concentrated in the central portion of the study region and mainly consists of paddy fields while forested lands are located at higher elevations and flooded areas proximate to the Tonle Sap. After trajectories of no-change, the next largest trajectory FFN (12.5%) indicates a pattern of deforestation between 1995 and 2005. Other trajectories of change range from 3% to 6%, with a higher percent of reforestation (5.1%) from 1989 to 1995 than deforestation (4.3%). The reverse pattern appears from 1995 to 2005 (FNF 2.4% and NFN 5.8%).

### Forest/Non-Forest Change within Elevation Zones

Four elevation zones representing distinct geographical areas were created within the basin (Figure 3-4). Zone one (6–9 m above sea level) comprises much of the floodplain and includes the most complex mosaic of forest and non-forest change trajectories. The forest and non-forested areas that have remained stable from 1989 to 2005 make up over 50% of Zone one. However, the area also has a 20.1% re-growth of forest from lands originally non-forested in 1989 (NFF) and 1995 (NNF). The complex forest-cover change may result from the lake-level change process that alters the reflectance of each pixel as a consequence of how much open water is showing through at the time of satellite image capture, or the consequence of cutting and re-growth, or a combination of the two. These alternative processes driving land-cover change require further study.

The majority of cleared lands remained in Zone two (10–42 m), in which rain-fed paddy agriculture continued to be the predominant land-use. This zone also includes the Angkor Wat complex, the town of Siem Reap, and its developing infrastructure. Considerable change is highlighted with forest to non-forest trajectories in Zone three (43–110 m). Traditionally, this zone has been more forested than not; however, this region had a decrease of ~37% in forest cover between 1995 and 2005 (Table 3-2). The most consistently forested region was Zone four (111–469 m) which includes part of Phnom Kulen national park.

**Principal Components Analysis**

The PCA transformation results in a set of uncorrelated variables in which the majority of variation within a multispectral, multitemporal image is reduced to fewer variables than the original number of bands. Cumulatively, the first four components explain 76% of the overall variation in the image. PC 1 explains the most variation in the image at 53% while subsequent components explain remaining variance which is 11.6%, 6.2%, and 5.2% respectively for the first four components (Table 3). Ecologically comparable landscape gradients are indicated by the close proximity of the pixel values over time (or PC scores) in ordination space as defined by the principal components (McGarigal, Cushman, and Stafford, 2000). In addition to explained variance, Table 3-3 also displays the factor loadings between the original dataset (bands) and the principal components. The correlation shows the strength of the relationship between each band *i* with each principal component *j* after the transformation.

Only the first four principle components (PCs) are included to explain spatial dynamics of both multispectral and multitemporal change within the study region. The rest of the components display minimal land-change features and are not included in interpretation. PC 1 represents the overall spatial landscape variability in the Angkor basin with high loadings in 1989 and 1995 on the mid-infrared and visible band reflectances. There are also high loadings in the visible bands (Blue and Green) for 2005. All the spectral bands save the infrared band are well represented in PC1 for at least two years. The mid-infrared bands support PC1 variance in changes of bare soil, built, and vegetation (grass) land-covers while the visible bands contribute to variation measured in water and vegetation (forest) characteristics.

Temporal changes in overall vegetation are represented in PC 2. The loadings for 1989 and 1995 near-infrared bands load high with more moderate loadings for the red, near-infrared, and mid-infrared bands in 2005. All of these bands are recognized to reflect strongly in vegetative land-covers (Boyd, Foody, Curran, Lucas, and Honzak, 1996; Jensen, 2005). The temporal variance of PC 2 is concentrated in the non-forested, central portion of the basin while the stable, forested areas (north and south boundaries of the basin) did not contribute as much variance in vegetation (Figure 3-5). After taking away the variance explained by PC 1 and PC2, temporal, location-specific changes are explained by the latent variables PC3 and PC4. These changes relate to the forest cover in the basin as the high loadings of the red band in PC 3 and the near-infrared band of PC 4 are used to characterize and detect vegetation change that occurred within the landscape occurred from 1995 to 2005.

Results of running a zonal analysis describe the PC characteristics of each of the different forest/non-forest trajectories (Figure 3-6). PC 1 mean values relate moderately high for every trajectory although trajectories with more non-forested years have higher mean values than predominantly forested trajectories (Figure 3-6a.). The relatively even distribution of mean values across the trajectories supports the interpretation that PC 1 describes overall spatial variation. Each trajectory was created from spectral values of different land-covers in the basin. Thus, the end product (eight land-cover trajectories) represents the distribution of different land-covers across the landscape. The other three components are interpreted to relate to vegetation dynamics in the basin. The PC 2 characteristics (Figure 3-6a. and 3-6b.) portray a stronger relationship to forested trajectories than non-forested trajectories. The trajectory with the lowest mean value for PC 2 is NNN, while the highest mean value is FFF. PC 3 and PC 4 portray characteristics that support other change detection methods in the study. PC 3 is positively characterized by trajectories of forest decline, with the most recent change in forest-cover having the highest mean values. In contrast, PC 4 seems to be characterized by non-forested trajectories with an emphasis on recent change of non-forest to forest. However, there is no clear distinction between the different trajectories and mean values for PC 4 which suggests more complex interactions are represented in the temporal variation of PC4 means.

**PCA Change and NDVI**

When the first four principal components are correlated with each NDVI image, an association can be made between which PCs are more highly correlated with vegetation production in the basin (Table 3-4). This analysis can help support the interpretation of the PC scores by providing an alternative relationship with an index that is strongly related to vegetation. The correlation between NDVI and the PCs indicates similar patterns in land-cover change in the basin.

PC 1 captures most of the landscape spatial variation across all years and loads high on mid-infrared and visible bands. In the Angkor basin, the mid-infrared and visible bands detect multiple land-covers such as bare, shrub, grass, built, and water. Forested areas are more representative by the red and infrared bands (especially when combined to create an NDVI measurement). With NDVI negatively correlated with PC1, pixel values that have high NDVI measures will have lower PC scores. In contrast, a positive correlation between NDVI and PC2 shows that high NDVI measures will have high PC scores. The correlation between PC 2 and the NDVI images highlights temporal change of vegetation. The decrease in the relationship between PC 2 and NDVI since 1995 supports the other change detection methods in identifying forest loss in the more recent time period (1995–2005). The high negative correlation values for PC3 and PC4 also relate to the temporal variation of change across all years. The most significant change occurred between 1995 and 2005. Again, PC3 and PC4 load high in the red and near-infrared bands respectively, which indicates the negative increase in NDVI correlation relates to vegetation change in the basin.

## Discussion

Multiple analyses identify spatial and temporal change on the landscape in the Angkor Basin. Each method of change analysis reinforces the interpretations of other change detection methods. Generally, the post-classification change trajectory indicated the largest overall land-cover change occurred from 1995 to 2005 (FFN- 12.5%) while a much smaller percent of non-forested lands regenerated since 1995 (NNF - 3.4%). The three-date land-cover change (NFN – 6.8%, FNF – 2.4%) suggests shifting land-uses as farmers rotate paddy fields for cultivation purposes. Another point of interest is the amount of original 1989 forest cover transformation to non-forest (FNN – 4.3%) compared to the original 1989 non-forest land cover transformation to forest (NFF – 5.1%). While this pattern indicates slightly more reforestation in the basin from

1989 to 1995, the increase in recent deforestation (NFN and FFN) is greater than the amount of regeneration and indicates a predominant pattern of land clearing. These overall changes give a good impression of general trends in the basin; however, to better understand the spatial dynamics of change, it is useful to discuss the changes relative to each elevation zone.

The most dynamic region of change is the low-elevation Zone one, which encompasses the majority of the Angkor basin floodplain around Tonle Sap. Changes that occur in the floodplain are most likely to be more strongly influenced by regional climate patterns that are part of the larger Mekong basin rather than local precipitation regimes and anthropogenic influences. The monsoonal climate patterns in Southeast Asia influence the fluctuation of the annual Tonle Sap Lake stage. Spring flooding from the melting Himalayan snows and increased rainfall throughout the upper Mekong catchment during the wet season causes a reversal of water flow in the Tonle Sap River. The reversal of water flow during the wet season causes the lake to fill and lake level to rise so more surface area within the Angkor Basin is inundated. This provides vital nutrients necessary for fisheries and rice production in the floodplain region of the Angkor Basin. When water level rises, the flooded forests are more saturated and spectral reflectance values for each individual pixel may appear to indicate open water, which are non-forested areas. When water level recedes or no water is present, then the same pixel may appear to be forested. These land-cover changes may be a simple consequence of this annual flooding pattern which alters the type of land-cover that is detected by the satellite. As a result, the regional influences on land-cover change in the floodplains contrasts to the more localized precipitation patterns and human influenced land-cover changes in the upland portion of the basin. Changes in one part of the system however will influence changes in the other and more investigation into the land-water relationship of the Tonle Sap floodplain coupled with household level management of paddy fields is necessary to completely understand the patterns and processes of land-cover change in this low-elevation, floodplain zone relative to the larger Angkor Basin.

Zone two represents the largest area in the basin (40.7%), and is comprised mostly of the paddy fields that dominate the region. Siem Reap town and the World Cultural Heritage Site of Angkor are also located within Zone two, which has received increasing tourism as economic progress and development continue at the national level. After accounting for the large percentage of land-cover that remained non-forested in this zone, the largest change is in the forest to non-forest trajectories (Table 2). However, the minimal re-growth from non-forested areas in 1989 and 1995 seem to be concentrated around Angkor Wat and might be a result of conservation efforts to maintain the grounds surrounding the tourist site.

Zone three experienced the most recent deforestation with ~37% of the land changing from forest to non-forest between 1995 and 2005. The area of land provides a transitional zone between traditional paddy fields in the low areas and the upland forests of Phnom Kulen. From 1995 to 2005, the area of transition (zone three) of forest to non-forest has noticeably decreased along the escarpment that leads to higher elevation areas in Phnom Kulen National Park. Field observations of extensive land clearing combined with quantitative results of forest-cover decline suggests a permanent conversion to bare land-cover rather than a rotation of fallow period and crop cultivation. As shown in other studies of the region, the increased deforestation may relate to agricultural expansion in conjunction with multi-scalar socio-economic shifts and physical environmental controls (Geist and Lambin, 2001; Fox and Vogler, 2005). Most of the land-cover change in this zone has happened since the 1992 declaration of the Angkor complex as a UNESCO World Heritage Site. Although the relationship between land-cover change in the Angkor Basin uplands and multi-scalar socio-economic trends must be explored further, a temporal correlation exists between initiatives taken to improve physical and social infrastructure within Cambodia and the landscape change in the basin uplands.

Zone four consists predominantly of forest, with more than 81% of the zone remaining forested (FFF) throughout the study period. The large transitions of forest to non-forest in Zone three come right up to the southern boundary of Zone four. These changes may have resulted from multiple drivers including selective logging (legal and illegal), shifting cultivation, and permanent clearing for agriculture. However, the more scattered changes of re-growth and deforestation at higher elevation are probably related to indigenous swidden cultivation practices rather than large-scale agricultural clearings. These shifting cultivation practices are typical of upland regions in Southeast Asia despite past directives and policies that attempt to control the amount of land used for shifting cultivation (Fox and Vogler, 2005).

The Angkor basin contains the entire Angkor protected landscape as well as parts of the Tonle Sap Multiple Use area and Phnom Kulen National Park. The re-establishment of protected area boundaries is relatively recent in Cambodia (1993) and is closely tied to population distribution, movement, and direction of growth. Most parks in Cambodia were created in more remote regions with low human population density. The notable exceptions were those parks created within Siem Reap Province. The same year the national park system was created, changes in national policies created easier avenues for international trade and investment in Cambodia. With these policy changes, forest concessions that comprised almost 6.4 million hectares or ~39% of the country were granted in the 1990s to international companies (ICEM, 2003). While none of the areas within park boundaries were conceded to concessionaires, illegal logging by concessionaires has been documented both within and outside protected areas (de Lopez, 2002; de Lopez, 2005). Within the Angkor Basin, deforestation is most concentrated in the upland area of Zone three (43–110 m). The elevated region (Zone four 111–469 m), which includes the interior portion of the national park has remained predominantly forested (81%) over the past sixteen years. This suggests that areas of higher elevation are less subject to deforestation than the lower areas of the Angkor Basin. These findings are similar to others that show the importance of topography, specifically elevation, as a biophysical control on forest-cover changes in tropical regions (Green and Sussman, 1990; Vagen, 2006).

However, despite the relation between forest-cover change and landscape position within the Angkor Basin, it is important to recognize land-cover changes are more complex than simple causation due to one variable (Geist and Lambin, 2002; Nagendra et al., 2003). Socio-economic factors such as population growth, government policy initiatives, and cultural practices are underlying factors that cause land-use/land-cover change and these factors play a prominent role in the ever changing landscape in the Angkor Basin. While further study is necessary into the socio-economic drivers that influence land-use/land-cover changes in the Angkor basin, the present study suggests different patterns on the landscape occur due to varying underlying climatic and anthropogenic influences for different areas of the basin. Understanding the dominant trends in land-cover change through the use of remote sensing provides spatially-explicit information that allows for the assessment of important environmental variables in the Angkor Basin (Kerr and Ostrovsky, 2003; Alpin, 2004). By determining the trajectories of land-cover change over space and time, the knowledge of a landscape's dynamics is strengthened.

## Conclusion

Results from this study provide a quantitative assessment of land-cover change in the Angkor Basin from 1989 to 2005. The division of the landscape into four elevation zones demonstrates the importance of landscape position on dynamic land-use and land-cover changes that have occurred over an important sixteen-year period in the history of Cambodia and

Southeast Asia. The most significant change was from forest to non-forest during the latter half of the study period (1995–2005). Forest to non-forest land-cover change occurred predominantly in zone three which is a transition zone between predominantly agricultural lands and protected upland forests. Complementing the change trajectory results for each elevation zone, principal components analysis identified important spatial and temporal changes in vegetation structure that visually correspond to changes mapped with the post-classification change detection method.

The complexity of landscape formation and change is shown through multiple change detection techniques (zonal analysis, PCA, NDVI) that suggest the importance of relations between biophysical and socio-economic influences on land-cover change. The upland forest decline in the Angkor basin provides an indication of extent and rate of human induced land-cover change. Floodplain dynamics are subject to more regional hydrological processes of the larger Mekong basin than by anthropogenic forces. Future research directions will investigate patterns and processes in each elevation zone and relate patterns of change to other known variables that drive land-cover change (e.g., accessibility to markets and roads, policy shifts, human population growth, etc). Given the geographical and historical complexities of the Angkor Basin, opportunities exist to further explore and identify underlying drivers of change.

Table 3-1. Confusion matrix detailing classification accuracy of forest (F) and non-forest (NF) land-cover in the Angkor Basin for the 2005 Landsat TM image. Producer's accuracy details omission errors – pixels omitted from the correct class. User's accuracy details commission errors – pixels committed to an incorrect class. The kappa statistic is a discrete multivariate technique that incorporates the off-diagonal elements in the error matrix (i.e. classification errors) in its accuracy assessment.

| Error Matrix | | | |
|---|---|---|---|
| Class | NF | Forest | Total |
| NF | 133 | 7 | 140 |
| Forest | 5 | 135 | 140 |
| Total | 138 | 142 | 280 |
| | | | |
| Producer's Accuracy | 96% | 95% | |
| User's Accuracy | 95% | 96% | |
| | | | |
| Overall Accuracy 96% | | | |
| Kappa Statistic 0.91 | | | |

Table 3-2. Land-cover change within elevation zones and overall change from 1989 – 1995 – 2005.

| % Area Change by Subset and Overall Change | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| | Zone one (< 9 m) | Zone two (10-42 m) | Zone Three (43-110 m) | Zone four (111-469 m) | Overall Change |
| % Total Basin Area | 29.50% | 40.70% | 20.10% | 9.70% | |
| | | | | | |
| FFF | 21.8% | 4.9% | 24.4% | 81.5% | 21.2% |
| NNN | 36.3% | 76.3% | 16.7% | 3.3% | 45.4% |
| FNN | 4.3% | 4.5% | 5.9% | 0.6% | 4.3% |
| FFN | 6.5% | 5.5% | 37.1% | 9.0% | 12.5% |
| NNF | 8.2% | 1.5% | 1.3% | 0.5% | 3.4% |
| NFF | 11.9% | 1.6% | 3.4% | 2.3% | 5.1% |
| FNF | 4.6% | 1.5% | 1.2% | 1.5% | 2.4% |
| NFN | 6.2% | 4.3% | 10.1% | 1.4% | 5.8% |

Table 3-3. Factor loadings and Eigenvalues (variance) for first four principal components of the three date (18 bands) multitemporal, multispectral PCA.

| Principal Component Matrix Loadings | | | | |
|---|---|---|---|---|
| | C1 | C2 | C3 | C4 |
| Eigenvalues | 9.55 | 2.09 | 1.18 | 0.939 |
| Variance % | 53.0 | 11.6 | 6.2 | 5.2 |
| Cumulative % | 53.0 | 64.7 | 70.8 | 76.0 |
| B1 2005 Blue | 0.782 | -0.195 | 0.153 | -0.141 |
| B2 2005 Green | 0.616 | -0.291 | 0.366 | -0.195 |
| B3 2005 Red | 0.049 | -0.457 | 0.609 | 0.366 |
| B4 2005 NIR | -0.160 | -0.404 | -0.353 | 0.710 |
| B5 2005 MIR | -0.287 | 0.440 | -0.157 | -0.211 |
| B6 2005 MIR | -0.453 | 0.353 | -0.366 | 0.095 |
| B7 1995 Blue | 0.915 | -0.017 | -0.151 | 0.044 |
| B8 1995 Green | 0.914 | -0.018 | -0.107 | 0.007 |
| B9 1995 Red | 0.699 | -0.218 | -0.021 | -0.141 |
| B10 1995 NIR | 0.328 | 0.728 | 0.288 | 0.287 |
| B11 1995 MIR | 0.907 | 0.175 | -0.034 | 0.151 |
| B12 1995 MIR | 0.925 | 0.098 | -0.069 | 0.118 |
| B13 1989 Blue | 0.934 | -0.015 | -0.117 | -0.044 |
| B14 1989 Green | 0.928 | -0.012 | -0.074 | -0.064 |
| B15 1989 Red | 0.945 | -0.040 | -0.097 | -0.050 |
| B16 1989 NIR | 0.047 | 0.775 | 0.363 | 0.154 |
| B17 1989 MIR | 0.894 | 0.217 | -0.060 | 0.106 |
| B18 1989 MIR | 0.931 | 0.112 | -0.094 | 0.071 |

Table 3-4. Correlation between Normalized Difference Vegetation Index (yrs: 1989, 1995, 2005) and PCA 1,2,3,&4. All correlations are significant at the 0.01 level.

| | PC 1 | PC 2 | PC 3 | PC 4 | NDVI05 | NDVI95 | NDVI89 |
|---|---|---|---|---|---|---|---|
| NDVI05 | -0.653 | 0.752 | -0.706 | -0.495 | | | |
| NDVI95 | -0.633 | 0.881 | -0.285 | -0.563 | 0.616 | | |
| NDVI89 | -0.712 | 0.873 | -0.219 | -0.569 | 0.610 | 0.865 | |

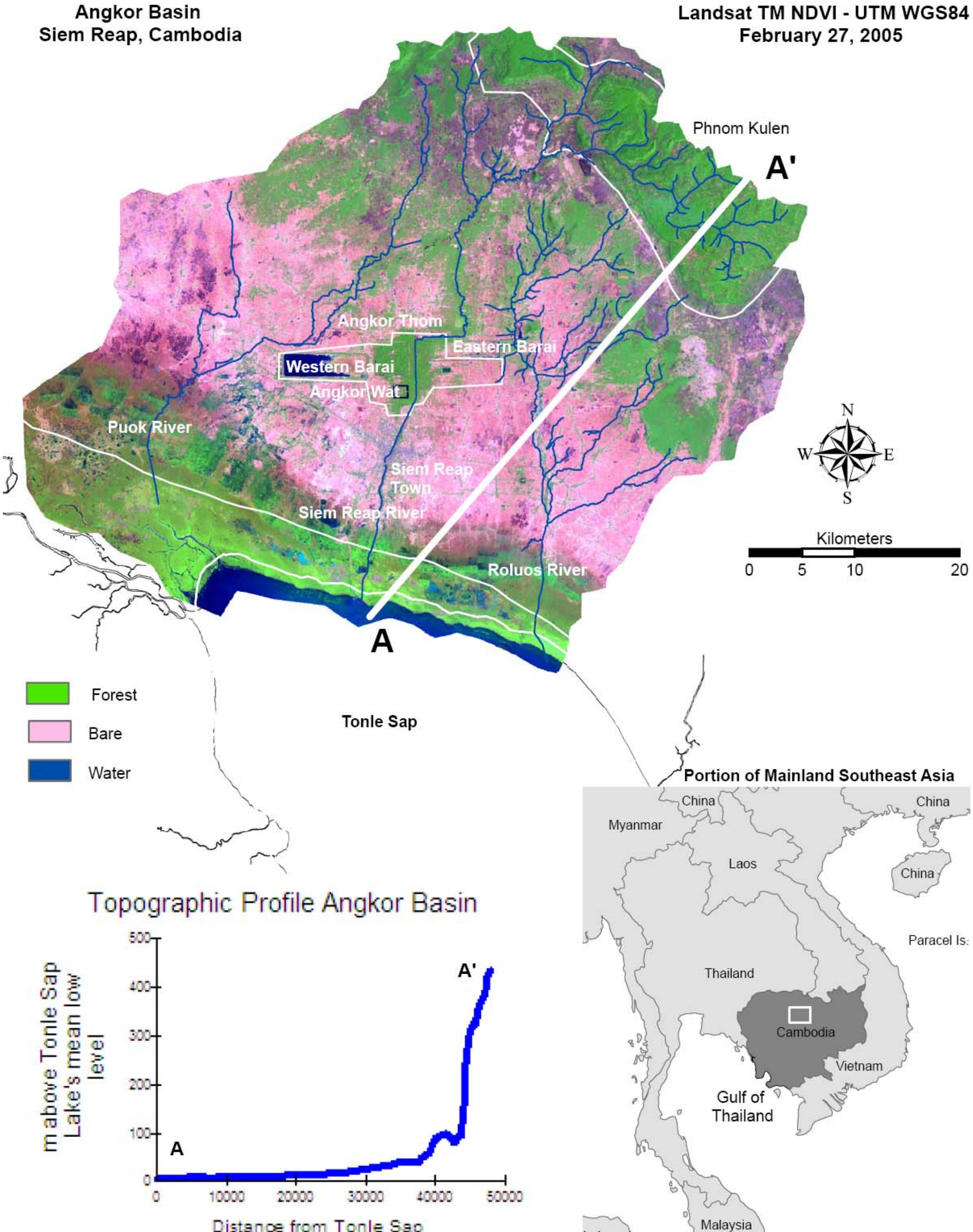


Figure 3-1. Study region of the Angkor basin in Siem Reap, Cambodia. Protected areas are delineated in white. Rivers are shown in blue.

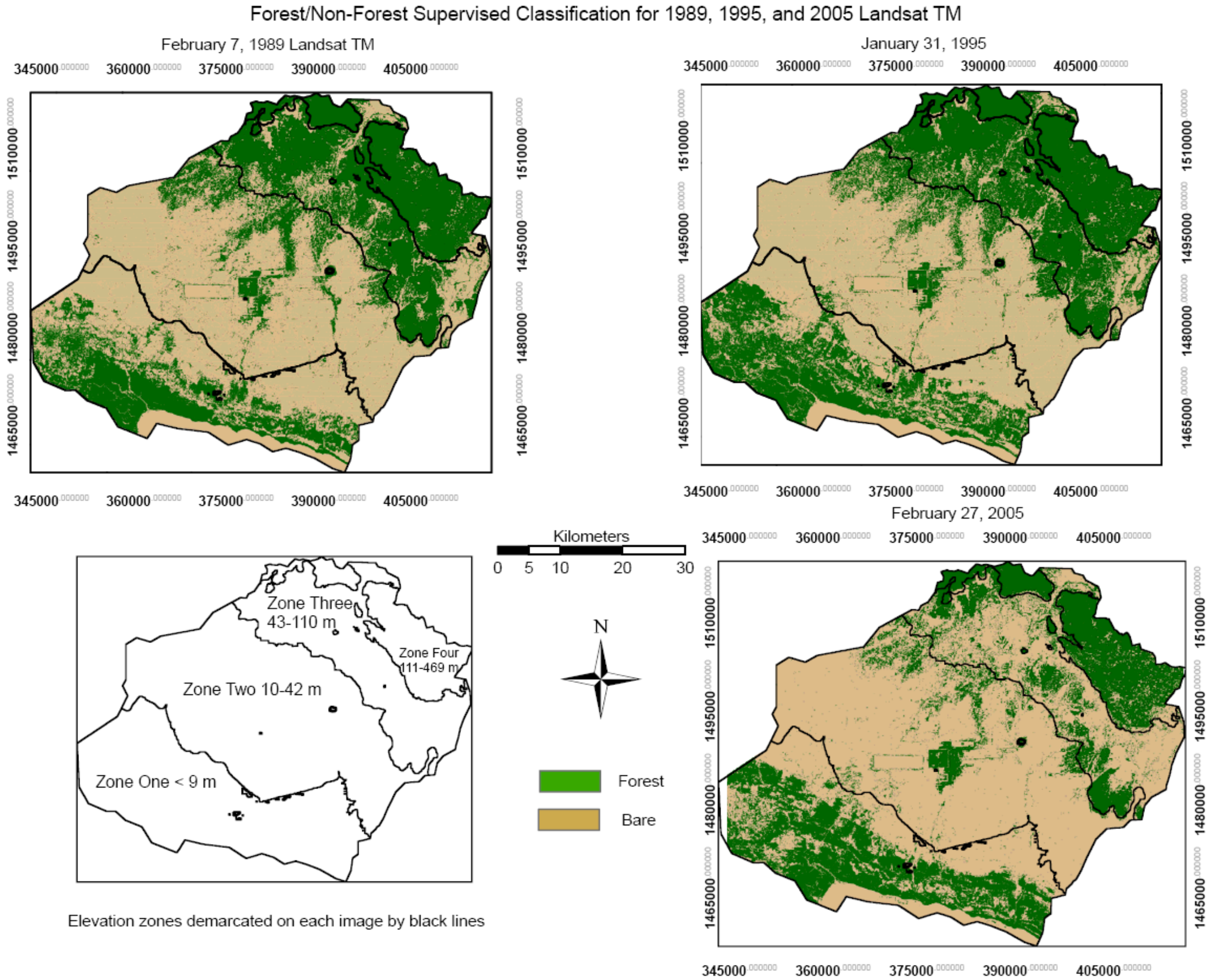


Figure 3-2. Land-Cover (forest/non-forest) for 1989, 1995, and 2005 respectively.

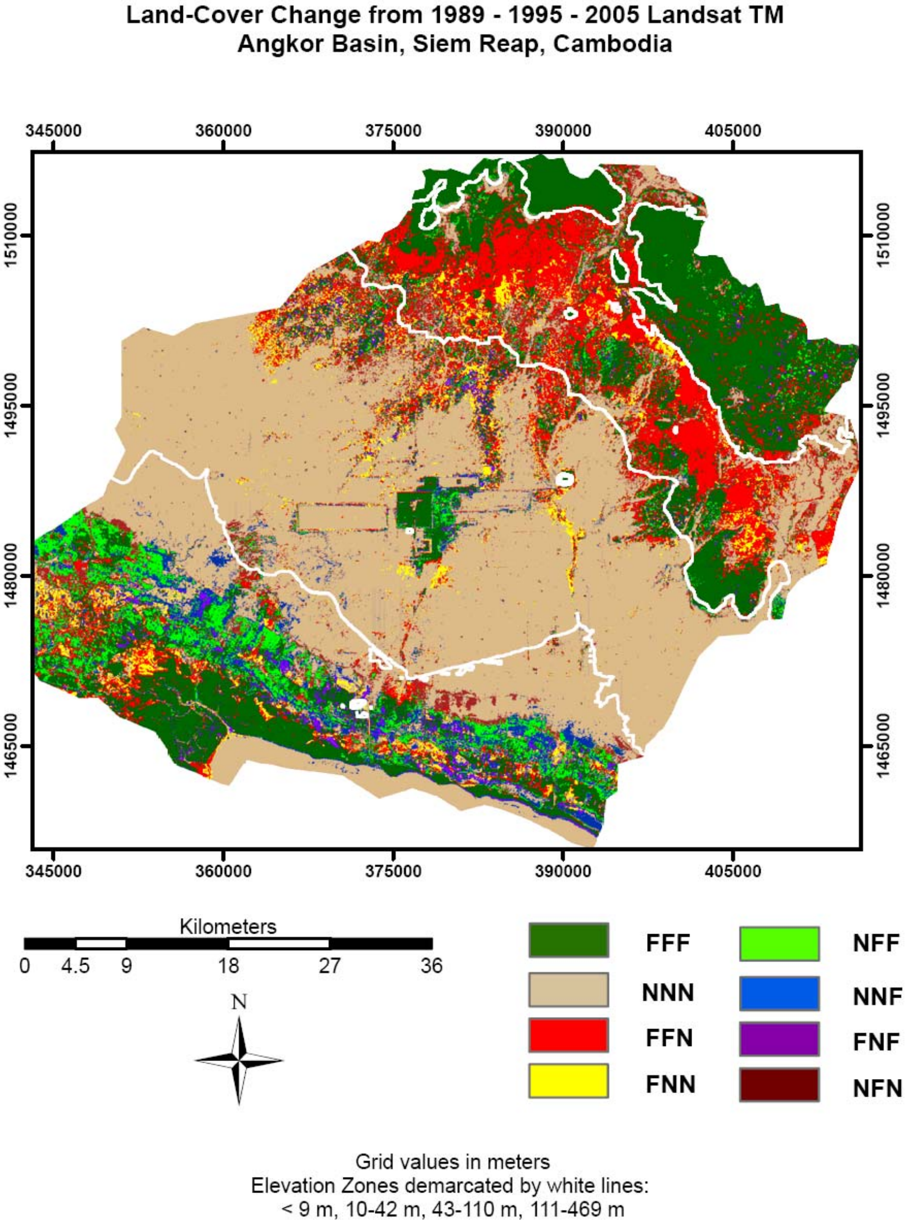


Figure 3-3. Overall change trajectory for 1989, 1995, and 2005. F means forest, N is non-forest, and the three-digit code is the sequence of land cover for each pixel. For example, FNF means forest in 1989, non-forest in 1995, and forest in 2005. Eight possible trajectories are displayed with the following percent of land-cover for each respective class: FFF (21.2%), FFN (12.5%), FNF (2.4%), FNN (4.3%), NFF (5.1%), NFN (5.8%), NNF (3.4%), and NNN (45.4%).

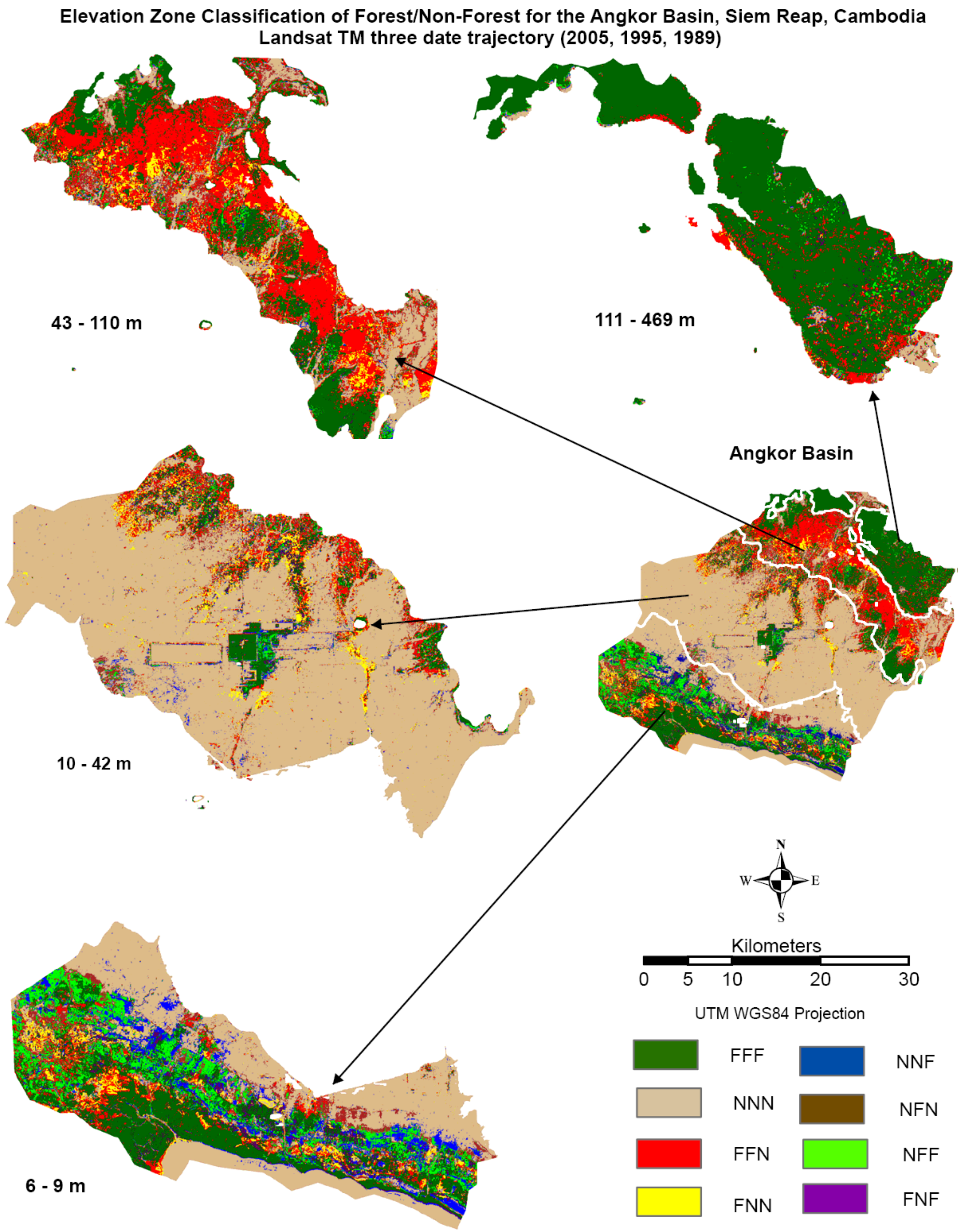


Figure 3-4. Four elevation zones representing distinct geographical areas within the basin.

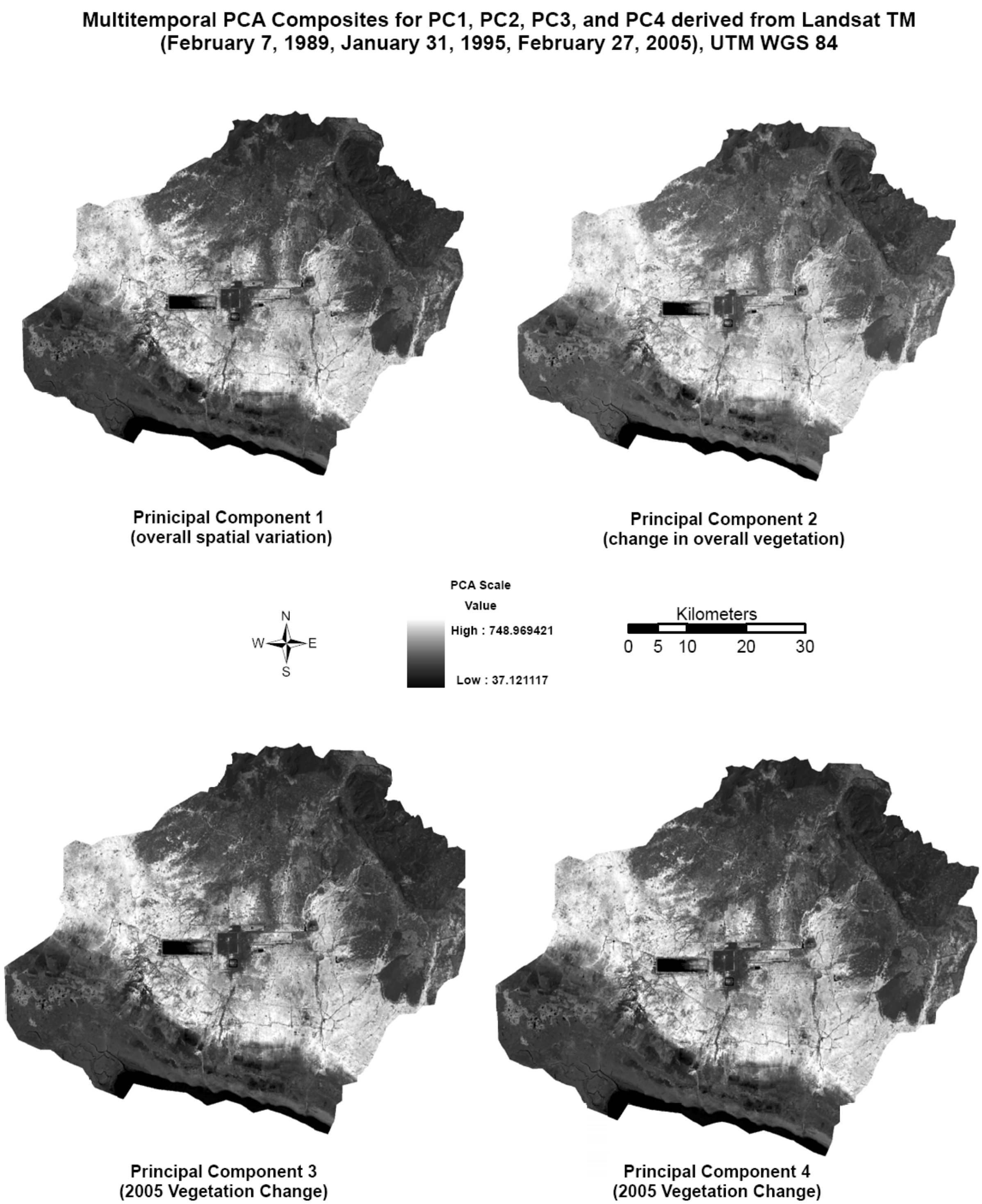


Figure 3-5. Multi-temporal Composites of PCA 1,2,3 and 4 Landsat TM images for 1989, 1995, and 2005.

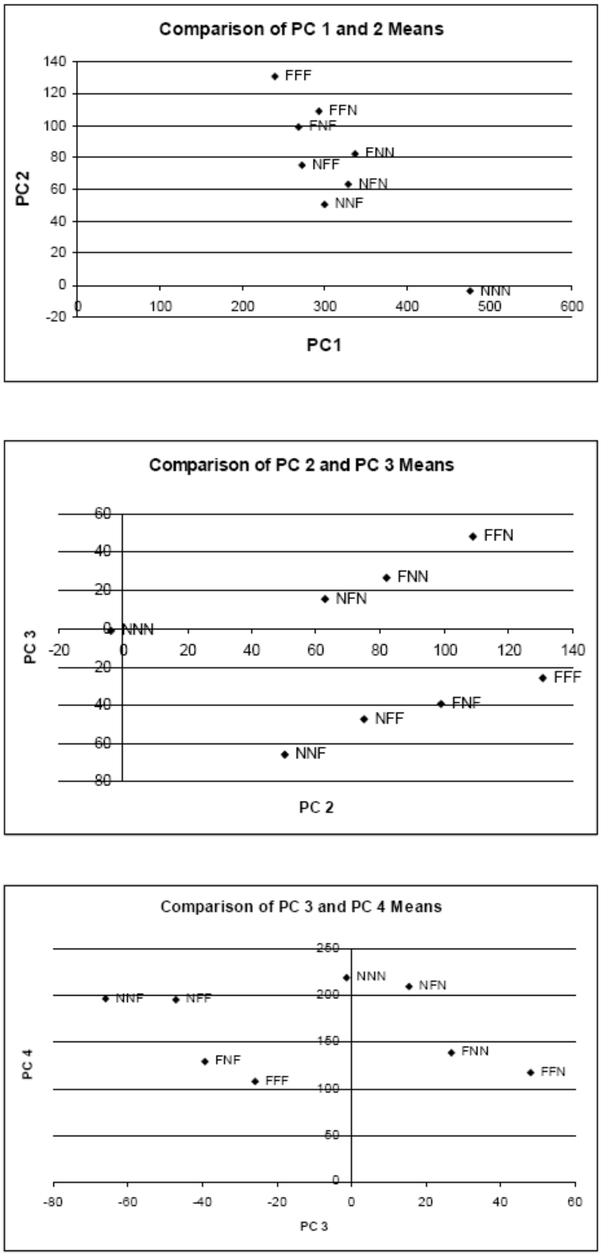


Figure 3-6. Relationship of mean PC scores to eight land-cover trajectories. A PC score represents the value of new uncorrelated variables (components) and represent the entities' location along each principal component axis. For each land-cover trajectory, the zonal analysis will calculate the mean value of all PC scores for a specific component that falls within that area. For example, within the FFF trajectory for PC 1, every pixel value that falls within the FFF trajectory will be averaged for a mean PC score for PC 1. The mean PC score indicates the relationship strength between each land-cover trajectory and a principal component. Graphs display three different combinations of PC Means for comparison purposes. The 95% confidence interval for each mean is very small. For example, in the FFF a count of 704,462 and a standard deviation of 35.04, the confidence interval is .08.

# CHAPTER 4
# SUMMARY AND CONCLUSIONS

This study of the Angkor basin in Siem Reap province, Cambodia provide a quantitative description of spatial and temporal land-cover change over a sixteen year period (1989-2005). I suggest that different biophysical and socio-economic factors influence land-cover change within the Angkor basin depending on landscape position and topography. The most significant land-cover changes in the basin are related to vegetation, especially upland and flooded forest patterns. The upland forest decline in the Angkor basin provides an indication of extent and rate of human induced land-cover change. The pattern of land-cover change in the floodplain area indicates much more complex vegetation dynamics are influenced also by anthropogenic forces but also are subject to more regional hydrological processes of the larger Mekong basin. Specifically, the regional monsoonal patterns that affect Southeast Asia play an influential role in the timing and distribution of pulses that flood Tonle Sap Lake each year. Years of high rainfall in the upper catchments of the Mekong Basin will cause flood levels in Tonle Sap Lake to be higher. Consequently, if attempting to monitor or analyze forest-cover change over time, changes detected through satellite imagery may be more indicative of seasonally fluctuating water levels than transformations of different land-covers. These biophysical factors play an important role in the land-use land-cover changes of the basin and detailed results for each paper are discussed.

In the first paper (Chapter 2), two questions were addressed regarding the land-cover change in the Angkor Basin. The first question asked how overall land cover changed throughout the entire basin from 1989 to 2005. To gain a complete picture of these changes, post-classification change analysis was combined with standardized NDVI change detection images to show varying patterns of land-cover change throughout the watershed. The most significant changes in the basin related to forest-cover dynamics but results of the two different techniques contrasted with one another in terms of temporal and spatial vegetation change. The forest class was thus separated into upland and flooded forest to create a more realistic pattern of land-cover change in the basin. The next research question related to the dynamics of vegetative-cover decline and re-growth in the basin. Results indicate that there has been a large increase in deforestation in the area between Angkor Wat and Phnom Kulen, with the highest percentage of forest decline since 2002. The acceleration of upland forest decline will have important socio-economic and hydrologic implications to the future health of the basin. During the same time period (2002–2005), the standardized NDVI results show a large increase in values which relate to the decreases in water level in the floodplain area and subsequent forest cover reflectance that is measured by the satellite. The differing results related to the different techniques used to assess land-cover change stresses the importance of multiple methods in detecting and identifying patterns of land-cover change.

The second paper (Chapter 3) builds from the initial findings by creating a dichotomous forest/non-forest classification to assess landscape position and topographic influences on land-cover change over the same time period (1989–2005). Similar to paper one, the overall changes of forest cover provided a good impression of general trends in the basin but a better understanding of the spatial and temporal dynamics of land-cover change is found by looking at separate areas of the basin as individual entities. Thus, by dividing the landscape into four elevation zones the importance of landscape position was enhanced relative to forest-cover change over the past sixteen years. Results identified more complex spatial and temporal land-cover changes for zone one (6–9 m), stability in non-forested lands for zone two (10–42), large decreases in forest cover within zone three (43–110 m), and a more stable forest cover in zone four (111–469). Complementing the change trajectory results for each elevation zone, principal components analysis identified important temporal changes in vegetation structure that visually correspond to changes mapped with the post-classification change detection method. Forest to non-forest change does not occur within the interior portions of Phnom Kulen National Park although a lot of forest to non-forest change seems to have occurred along the perimeter. The World Heritage Site of Angkor has retained its forests within temple walls and forest may have slightly increased along the eastern side. The multiple use area of Tonle Sap Lake is the least protected in term of human-use and displays the most complex landscape patterns due to seasonal changes in lake level fluctuations.

The results of this thesis identify the importance of landscape position and topography on land-cover changes in the Angkor basin. Overall changes reflect a dominant trend in deforestation in the area between Angkor Wat and Phnom Kulen and a more complex pattern of vegetation dynamics in the floodplain area. The proximate and underlying drivers that have caused the pattern of land-cover change have not been determined. However, given the geographical and historical complexities of the Angkor Basin, opportunities exist to further explore and identify these drivers of change. This thesis lays the groundwork for future research with the establishment of a quantitatively descriptive analysis of the Angkor basin through the use of multiple remote sensing change detection techniques.

## LIST OF REFERENCES

Achard, F., Eva, H.D., Stibig, H.J., Mayaux, P., Gallego, J., Richards, T., Malingreau, J.P., 2002. Determination of deforestation rates of the world's humid tropical forests. Science. 297, 999-1002.

Agrawal, A., Ostrom, E., 2001. Collective action, property rights, and decentralization in resource use in India and Nepal. Politics and Society. 29(4), 485-514.

Aplin, P., 2004. Remote sensing: land cover. Progress in Physical Geography. 28(2), 283-293.

Boyd, D.S., Foody, G.M., Curran, P.J., Lucas, R.M., Honzak, M., 1996. An assessment of radiance in Landsat TM middle and thermal infrared wavebands for the detection of tropical forest regeneration. International Journal of Remote Sensing. 17(2), 249-261.

Boyd, D.S., Danson, F.M., 2005. Satellite remote sensing of forest resources: three decades of research development. 29(1), 1-26.

Brandt, J.S., Townsend, P.A., 2006. Land use-land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. Landscape Ecology. 21, 607-623.

Bruner, A.G., Gullison, R.E., Rice, R.E., da Fonseca, G.A.B., 2001. Effectiveness of parks in protecting tropical biodiversity. Science. 291, 125-128.

Carr, D, L., 2004. Proximate population factors and deforestation in tropical agricultural frontiers. Population and Environment. 25(6), 585-612.

Castella, J., Manh, P.H., Kam, S.P., Villano, L., Tronche, N.R., 2005. Analysis of village accessibility and its impact on land use dynamics in a mountainous province of northern Vietnam. Applied Geography. 25, 308-326.

Chandler, D., 2000. A History of Cambodia. 3rd Ed. Westview Press. Oxford.

Child, B., 2004. Parks in transition: Biodiversity, Rural Development and the Bottom Line. London, England: Earthscan, pp 267.

Chowdury, R., 2006a. Landscape change in the Calakmul Biosphere Reserve, Mexico: Modeling the driving forces of smallholder deforestation in land parcels. Applied Geography. 26, 129-152.

Chowdhury, R., 2006b. Driving forces of tropical deforestation: The role of remote sensing and spatial models. Singapore Journal of Tropical Geography. 27, 82-101.

Coe, M., 2004. Angkor and the Khmer Civilization. Thames and Hudson. London.

Cunnane, C., 1978. Unbiased plotting positions – review. Journal of Hydrology. 37(3-4), 205-222.

DeFries, R.S., Hansen, M.C., Townshend, J.R.G., Janetos, A.C., Loveland, T.R., 2000. A new global 1-km dataset of percentage tree cover derived from remote sensing. Global Change Biology. 6, 247-254.

DeFries, R., Hansen, A., Newton, A.C., Hansen, M.C., 2005. Increasing isolation of protected areas in tropical forests over the past twenty years. Ecological Applications. 15(1), 19-26.

De Lopez, T.T., 2002. Natural resource exploitation in Cambodia: An examination of use, appropriation, and exclusion. Journal of Environment and Development. 11 (4), 355-379.

De Lopez, T. T., 2005. Resource degradation, property rights, social capital and community forestry in Cambodia. Cambodian Research Centre for Development, 35-44.

Etter, A. McAlpine, C., Wilson, K., Phinn, S., Possingham, H. 2006., Regional patterns of agricultural land use and deforestation in Columbia. Agriculture, Ecosystems and Environment. 114, 369-386.

Foley, J.A., DeFries, R., Asner, G., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use. Science. 309, 570-574.

Food and Agricultural Organization of the United Nations (FAO), 2005. Global forest resources assessment update 2005: Progress towards sustainable forest management. (FAO, Rome). FAO Forest Paper 147. Accessed at the following link: http://www.fao.org/docrep/008/a0400e/a0400e00.htm

Fox, J., Vogler, J.B., 2005. Land-use and land-cover change in montane mainland Southeast Asia. Environmental Management. 36 (3), 394-403.

Fujii, H., Garsdal, H., Ward, P., Ishii, M., Morishita, K., Boivin, T., 2003. Hydrological roles of the Cambodian floodplain of the Mekong River. International Journal of River Basin Management. 1 (3), 1-14.

Fujita, S.T.Y., Fox, J., 2005. Resource use dynamics and land-cover change in Ang Nhai village and Phou Phanang National Reserve Forest, Lao PDR. Environmental Management. 36(3), 382-393.

Fung, T., LeDrew, E., 1987. Application of Principal Components Analysis to Change Detection. Photogramm.Eng. Remote Sens. 53 (12), 1649-1658.

Gautam, A.P., Webb, E.L., Shivakoti, G.P., Zoebisch, M.A., 2003. Land use dynamics and landscape change pattern in a mountain watershed in Nepal. Agriculture, Ecosystem, and Environment. 99, 83-96.

Geist, H.J. Lambin, E.F., 2001. What Drives Tropical Deforestation? LUCC Report Series No.4. Louvain-la-Neuve, Belgium, LUCC International Project Office, University of Louvain.

Geist, H. J, Lambin, E.F., 2002. Proximate causes and underlying forces of tropical deforestation. BioScience. 52 (2), 143-150.

Giambelluca, T.W., 2002. Hydrology of altered tropical forest. Hydrological Processes. 16, 1665-1669.

Giri, C., Defourny, P., Shrestha, S., 2003. Land cover characterization and mapping of continental Southeast Asia using multi-resolution satellite sensor data. International Journal of Remote Sensing. 24(21), 4181-4196.

Gottesman, E., 2003. Cambodia After the Khmer Rouge: Inside the Politics of Nation Building. Yale University Press, New Haven & London.

Green, G.M., Sussman, R.W., 1990. Deforestation history of the Eastern rain forests of Madagascar from satellite images. Science. 248 (4952), 212-215.

Green, G.M., Schweik, C.M., Randolf, J.C., 2005. Retrieving land-cover change information from Landsat satellite images by minimizing other sources of reflectance variability. In Moran, E.F., and Ostrom, E. (Eds.), Seeing the Forest and the Trees: Human-Environment Interactions in Forest Ecosystems. MIT Press. Cambridge, MA. (151pp).

Guild, L.S., Cohen, W.B., and Kauffman, J.B., 2004. Detection of deforestation and land conversion in Rondonia, Brazil using change detection techniques. International Journal of Remote Sensing. 25(4), 731-750.

Hansen, M.C., DeFries, R.S., 2004. Detecting long-term global forest change using continuous fields of tree-cover maps from 8-km advanced very high resolution radiometer (AVHRR) data for the years 1982-99. Ecosystems. 7, 695-716**.**

Hirch, P., 2001. Globalization, regionalization and local voices: the Asian Development Bank and re-scaled politics of environment in the Mekong region. Singapore Journal of Tropical Geography. 22(3), 237-251.

Houghton, R.A., 1994. The worldwide extent of land-use change. BioScience. 44(5), 305-309.

International Center for Environmental Management (ICEM), 2003. Cambodia National Report on Protected Areas and Development. Review of Protected Areas and Development in the Lower Mekong River Region, Indooroopilly, Queensland, Australia. 148 pp.

Janssen, L.L.F., Jaarsma, M.N., Vanderlinden, E.T.M., 1990. Integrating topographic data with remote sensing for land cover classification. Photogram Engineering and Remote Sensing. 56 (11), 1503-1506.

Jensen, J.R., 2005. Introductory Digital Image Processing. Prentice Hall. Upper Saddle River, NJ, 471p.

Kerr, J.T., Ostrovsky, M., 2003. From space to species: ecological applications for remote sensing. TRENDS in Ecology and Evolution. 18(6), 299-305.

Kiernan, B., 2002. Introduction: Conflict in Cambodia, 1945-2002. Critical Asian Studies. 34(4), 483-495.

Kite, G., 2001. Modelling the Mekong: hydrological simulation for environmental impact studies. Journal of Hydrology. 253, 1-13.

Kummer, D.M, and Turner, B.L, II., 1994. The human causes of deforestation in Southeast Asia. BioScience. 44(5), 323-326.

Lambin, E.F., Geist, H.J., 2003. Regional differences in tropical deforestation. Environment. 45 (6), 22-36.

Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. Annual Review of Environmental Resources. 28, 205-241.

Lebel, L., Garden, P., Imamura, M., 2005. The politics of scale, position, and place in the governance of water resources in the Mekong region. Ecology and Society. 10 (2): 18 {online} URL: http://www.ecologyandsociety.org/vol10/iss2/art18/

Le Billon, P., 2000. The political ecology of transition in Cambodia 1989-1999: War, Peace, and Forest Exploitation. Development and Change. 31, 785-805.

Le Billon, P., 2002. Logging in muddy waters: The politics of forest exploitation in Cambodia. Critical Asian Studies. 34(4), 563-586.

Lepers, E., Lambin, E.F., Janetos, A.C., DeFries, R., Achard, F., Ramankutty, N., Scholes, R.J., 2005. A synthesis of information on rapid land-cover change for the period 1981-2000. 55(2), 115-124.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, Z., Yang, L., Merchant, J.W., 2000. Development of a global land cover characteristic database and IGBP Discover from 1km AVHRR data. International Journal of Remote Sensing. 21 (6-7), 1303-1330.

Lu, D. Mausel, P., Brondizio, E., Moran, E., 2004. Change detection techniques. International Journal of Remote Sensing. 25 (12), 2365-2407.

Mas, J.F., 1999. Monitoring land-cover changes: a comparison of change detection techniques. International Journal of Remote Sensing. 20 (1), 139-152.

McGarigal, K., Cushman, S., Stafford, S., 2000. Mulitivariate Statistics for Wildlife and Ecology Research. Springer Science and Business Media, Inc. New York. (57p.)

Mertens, B., Lambin, E.F., 2000. Land-cover-change trajectories in Southern Cameroon. Annals of the Association of American Geographers. 90(3), 467-494.

Moran, E.F., 2005. Human-environment interactions in forest ecosystems: an introduction.. In Moran, E.F., and Ostrom, E. (Eds.), Seeing the Forest and the Trees: Human-Environment Interactions in Forest Ecosystems. MIT Press. Cambridge, MA.

Nagendra, H., Southworth, J., Tucker, C., 2003. Accessibility as a determinant of landscape transformation in western Honduras: linking pattern and process. Landscape Ecology. 18, 141-158.

Nagendra, H., Tucker, C., Carlson, L., 2004. Monitoring parks through remote sensing: studies in Nepal and Honduras. Environmental Management. 34(5), 748-760.

Pattanayak, S.K., 2004. Valuing watershed services: concepts and empirics from Southeast Asia. Agriculture, Ecosystems, and Environment. 104, 171-184.

Redford, K.H., Sanderson, S.E., 2000. Extracting humans from nature. Conservation Biology. 14(5), 1362-1364.

Richards, J.A., 1984. Thematic mapping from multitemporal image data using the principal components transformation. Remote Sens. Environ. 16, 35-46.

Rindfuss, R.R., Walsh, S.J., Turner II, B.L., Fox, J. and Mishra, V., 2004 Developing a science of land change: challenges and methodological issues. In PNAS, 10(3): 13976–13981.

Sánchez-Azofeifa, G.A., Daily, G.C., Plaff, A.S.P., Busch, C., 2003. Integrity and isolation of Costa Rica's national parks and biological reserves: examining the dynamics of land-cover change. Biological Conservation. 109, 123-135.

Schwartzman, S., Napstad, D., Moreira, A., 2000. Arguing tropical forest conservation: people versus parks. Conservation Biology. 14(5), 1370-1374.

Schweik, C.M. Green, G.M., 1999. The use of spectral mixture analysis to study human incentives, actions, and environmental outcomes. Social Science Computer Review. 17(1), 40-63.

Skole, D., Tucker, C. 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978-1988. Science. 260(5116), 1905-1910.

Southworth, J., 2004. An assessment of Landsat TM band 6 thermal data for analysing land cover in tropical dry forest regions. International Journal of Remote Sensing. 25(4), 689-706.

Southworth, J., Munroe, D., Nagendra, H. 2004. Land cover change and landscape fragmentation – comparing the utility of continuous and discrete analyses for a western Honduras region. Agriculture, Ecosystems and Environment. 101, 185-205.

Southworth, J., Nagendra, H., Munroe, D.K., 2006. Introduction to the special issue: Are parks working? Exploring human-environment tradeoffs in protected area conservation. Applied Geography. 26, 87-95.

Stibig, H.J., Achard, F., Fritz, S., 2004. A new forest cover map of continental southeast Asia derived from SPOT-VEGETATION satellite imagery. Applied Vegetation Science. 7, 153-162.

Turner, B.L., II, Clark, W.C, Kates, R. W., Richards, J.F., Mathews, J.T., and Meyer, W.B. eds., 1990. The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years. Cambridge University Press, Cambridge.

Turner, B.L., Villar S.C., Foster D., Geoghegan J., Keys E., Klepeis P., Lawrence D., Mendoza P.M., Manson S., Ogneva-Himmelberger Y., Plotkin A.B., Salicrup D.P., Chowdhury R.R., Savitsky B., Schneider L., Schmook B., Vance C., 2001. Deforestation in the southern Yucatan peninsular region: an integrative approach. Forest Ecology and Management 154 (3), 353-370.

Turner, M.G., 1989. Landscape ecology: The effect of pattern on process. Annu. Rev. Ecol. Syst. 20, 171-197.

Varis, O., 2003. WUP-FIN Policy Model – Finding Ways to Economic Growth, Poverty Reduction and Sustainable Environment, WUP-FIN Socio-economic Studies on Tonle Sap 10, MRCS/WUP-FIN, Phnom Penh.

Vagen, T., 2006. Remote sensing of complex land use change trajectories – a case study from the highlands of Madagascar. Agriculture, Ecosystems, and Environment. 115, 219-228.

Varis, O., Keskinen, M., 2003. Socio-economic analysis of the Tonle Sap region, Cambodia: Building links and capacity for targeted poverty alleviation. Water Resources Development. 19 (2), 295-310.

Verburg, P.H., Overmars, Witte, N., 2004. Accessibility and land-use patterns at the forest fringe in the northeastern part of the Philippines. The Geographical Journal. 170 (3), 238-255.

Verburg, P.H., Overmars, K.P., Huigen, M.G.A., de Groot, W.T., Veldkamp, A., 2006. Analysis of the effects of land use change on protected areas in the Philippines. Applied Geography. 26, 153-173.

Walker, R., 2004. Theorizing land-cover and land-use change: the case of tropical deforestation. International Regional Science Review. 27(3), 247–270.

Wilson, K., Newton, A., Echeverria, C., Weston, C., Burgman, M., 2005. A vulnerability analysis of the temperate forests of south central Chile. Biological Conservation. 122, 9-21.

Wright, S.J., 2005. Tropical forests in a changing environment. TRENDS in Ecology and Evolution. 20(10), 553-560.

Xiuwan, C., 2002. Using remote sensing and GIS to analyse land cover change and its impacts on regional sustainable development. International Journal of Remote Sensing. 23 (1), 107-124.

Zhan, X., Sohlberg, R.A., Townshend, J.R.G., DiMiceli, C., Carroll, M.L., Eastman, J.C., Hansen, M.C., and DeFries, R.S., 2002. Detection of land cover changes using MODIS 250 m data. Remote Sensing of the Environment. 83, 336-350.

# BIOGRAPHICAL SKETCH

Andrea E. Gaughan was born in Dallas, TX, and grew up in Texas, Southern California, and Tennessee. In May of 2003, she received a Bachelor of Arts in English and a concentration in environmental studies from Furman University. During her time at Furman, Andrea also spent a term in Chile studying environmental and community health and another term in Hawaii researching effects of engine noise on behaviors of humpback whales. In the year between undergrad and graduate school, Andrea worked at the Newfound Marine Harbor Institute as an intern teaching coastal and nearshore ecology and also traveled in the South Pacific. Andrea began the M.S. in geography at the University of Florida in August of 2004 and completed the degree in December of 2006. She focused on land-use and land-cover change in a tropical watershed in Siem Reap, Cambodia.