USING REMOTE SENSING TO CREATE INDICATORS OF ECOSYSTEM VARIABILITY FOR A SEMI-ARID SAVANNA WATERSHED IN THE KAVANGO-ZAMBEZI REGION OF SOUTHERN AFRICA

By

NARCISA GABRIELA PRICOPE

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2011

© 2011 Narcisa Gabriela Pricope

To my parents, Margareta and Pavel Pricope, my brother, Paul Pricope, and my late grandmother, Marioara Gheorghe, who have always given me unconditional support and inspired me to pursue my dreams

ACKNOWLEDGMENTS

First of all, I would like to thank my committee members for their continued support and advice and for making this dissertation possible. My most sincere gratitude goes to my advisor, Dr. Michael Binford, whose guidance and support have helped me finalize this project and whose advice has always been, if not the most straightforward to interpret and apply, but definitely most enlightening as time went by. I would like to particularly thank Dr. Mark Brown, the Principal Investigator on the National Science Foundation (NSF) Adaptive Management Water, Wetlands, Watersheds (AMW3) Interdisciplinary Graduate Education Research Traineeship (IGERT) at University of Florida, for providing immensely more than my graduate funding for four years throughout graduate school: he has been (and will always remain) my mentor and the person who has taught me more about life and graduate school than anyone else. I would also like to extend a special thanks Dr. Jane Southworth for her support, advice, and inspiration through trying times. I would like to acknowledge Dr. Julie Silva's contribution to my academic development and thank her for being such an incredible adviser and friend and Dr. Abraham Goldman for kindly agreeing to step in and serve as a committee member in her stead. My gratitude also goes to my peers both in the Geography Department and especially the AMW3 IGERT group at University of Florida who have been a continued source of motivation and inspiration for me, as well as to Miss Carol Binello, Desiree Price and Julia Williams who always helped in the most necessary ways and in most critical times.

I would like to thank, once more, the NSF AMW3 IGERT (No. 0504422) program for funding for my entire graduate education at University of Florida. My research was also partially funded through an NSF Doctoral Dissertation Improvement Grant (No.

0824720). I would like to thank Dr. Brian Child for field work funding during the summer of 2007 and Dr. John All from Western Kentucky University for help during two field seasons in Namibia and Botswana. I would also like to thank Miss Dorothea Simpson, University of Namibia, for help during fieldwork and for being such a great friend. My thanks also go to the numerous colleagues, collaborators, and government officials in both Namibia and Botswana who have provided support and data, especially Mr. Dawie van Zyl (Coarse Resolution Imagery Database, South Africa), Dr. Lucas Rutina (Department of Wildlife and National Parks, Botswana), Mr. G. Mafoko (Department of Forestry and Range Resources, Botswana), Dr. Alex Verlinden (National Planning Commission, Namibia), Dr. Ben C W van der Waal (Venda University, South Africa), Dr. Susan Ringrose, Dr. Cornelius van der Post, Dr. Mike Murray-Hudson (Okavango Research Institute, Botswana), and many, many others in both Namibia and Botswana who have shown kindness when I knocked on their doors asking for data, advice, or input.

Last but not least, I would like to acknowledge my parents' and brother's unconditional love and support and thank them for believing in me when I didn't. My heartfelt gratitude also goes to Dr. E. Margaret Curtis who has been a friend, mother, and mentor to me throughout the years. Thank you to Miss Madeline Goodwin for being a great help and inspiration during busy months of teaching at Southern Oregon University. Finally, I would like to thank my ex-husband, Dr. John D. All, for continued emotional support and advice.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

USING REMOTE SENSING TO CREATE INDICATORS OF ECOSYSTEM VARIABILITY IN A SEMI-ARID SAVANNA WATERSHED IN THE KAVANGO-ZAMBEZI REGION OF SOUTHERN AFRICA

By

Narcisa Gabriela Pricope

December 2011

Chair: Dr. Michael W. Binford

Major: Geography

This dissertation addresses changes in land and resource availability occurring as a result of climate, water variability and changes in fire regimes in a semi-arid savanna region in Southern Africa. The research combines geospatial analyses of climatological and hydrologic data and various remotely-sensed datasets to create measures of ecosystem variability and adaptability to natural and anthropogenic changes in sensitive ecosystems. The study area is the Chobe River Basin (CRB), a watershed shared between Botswana and Namibia situated at the heart of one of the world's largest transfrontier conservation areas, where different land-use management strategies and economic policies affect both the ecosystem and the livelihoods support system differentially.

The southern African savanna is a highly variable environment and people have adapted to its harshness through the generations. However, in light of past and ongoing environmental changes, their ability to adapt may become threatened. By mapping and then analyzing the spatial and temporal variability of two important factors, namely flooding and fires, in conjunction with indices of vegetation health and productivity, the findings of this research can ultimately contribute to enhancing our understanding of local adaptation mechanisms to future environmental change. This is the first reconstruction of the spatial and temporal patterns of inundation for the last 25 years in the CRB, a transboundary basin with an unusual hydrologic regime and an important

water resource for both human and wildlife populations. In the context of increasing temperatures, decreasing precipitation trends and increasing frequencies and intensities of El Niño episodes in southern Africa (Boko et al., 2007), I also investigated changes in fire incidences and marked shifts in fire seasonality both within and outside of protected areas of central Kavango Zambezi Transfrontier Conservation Area (KAZA TFCA). These changes are likely to have a series of strong impacts on other components of fire regimes in semi-arid ecosystems that will, in turn, affect their ecology, structure, and function.

This dissertation contributes to the field of land use and land change science by proposing a novel spatial coincidence analysis framework for analyzing how the inter- and intra-annual extents of inundation and fire are correlated with both annual patterns of vegetation productivity and multi-date changes in vegetation productivity.

CHAPTER 1
INTRODUCTION

Outline and Scope of the Research

Southern Africa is often identified as potentially the world's most affected populated region by future climate change and variability, adding to the current problems of recurring droughts and crop failures, water scarcity issues, and high HIV infection rates. In particular, the savanna ecosystems throughout Southern Africa, on which millions of people depend for their livelihoods, are changing at a rapidly increasing rate. This dissertation addresses changes in land and resource availability occurring as a result of climate, water variability, and changes in fire regimes in a semi-arid savanna region in Southern Africa. The overarching research question of this dissertation is *how do different management regimes and environmental variability create different ecosystem responses in a semi-arid savanna of southern Africa?* The research combines geospatial analyses of climatological and hydrologic data and various remotely-sensed datasets to create measures of ecosystem variability and adaptability to natural and anthropogenic changes in sensitive ecosystems.

The study area for this dissertation is the Chobe River Basin (CRB), a watershed shared between Botswana and Namibia situated at the heart of one of the world's largest transfrontier conservation areas (the Kavango-Zambezi Transfrontier Conservation Area – KAZA), where different land-use management strategies and economic policies affect both the ecosystem and the livelihoods support system differentially (Figure 1-1). Because the local communities in both countries are predominantly resource-dependent or derive substantial benefits from ecotourism, changes in the health of the ecosystem would have detrimental effects for the human system. Thus, understanding underlying biophysical drivers of change by taking into account different management regimes in the two countries and establishing the relative importance of flooding and fire regimes in driving vegetation dynamics represents an important step in understanding landscape-level change at the regional level.

Chobe River is a key water resource for Botswana both currently and more so in the future for both domestic and irrigated agriculture, as well as for the subsistence communities of Eastern Namibia. The interest in designing this dissertation research project in its current form resulted primarily from key informant interviews with both locals and government officials in Botswana and Namibia during several field visits. These interviews mentioned changes in the extent of flooding, in the extent and timing of vegetation burning and, most visibly, in the vegetation structure particularly in floodplain areas, expressed as increased shrub encroachment. Also, relevant literature on southern Africa and climate change predictions indicate potentially decreasing annual precipitation values (Gaughan and Waylen, 2011) and subsequently decreases in river runoffs that might adversely affect both commercial and subsistence agricultural production, as well as other water resources-related and subsistence activities in the CRB system in the near future. I therefore created a research design that attempted to incorporate the main drivers of vegetation change in semi-arid savannas, namely water availability and natural and anthropogenic fires, into a set of papers that analyzed both drivers in detail and then used the data thus generated to understand how they might drive vegetation productivity dynamics through time in CRB.

Study Area

The Chobe River Basin is a mosaic of land-use and management units: subsistence communal lands predominantly utilized for livestock grazing (Chobe Enclave Community Trust, CECT) or agricultural lands (Salambala Conservancy), two differently-managed forest reserves (Chobe and Kasane Forest Reserves), three national parks (Chobe National Park in Botswana, and Mudumu and Mamili National Parks in Namibia), and an urbanizing area, the town of Kasane (Figure 1-1). Significant vegetation changes have occurred in this region over the last thirty years, possibly caused by significant increases in wildlife populations, decreases in rainfall and river inundation extent, and increasing human and cattle populations (Mosugelo et al., 2002; Skarpe et al., 2004; Rutina et al. 2005).

Location and general description of the landscape mosaic in Chobe River Basin (CRB). CRB is part of the Kalahari Desert, and is characterized by a relatively flat terrain with fairly low relief (Field, 1978). In the Chobe National Park region, elevations range only from 910 to 1050 m (Omphile and Powell, 2002), while for the rest of the study area from the range is approximately 830 to 980 m. CRB is located in the region of subtropical dry climates characterized by an alternating dry and wet season. Precipitation in the Chobe Basin is seasonal, influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), with the wet season occurring during the summer between November and April. The variability in precipitation patterns is also related to El Niño Southern Oscillation (ENSO) events (Nicholson et al., 2000; Wessels et al., 2004). Annual average rainfall is approximately 640 mm. The period from May to October represents the dry season, when the mean maximum and mean minimum monthly temperatures during October (hottest month) of 39 ◦C and 14 ◦C respectively are reached. The coldest month is July, with a mean max temperature of 30 ◦C and a mean min monthly temperature of 4 ◦C (Child and Von Richter, 1968; Barnes, 2001; Nelleman et al., 2002).

Chobe National Park (CNP), established in 1967, is the second largest park in Southern Africa with a total extent of 10,566 km^2 and has one of the largest elephant populations in Africa (over 120,000 individuals, CSO 2004). Significant vegetation degradation is occurring in the park, especially in the areas adjacent to the river where most wildlife is concentrated during the dry season. Work along the Chobe floodplain in the park indicates severe vegetation degradation: tree species loss and a shift in tree species composition from predominantly *Acacia nigrescens* to an overwhelming dominance by *Croton megalobotrys*, a fast-growing tree species (Wolf, 2008). While in 1965 nearly 47% of riparian trees were untouched by elephants or had few healed scars, there were no trees observed without elephant damage recently (Wolf, 2008). Mudumu NP (only partially included within the boundaries of CRB) and Mamili NP are much smaller by comparison and were established in the 1990s (Figure 1-1).

Chobe and Kasane Forest Reserves were established in the 1980s for the protection of economically-important tree species (*Baikea plurijuga* especially) and are currently managed by the Department of Forestry and Range Resources, Botswana. They are both separated from the park and adjacent land use units by an extensive network of firebreaks and are being actively managed for prevention of anthropogenic fires, usually originating from Zimbabwe (especially for Kasane Forest Reserve). Evidence of elephant damage abounds in both forest reserves, especially in areas originally cleared in the 1990s by a Zimbabwean logging company (personal observations through fieldwork, 2007 and 2009).

The communal lands (organized and managed as community-based organizations in Botswana and conservancies in Namibia) in both countries are primarily used for subsistence agriculture, cattle grazing, and photographic and hunting safaris. The predominant vegetation types in the communal lands along the Chobe River are *Acacia tortilis* woodlands along the river (actively being ring-barked or pushed-over by elephants), grasslands in the lower floodplain areas, and mixed woodlands of *Combretum eleagnoides, Lonchocarpus nelsii,* and *Acacia erioloba* on the higher-elevation ridges. Species such as *Dichrostachys cinerea*, *Terminalia seriscia*, *Combretum hereorense*, and *Acacia erioloba* actively encroach into grasslands and sparse woodlands especially in areas that maintain signs of recent overgrazing by cattle (abandoned corrals). Key informant interviews with locals have revealed growing concerns about the disruption of agriculture by increasing elephant numbers no longer constrained to the park boundaries, expansion of bush encroachment due to an increased emphasis on cattle grazing, and drought-induced risks. Salambala Conservancy for instance, the largest community-managed area in the Eastern Caprivi of Namibia, is one of Namibia's most biologically diverse areas despite significant decreases in wildlife numbers during the prolonged war of independence in Namibia (1968 to 1989).

Dissertation Structure

This dissertation consists of five chapters, with three of them structured as individual publishable papers (one in resubmission process, one accepted with minor revisions). The first chapter is an outline of this dissertation, clearly outlining the broader scope and implications of this research and the research questions and objectives of each of the following chapters. Paper one maps the intra- and inter-annual distribution of the flood pulse in CRB using coarse and moderate resolution satellite imagery and shows that there has been a decrease in the spatial extent of flooding through time. Paper two uses two distinct satellite-derived fire products to map the spatial distribution of fires in the protected areas of the five member countries of KAZA and shows that there has been a significant increase in fire incidence in the region during the last decade. Paper three proposes a spatial coincidence analysis that integrates the spatial and temporal distribution of inundation and fires generated in the first two papers into an analysis of vegetation productivity and changes through time.

Specifically, I ask the following research questions in each of the three papers in this dissertation:

Paper 1 research questions

(1) What is the intra-annual timing and spatial distribution of inundation in the CRB relative to the distribution of regional precipitation and discharge in the two main contributing rivers (the Zambezi and Kwando Rivers)?

(2) Has the spatial extent of flooding changed in the CRB over the last 30 years?

The specific research objectives addressed in paper one were to:

i. To map the intra-annual spatial distribution of the flood pulse in the CRB relative to runoff in the Zambezi and Kwando Rivers and regional precipitation;

ii. To reconstitute the inter-annual distribution of the flood pulse in CRB and create a flooding extent index (focusing primarily on the higher-resolution MODIS time-series data, so 2000 to 2010);

iii. To conduct a longitudinal (time-series) analysis of changes in the spatial extent of flooding in CRB.

Paper 2 research questions

(1) Do different fire management policies result in changes in the annual extent of burned area in protected areas (PA) in five countries of the Kavango Zambezi Transfrontier Conservation Area (KAZA)?

(2) Has the seasonality, extent and frequency of fires changed through time in a specific area of KAZA (the Caprivi Strip of Namibia and northern Botswana) with a mosaic of land uses given the two areas are actively managed in different ways, one to prevent fires (Botswana) and one with seasonal prescribed burns (Namibia)?

(3) What is the general trend in fire frequency and seasonality among the two neighboring countries with different fire policies and management and is there an increasing trend in fire occurrences irrespective of fire policies and management regimes?

The main objectives of paper two were to:

(i) To map the annual extent of burning in KAZA's core protected areas and to create a fire recurrence index (FRI) map for the last decade, showing the areas that burn most frequently.

(ii) To determine what the trend in fire occurrences is and whether a change in fire seasonality has taken place irrespective of expressed fire policies and management regimes in neighboring countries.

Paper 3 research questions

(1) What is the general state of Chobe watershed's vegetation productivity trajectory as measured by multi-temporal NDVI analyses from 1985 to 2010?

(2) How are the observed patterns of vegetation productivity in CRB linked to regional inundation pulses and interannual fire regimes?

The research objectives of paper three were to:

(i) To describe vegetation dynamics in CRB over 25 years in relation to general climatic conditions for the region by using mean-variance analysis, a form of graphical dynamical systems analysis previously used successfully in drylands ecosystems by Washington-Allen et al. (2008).

(ii) To determine how much of the variability in vegetation productivity during individual growing seasons is explained by a) variations in the annual flooding extent in CRB and b) variations in the total amount of area burned in the CRB during a year;

(iii) To supplement mean-variance analyses with an analysis of the spatial patterns of vegetation productivity in relation to two important drivers of change (flooding and fire) to provide an initial assessment of the relationship between these factors of change and spatial patterns of vegetation productivity and change.

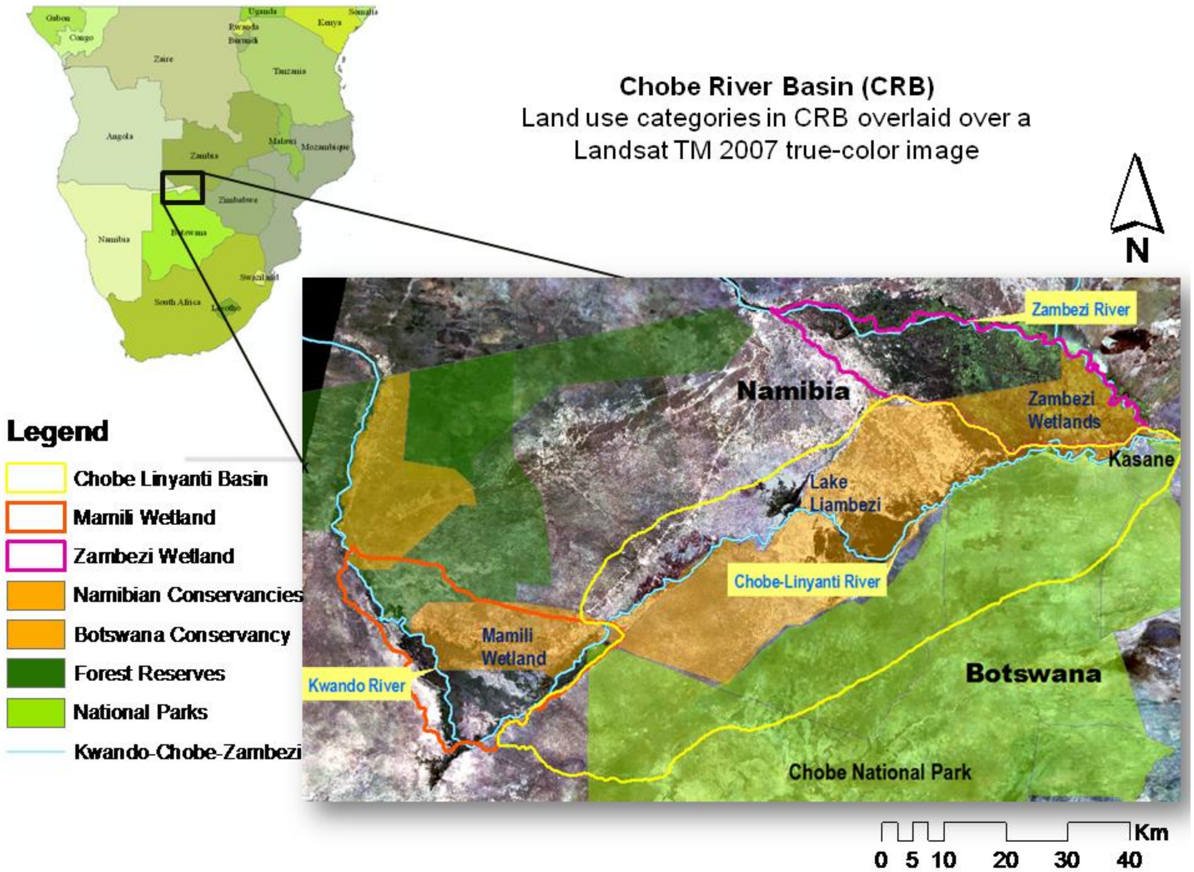


Figure 1-1 Location of the study area in southern Africa.

CHAPTER 2
VARIABLE-SOURCE FLOOD PULSING IN A SEMI-ARID TRANSBOUNDARY WATERSHED: THE CHOBE RIVER, BOTSWANA AND NAMIBIA

1. Flood Pulsing in Semi-Arid Environments

Wetlands and seasonally-inundated floodplains in semi-arid environments play major roles in the regional and global biogeochemical cycling of methane and carbon dioxide, habitat diversity, hydrologic cycles and their influence on human disease and livelihoods support systems through controls on fisheries productivity, water availability and flood recession agriculture (Prigent et al., 2007; Appleton et al., 2008). Wetlands and seasonally-inundated systems have historically been recharged during regular flooding events but their hydrology has been altered to various degrees by climatic variability and shifts in large-scale atmospheric circulation patterns, human control over natural rivers, or increasing demand for growing population centers (Jia and Luo, 2009). In semi-arid regions in particular, flooding regimes are increasingly influenced by climate change and variability, water regulations and water shortages, and increasing water demands from agricultural, industrial, and domestic uses. In water-scarce regions, analyses of the spatial extent and temporal pattern of flooding are important for understanding ecosystem processes and changes. Also, understanding past spatio-temporal changes in flooding regimes is critical in water resources management and for flood prediction and mitigation measures. However, long-term flood-inundation mapping in these regions is difficult due to the lack of historical flow data and of spatially-distributed ground data. Therefore, repetitive, synoptic, remotely-sensed data (usually of moderate or coarse resolution) are used to reconstruct the flooding regime. Understanding how the flooding regime in a semi-arid watershed adapted to seasonal flood pulses has changed through time can then enable us to understand the links with ecosystem-level changes and to make more informed management decisions to optimize allocation of a scarce resource among relatively conflicting uses.

While the interaction between precipitation, drought, fire, and grazing on arid environments has been the subject of considerable research, less is known about the impact of flooding, or the lack of flooding in flood-adapted ecosystems, and how it interacts with other factors in modifying vegetation structure and driving landscape dynamics (Westbrooke and Florentine, 2005). Westbrooke et al. (2005) have shown that flooding was the most important factor for determining changes in vegetation composition in an arid basin in Australia, while fire and grazing were of much less importance, as water availability directly affects rooting depth for grasses vs. shrubs. Ringrose et al. (2007) concluded that water-table lowering, driven by localized desiccation, and resulting in increased soil salinization lead to compositional and functional changes in trees and shrubs in the semi-distal areas of the Okavango Delta in Botswana. More specifically, the lowering of the water table below the effective root depth of trees and increasing salinization, lead to invasions by relatively shallower-rooted woody vegetation, which is also more brackish-water tolerant. Westbrooke and Florentine (2005) also showed that perennial grass and perennial shrubs are the most likely to be influenced by rare flooding events which means that water availability is a significant control in grassland to scrub transitions. This is because, as surface layers become drier, the density of shrub species increases and species are selected based on their ability to access water in deeper layers of the soil horizon.

Variations in water availability at different temporal and spatial scales in semi-arid ecosystems in terms of mean annual precipitation (MAP) variability, length of growing season, days between precipitation events, and number of precipitation events during the wet season are one of the most important drivers of ecosystem change (Snyder and Tartowski, 2006; Peters and Havstad, 2006). For flood-dependent ecosystems, soil moisture availability and extent of flooding are also important drivers of change in vegetation (Boulain et al., 2006). In semi-arid savannas characterized by a MAP value <650 mm, trees and grasses coexist as a result of water limitations on woody cover. While disturbances (fire and grazing) are able to modify tree-grass ratios, they are not required for coexistence of trees and grasses as opposed to savannas with an MAP >650 mm where disturbances are needed for coexistence (Sankaran et al., 2005). This might mean that future changes in precipitation and in flooding patterns for the flood-adapted ecosystems can have effects on savanna dynamics and, depending on the temporal scale of change, determine the nature of interaction between precipitation and disturbances.

To understand the dynamics of flood pulsing and the potential implications for ecosystem change, we need to consider the relationship between climate variability, long-term river runoff variations and flooding dynamics through time. While climate-change forecasts are mixed for the southern African region, some indicate a potential reduction in river runoffs associated with changing patterns of precipitation and increasing temperatures (Boko et al., 2007). This might mean that allocating water between ecological flows and economic and domestic uses will become increasingly challenging, especially for watersheds with limited historical flow data. Such a watershed is where we focused our analysis on. The Chobe River Basin (CRB) is a basin shared between Namibia and Botswana, situated at the heart of one of Southern

Africa’s largest transfrontier conservation areas: the Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA), an ongoing joint multilateral effort of several southern African countries towards resource co-management and wildlife habitat conservation.

Climatically, Nicholson et al. 2000 have shown that, while before the 1960s rainfall was above the long-term mean in much of Africa, southern Africa experienced negative anomalies in the order of 10 to 20%. These rainfall deficits continued through the 1970s and 1980s and well into the 1990s when rainfall in southern Africa remained below the long-term mean (Nicholson et al, 2000; Nicholson 2001). Work by Wessels et al. (2004) in South Africa, also found that rainfall for the late 1980s was below the 50-year average, while oscillations between wet and dry years starting with the early 1990s have become more extreme under the influence of stronger El Niño or La Niña years. They also found that for Southern Africa, 1991-1992, 1994-1995, and 1997-1998 have been the driest El Niño seasons, while 1999-2000 and 1995-1996 the wettest seasons, with the 2001-2002 and 2003-2004 growth seasons being the driest. Studies which link long-term climate variability to river runoffs and seasonal inundation extents for this region of Africa have been scarce and we include analyses of long-term discharge and precipitation data to understand what the overall trends in these data have been for the last three decades.

Monitoring surface water resources using satellite imagery is an increasingly important tool for prediction of floods and droughts (Alsdorf and Lettenmaier, 2003). For instance, Landsat imagery has been used extensively to measure areas inundated by flood-waters (Smith, 1997; Domenikiotis et al., 2003; McCarthy et al., 2003). Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging

Sprectroradiometer (MODIS) time-series vegetation indices data were used successfully in previous studies for mapping flooding and extents of inundation (Bryant, 1999; Bryant, 2003; All and Yool, 2004; Brown et al., 2006; Chipman and Lillesand, 2007; Sakamoto et al., 2007; Wang and D'Sa, 2010). The delineation of flooded areas using vegetation indices as a proxy for the amount of green vegetation depends on the type of vegetation, canopy cover percentages, soil type, time interval after the event, and the spatial extent of the area affected (Domenikiotis et al., 2003). Vegetation indices represent a continuous variable related to productivity of land cover or vegetation biomass, which varies both in space and time, and have a very distinct spectral signature for water as opposed to land (Domenikiotis et al., 2003). Of the multitude of multi-spectral vegetation remote sensing-based indices that have been developed, the Normalized Difference Vegetation Index (NDVI) is the most widely used (Teillet et al., 1997); however, it is sensitive to atmospheric aerosols and soil background.

Others working in estuarine wetlands for example, have found the Enhanced Vegetation Index (EVI) to be more suitable because it provides better results than the NDVI when the humidity and soil moisture are high (Sakamoto et al., 2007). EVI is calculated using the red, near-infrared, and blue reflectance values of MODIS bands 1, 2 and 3, respectively, and uses a gain factor and a canopy background adjustment factor, as well as two coefficients of aerosol resistance that employ the blue band to correct aerosol influences in the red band (Liu and Huete, 1995; Yan et al., 2010). The EVI is more sensitive in dense vegetation types such as forests and agricultural areas and usually reduces the noise effects of canopy background and atmospheric aerosols

(Justice et al., 1998). Sakamoto et al. 2007 have employed the MODIS EVI product to determine temporal changes in annual flooding extent in the Mekong Delta and have shown that the spatial extent of flooding determined from the satellite data is in excellent agreement with water-level data recorded at hydrologic stations on the ground. The main drawback to such datasets (AVHRR and MODIS) however is their low spatial resolution, but their high temporal frequency of global coverage, high repetivity, wide swath, and low cost compensate for the low spatial resolution (McCarthy et al., 2003; Jain et al., 2006).

Chobe River is, in most stream classification systems in the region, considered a tributary of the Zambezi River but in reality it has a most unusual flow regime consisting of variable flood pulses at different times of the year from rivers with headwaters in the tropical regions of Angola and Zambia, namely the Kwando and Zambezi Rivers. Little is understood in this system about the spatial and temporal dynamics of inundation as it has never been studied from this perspective before. This paper addresses two interrelated research questions:

(1) What is the intra-annual timing and spatial distribution of inundation in the CRB relative to the distribution of regional precipitation and discharge in the two main contributing rivers (the Zambezi and Kwando Rivers)?

(2) Has the spatial extent of flooding changed in the CRB over the last 30 years?

We hypothesized that there has been a decrease in the spatial flooding extent, and more generally a change in the timing and frequency of flooding in the CRB system in the last thirty years. This hypothesis was tested using remote sensing techniques to determine flooded vs. non-flooded areas and hydrologic and climatologic records to compare to the time-series remote sensing analysis. If this hypothesis was supported, we expected the time-series analysis using bimonthly 1985-2000 AVHRR and 2000-

2010 MODIS vegetation indices data to indicate a bimonthly and seasonal reduction in the extent of flooding, expressed in the ratio of water to land pixels in every image for the basin. As such, the specific research objectives addressed in this paper are:

(i) To map the intra-annual spatial distribution of the flood pulse in the CRB relative to runoff in the Zambezi and Kwando Rivers and regional precipitation;

(ii) To reconstitute the inter-annual distribution of the flood pulse in CRB and create a flooding extent index (focusing primarily on the higher-resolution MODIS time-series data, so 2000 to 2010);

(iii) To conduct a longitudinal (time-series) analysis of changes in the spatial extent of flooding in CRB.

2. Data and Methods

2.1 Study Area

In order to examine changes in the extent of flooding in CRB and get a thorough understanding of the variable surface water contributions from the spatially adjacent Kwando and Zambezi rivers, CRB was divided into three distinct sub-systems: Mamili Wetland, the Chobe-Linyanti system and Zambezi Wetlands (Figure 2-1). The CRB is a mosaic of land-use and management units: subsistence communal lands predominantly utilized for livestock grazing or agricultural lands, differently-managed forest reserves in both countries, a national park (Chobe National Park), and an increasingly urbanizing area, the town of Kasane. Significant ecological and vegetation changes have occurred in this region in the last thirty years, possibly caused by significant increases in wildlife populations, decreases in rainfall and river inundation extent, and increasing population and utilization by cattle (Mosugelo et al., 2002; Skarpe et al., 2004; Rutina et al. 2005).

The most important source in terms of the amount of water is the Zambezi River which pushes various amounts of water back into the Chobe, depending on its discharge and to a smaller degree on regional precipitation. During a secondary flood pulse, CRB receives water through sporadic connections from Lake Liambezi and the Lynianti channel, which are directly fed by flood waters from the Kwando River making their way into Mamili Wetlands. This secondary, dry-season flood pulse is due to the different flow regime of the Kwando River, whose discharge peaks in June-July, as opposed to March-April as is the case for the Zambezi River (Figure 2-2). Once the peak discharge in the main trunk of the Zambezi begins to recede, and depending also on the amount of water being pushed forward from the Kwando through the Linyanti channel and Lake Liambezi into CRB, the Chobe then flows forward into the Zambezi, becoming a tributary. Other sources of water inflow into CRB are represented by surface and groundwater connections with the Zambezi River across the Caprivi Strip through the Zambezi Wetlands and by variable contributions from local and regional precipitation, primarily during the wettest months from December to February (Figure 2-3). Very infrequently and only during years of high flooding such as 2009 and 2010, the CRB receives small amounts of inflow from the Kavango River and Okavango Delta through an ephemeral channel called the Selinda Spillway. This unusual flow regime, which has never before been studied in detail, is mainly the result of geo-tectonic modifications through time and is currently reinforced by the presence of relatively active fault lines in the region, such as the Linyanti Fault which is the main geologic control for the present-day location of the Chobe-Linyanti channel (Gumbricht et al., 2001).

The contributions and timing of inflow into CRB from these different sources are variable in both time and space and have never been studied in any detail, therefore the understanding of the annual flow and flood pulsing regime of the Chobe system is relatively poor. The annual flood pulse in the Chobe River is one of the major factors characterizing the regional ecosystem and human activities in the region. Chobe River is economically and ecologically important to both Namibia and Botswana and is especially important for the KAZA region as it provides critical habitat for various migratory wildlife populations, in particular the largest elephant population in Africa – over 200,000 elephants (DWNP, 2006) – centered around Chobe National Park. Given the fact that 94% of Botswana's water resources have their headwaters in other southern African countries (Turton, 1999), and that the flow of Chobe River is largely regulated by back-flooding from the Zambezi River and seasonal contributions from the Kwando River to the north-west, establishing the flooding regime of the Chobe River for the last thirty years is of significance to water-resources and land-resources managers, especially given new developments in irrigated agriculture proposed by Botswana and the crucial importance of this water source to both wildlife and human populations in both riverine countries.

2.2 Data Sources

We used a combination of varying-spatial and temporal resolution remotely-sensed datasets, such as AVHRR, MODIS, and Landsat ETM+, ground data from several field seasons in the region, and ground and satellite climatologic and hydrologic datasets to understand the timing and dynamics of flooding in the Chobe River Basin (Table 2-1).

2.2.1 AVHRR and MODIS time-series vegetation indices

The AVHRR instrument aboard the polar-orbiting environmental satellites maintained by the US National Oceanographic and Atmospheric Administration (NOAA) has a spatial resolution of 1.1 km at nadir and temporal coverage of twenty years, from

1984 to 2004, for this region. A continuous series of 623 AVHRR high-resolution picture transmission (HRTP) images were acquired in atmospherically and spectrally calibrated maximum value composite (MVC) 10-day normalized difference vegetation index (NDVI) form from the archive of the Coarse Resolution Imagery Database (CRID) of the Institute for Soil, Climate and Water, Agricultural Research Council of South Africa. AVHRR vegetation indices, particularly NDVI, data has been used successfully in previous studies to determine the extent of inundation at various geographic scales (Birkett, 2000; Prigent et al., 2007).

The MODIS instrument is part of a five-sensor suite on board the Terra satellite, operated by the US National Aeronautic and Space Administration (NASA). Terra was launched in December 1999, and thus the first MODIS image available for the region is for February 2000. The MODIS VI (Vegetation Indices) 250-m spatial resolution data (MOD13Q1A) were acquired from USGS's Land Processes Distributed Active Archive Center (LP DAAC) and reprojected to the Universal Transverse Mercator (UTM), WGS84 coordinate system using nearest neighbor resampling. The MOD13Q1A product is a composite of eight layers including NDVI, Enhanced Vegetation Index (EVI), and reflectance in the red, near-infrared, and blue wavelengths.

2.2.2 Multispectral and multitemporal Landsat ETM+ data

To test the accuracy of the flooding extent index calculated based on AVHRR and MODIS imagery, a set of higher-resolution images collected by Landsat-7 satellite's Enhanced Thematic Mapper Plus (ETM+) multispectral scanner were also acquired for April/May 1986, 1990, 1996, 2002, 2003, 2004, 2007, 2009 and one for August 2001. We chose the months April and/or May because they represent the beginning of the dry season when vegetation has not reached full senescence yet and are also generally cloud-free months. The data were acquired from a variety of sources, including the USGS Earth Explorer, University of Maryland Global Land Cover Facility, and the Council for Scientific and Industrial Research, South Africa. The nominal spatial resolution of ETM+ is 30 m and the Landsat scenes were acquired as close as possible or on the same date as some images from the AVHRR and MODIS continuous series.

2.2.3 Climatologic data for the region: Multivariate ENSO Index, TRMM and station data

Climatologic and hydrologic data were acquired from the government agencies in charge from both Namibia and Botswana and from other available sources and were used as a secondary means of data validation for the remote sensing analysis. In order to gain an initial understanding of the dynamics of dry and wet years for the southern African region in relation to larger-scale sea-land teleconnections, we used the Multivariate ENSO Index for the period 1950 to 2010. MEI is calculated based on six major variables measures over the Tropical Pacific Ocean: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky (Wolter, 1987; Wolter and Timlin, 1998).

Mean monthly and annual total precipitation data between 1945 and 2008 for several stations, including Kasane meteorological station, in the basin were obtained from the Department of Meteorological Services Botswana. Secondly, monthly averages of rainfall calculated from daily rainfall values for the basin were obtained from the Tropical Rainfall Measuring Mission (TRMM) 3B43 for the period between January 1998, when the mission started, and May 2009 (Figure 2-3). TRMM data has been used successfully in previous studies and has been shown to perform well for these latitudes, comparing well with measured rainfall stations throughout the region (Huffman et al., 1997; Kummerow et al., 2000; Nicholson et al., 2003).

2.2. 4 Hydrologic and stage data: monthly-averaged discharge and water level data on the Zambezi River and ENVISAT Altimeter stage data for the Chobe River at Kasane

Mean, maximum, and minimum monthly discharge data for the Zambezi River at Katima Mulilo and the Kwando River at Kongola between 1965 and 2009 were obtained from the Department of Water Affairs, Namibia, while the same type of hydrologic measurements for the Chobe and Kwando Rivers were obtained for 1978 to 2008 from the Department of Water Affairs, Botswana. The data for the Kwando were, however, very unreliable and scattered and were therefore impossible to use in the analysis. Finally, average monthly stage data (water level measured relative to bank elevations) for a representative Chobe reach upstream from the confluence with the Zambezi River were retrieved from the European Space Agency's ENVISAT Radar Altimeter for the period of operation from 2002 to 2009.

2.2.5 Training samples collected throughout CRB during field visits in 2007 and 2009

Training samples were collected using the standardized CIPEC training sample protocol, customized for semi-arid environments (CIPEC, 2005). The field data collection includes data such as: geolocation, topography, land-use and land cover type, amount of disturbance, presence of wild/domestic animals, vegetation structure estimates (dominant and secondary species, percent canopy closure, percent ground cover, species diameter at breast height and height), presence of managed species, land use history, multidirectional photographs, and other site-specific information. We used a randomly stratified data collection approach and gathered a total of 129 permanent water and/or seasonally-inundated samples from both field visits.

2.3 Data Analysis Methods

We investigated how regional precipitation and discharge are mechanistically related to the spatial extent and timing of flooding and how the connection between the Zambezi, Chobe, and the Kwando River through the Linyanti Swamp affects the spatial extent of flooding in the Chobe floodplain. The end objective was the creation of a 30-year time series of inundation in the CRB.

2.3.1 Chobe River Basin delineation

To begin examining changes in the extent of flooding of the Chobe River basin and adjacent Mamili Wetland and Zambezi Wetland through time, the first step was delineating the catchment area of the Chobe-Linyanti system. Typical hydrological-GIS tools for delineating drainage areas are not effective in semi-arid regions with low topographic gradients and underlain by porous sandy substrates. Moreover, the lack of an accepted hydrologic definition for the Chobe basin and the poor understanding of the region’s surficial hydrology complicated the process of basin delineation. We digitized the drainage area of the Chobe-Linyanti system, as well as the Mamili and Zambezi Wetlands, on screen with visual analysis and based on a 10-m spatial resolution DEM, 1-m spatial resolution orthophotographs for 2007, a set of AVHRR NDVI and MODIS EVI images for various months of the year, permanent water training samples collected during 2007 and 2009, and various other hydrologic geospatial datasets for the larger Zambezi watershed. Other ancillary datasets such as NASA/GSFC MODIS Rapid Response images for the 2004 floods and UNOSAT imagery provided by the Department of Water Affairs in Namibia for the 2009 floods in the Zambezi Basin were also used for reference in the drainage delineation process. To better understand the surficial hydrology and connectivity within Chobe watershed and better quantify the change in flooding extent through time, we included the Zambezi West Wetland (hereafter referred to as Zambezi Wetland), and the Mamili Wetland, directly fed by the Zambezi and Kwando River respectively in the Caprivi Strip of Namibia.

2.3.2 Identification of flooding extents from Landsat ETM+ data and ground data

We tested several methods for deriving inundation extents from Landsat imagery and decided on the use of two main methods: (a) supervised classifications using training sample data and (b) a normalized difference water index (NDWI) (Rogers and Kearny, 2004). First, the Landsat scenes used for this analysis underwent a set of standard pre-processing operations, including atmospheric calibration, geometric correction and reprojection, and image mosaicking as the study area extends over more than one single path and row.

(1) We created a series of supervised classifications to extract the water extent for CRB based on a combination of visible, near-infrared and shortwave-infrared bands. The accuracy testing was performed based on ground data collected during May-July 2007 and May-August 2009 (129 water training samples total). The overall classification accuracy was higher for the April 2009 mosaic (93%, with a kappa value of 0.82) because we had more training samples than for the May 2007 mosaic (89%, with a kappa value of 0.74). Signatures from the 2009 classification were then applied back in time to all the other dates, except for 2007. The spatial extent of inundation thus obtained from the supervised classifications on Landsat data was then compared to the corresponding dates/months of the AVHRR/MODIS-derived inundation (see section 2.3.3) and a per-image regression coefficient was calculated for each image pair (Table 2-2).

(2) Secondly, we calculated an NDWI for each Landsat image: [(RED – SWIR)/(RED + SWIR)], where RED is the surface reflectance value (0.63–0.69 μm, ETM+ Band 3) and SWIR is the short-wave infrared band (1.55–1.75 μm, ETM+ Band 5). Water pixels were reclassified where NDWI was greater than or equal to 0.8, as shown in the literature (Rogers and Kearny, 2004; Sakamoto et al., 2007). We used the NDWI to compare to the supervised classifications and the agreement was generally high, except for the 2001 image which was an August image instead of April/May images.

2.3.3 Delineation of flooding extents in CRB from coarse and moderate resolution satellite imagery

Given that the only dataset available for our region as far back as 1985 was an AVHRR NDVI dataset, we used the NDVI product to obtain the spatial extent of the flooding for that time period. For the period 2000 to 2010, we used both the NDVI and EVI products and concluded that the EVI product performed much better by comparison and when tested against higher resolution imagery.

For the AVHRR and MODIS NDVI data, we tried using an image-specific threshold to determine the extent of flooding relative to the larger known water body in the image, namely Lake Kariba, and ground referenced water pixels along a stretch of the Chobe River before its confluence with the Zambezi at Kasane similar to the approach by Birkett (2000) and All (2006) (Figure 2-4). The threshold differed from image to image as a function of the season and extent of inundation in each image, but because the approach of selecting the histogram-based midpoint between water and land as the upper limit for thresholding the image could not remain consistent for the entire time-series analysis of NDVI data from 1985 to 2010, we used this as a baseline and complemented the analysis with a series of 10-class maximum likelihood unsupervised classifications (McCarthy et al., 2003). Thus, we took water classes obtained from supervised maximum likelihood classifications of the Landsat images were then matched in extent to the water extent obtained from unsupervised classifications of both the AVHRR and MODIS NDVI data to determine what number of classes from the unsupervised classification should be retained. We selected two classes: one of pure water and one of mixed pixels. Once the number of classes that represent water in the unsupervised AVHRR and MODIS classifications have been determined using the validation Landsat supervised classifications, the total flooding extent for each image date was computed for each of the image subsets by adding the total number of pixels and multiplying them by the sensor's pixel area (0.0625 km^2 for MODIS and 1.1km^2 for AVHRR).

Furthermore, because the flooding extent analysis using only NDVI for the MODIS images compared relatively poorly with the validation Landsat images, we decided to run a subsequent analysis of annual inundation extent using the MODIS EVI data (Sakamoto et al., 2007; Sakamoto et al., 2009). Each 16-day EVI image was individually reclassified using a baseline threshold of ≤ 0.2 (pure water pixels) and ≤ 0.3 (mixed pixels) which represents the lower boundary condition of vegetation (Huete et al., 1999). These EVI values are primarily associated with water bodies and snow/ice and the basic premise is that the lower baseline contains only non-photosynthetic targets (Sakamoto et al., 2007; Mildrexler et al., 2009; Yan et al., 2010). If the EVI value was ≤ 0.2, the water-related pixels were defined as flooded pixels and if 0.2 ≥ EVI ≤ 0.3 they were reclassified as mixed pixels. If EVI was > 0.3, the pixel was reclassified as non-flooded. This was performed on an individual image basis. Next, we created maps of the intra-annual inundation distribution to capture the progressive movement of the flood pulse through the landscape (Figure 2-5).

2.3. 4 Analysis of remotely-sensed-derived time series of flooding extent relative to our specific objectives

Objective 1: intra-annual distribution of the flood pulse in the CRB relative to runoff in the Zambezi and Kwando Rivers and regional precipitation To understand the relative contributions of flood waters spreading into the Chobe-Linyanti floodplain from the Zambezi vs. the Kwando Rivers at different times of the year, we subset the flooding extent maps into three individual sub-basins: the Zambezi Wetlands, Chobe-Linyanti and Mamili Wetland. We calculated the area flooded through time in each of the three sub-basins and the percentage of the total area flooded for every month. We then correlated the area flooded in every sub-basin with the average monthly discharge for individual years in the Zambezi and Kwando respectively and with mean monthly regional precipitation values to account for the relative importance of these sources to flooding.

Objective 2: inter-annual distribution of the flood pulse in the CRB To determine the change in spatial extent of the flooding through time and compute an annual flooding extent index (FEI), the images for all the years were recoded into binary values (1 = water and 0 = non-water), without inclusion of the mixed pixel classes for either AVHRR or MODIS data. We aggregated both the AVHRR 10-day data to a monthly MVC and the MODIS 16-day data to a single-value MVC (approximately representing a monthly composite based on Julian dates). The monthly scenes for individual years were added together, so areas that are flooded throughout the year received a score of 12 and areas that are flooded only partially throughout the year will receive a score that indicates the number of months each pixel was flooded.

Objective 3: longitudinal (time-series) analysis of changes in the spatial extent of flooding in the CRB Finally, to address the question of whether, as indicated by key informant interviews in the region, the annual flooding extent in CRB has decreased through time, we plotted the AVHRR and MODIS EVI data through time on a monthly and yearly basis and calculated a linear trend and a departure from the median value for both data series. We also calculated a linear trend in total annual precipitation for the Kasane and Katima Mulilo meteorological stations and TRMM data, as well as a similar trend in the Zambezi discharge data.

3. Results and Discussion

3.1 Intra-Annual Timing and Spatial Distribution of the Flood Pulse in the Chobe River Basin

Our assessment of the magnitude and timing of the flood pulse in the Chobe River basin is the first such attempt to understanding the surface water connections in this semi-arid watershed. In was previously held that most of the water in Chobe and its floodplains arrives by back-flow from the main trunk of the Zambezi River, near Kasane in Botswana (Susan Ringrose, Okavango Research Institute, personal communication 2009). However, our analysis shows that the primary and largest flood pulse arrives as the discharge in the Zambezi reaches its peak, at the end of March-April (Figure 2-6) and subsequently slowly spreads across the Zambezi Wetlands in the Caprivi Strip of Namibia first (Figure 2-7). The intra-annual flow distribution of the Zambezi is, typically this climate region with a distinct wet and dry season, unimodal and correlates well with stage data recorded by the ENVISAT Altimeter (r = 0.91). This is the first instance when station-measured discharge data was plotted against altimeter-derived stage data for this river system and an important cross-check of both data types. They both in turn correlate well with our satellite-derived spatial extents of flooding in the basin (Figures 2-7 and 2-8). We chose 2008 because it was the most complete stage record retrieved from ENVISAT.

Because the hydrologic year for this region actually begins at the beginning of the wet season, in November, water throughout the basin is relatively dispersed spatially and generally concentrated in the Lake Liambezi region or shallow depressions in the landscape, called pans (Figure 2-7). As Figure 2-7 shows, the number of pixels reclassified as mixed ($0.2 \geq EVI \leq 0.3$) is highest during this the period November to February before the flood pulse from the Zambezi starts moving through the system and a larger volume of water spreads on the landscape. As discharge peaks in the Zambezi starting in mid-March and April, water spreads out across Zambezi Wetlands first and primarily and is also being pushed as back-flow into the main Chobe channel, so by the end of March (DOY 081) the flood pulse enters the floodplains of the Chobe (Figure 2-7). The maximum extent of flooding in CRB occurs in April and May and, as the water recedes for the Zambezi Wetlands and north-eastern part of the basin, it begins to concentrate in Lake Liambezi and surrounding lower floodplain of the Chobe-Linyanti.

By the middle of the dry season and depending on the hydro-climatological nature of the year, CRB receives water through sporadic connections from the Lynianti channel, which are directly fed by flood waters from the Kwando River making their way into Mamili Wetlands. This secondary, smaller, dry-season flood pulse is due to the different flow regime of the Kwando River, whose discharge peaks in June-August, as opposed to March-April as is the case for the Zambezi River (Figure 2-6). The intra-annual flood pulse distribution in CRB described in Figure 7 for 2009 is representative in terms of the progressive spatial distribution of the flood pulse, with variations in extent captured in later figures, for the entire time-series analyzed from both AVHRR NDVI and MODIS EVI data. We chose the 2009 data to show the intra-annual distribution of flooding because we had very recent station and altimeter-derived data, as well as ground data (training samples) to validate the flooding extent areas. The year 2009 also happened to be one of most noise-free annual time series derived from the MODIS EVI data.

Figure 2-8 shows a breakdown of CRB into the three hydrologically-different constituent sub-basins and the typical timing of the flood pulse moving through the system. Similarly to Figure 2-7, Figure 8a shows the flooding extent at its greatest in Zambezi Wetlands from the beginning of March to May; on an usual basis, between 45 and 60 percent of the Zambezi Wetlands area is flooded, the extent being the highest during the 2009 and 2010 high years of flooding (almost 70 percent of the total sub-basin area, Figure 2-8b). Within less than two weeks, the flood pulse makes its way into the Chobe, in the low floodplains of the communal lands in Botswana and also into Lake Liambezi (Figure 2-8a).

Throughout the year in the Chobe, the extent of flooding decreases after the Zambezi-water pulse recedes and then increases once more, although not as dramatically and depending on the discharge in Kwando, towards the end of June-July when the flood pulse from the Kwando arrives in Mamili (Figure 2-8a). The mean of the total area of the Chobe flooded on an annual basis ranges from about 5 percent to almost 20 percent during the peak extent of flooding and for the years with higher flooding, such as 1989, 1991 and 2009 and 2010.

In the Mamili Wetland, the flood pulse from the Kwando River arrives as the discharge peaks at the hydrologic station upstream of the wetland towards the end of June and July (Figure 2-8a). During the year, typically, the lowest extent of flooding occurs between March and June and at the end of the dry season and because most of this area lies in a depression created by the extensive fault system underlying the region (Gumbricht et al., 2001), water also tends to accumulate on the surface with the onset of the rainy period, covering between 20 to 40 percent of the area (Figure 2-8b).

Finally, in order to understand the mechanistical relationship between discharge in the Zambezi, which accounts for most of the flood pulse to the Chobe, and area inundated on an annual basis, we ran correlations between mean monthly discharge calculated from daily data and total area flooded on a monthly basis. The proportion of area of Zambezi Wetlands inundated on an annual basis correlates strongly with discharge in the Zambezi ($0.89 \geq r \leq 0.93$, correlation significant at the 95% confidence interval) for most of the years in the time series of both AVHRR and MODIS data. However, discharge in the Zambezi only accounts for between 32 and 39% of variation in the annual extent of flooding in the main Chobe basin ($0.32 \geq r \leq 0.39$, significant correlation at the 95% confidence interval) and this is probably explained by, on the one hand, the two weeks to one month lag between peak discharge in the Zambezi and highest extent of flooding in the Chobe, and on the other by variations in surficial flow connections with Mamili, the amount of water accumulated into Lake Liambezi and the length of time before evaporation, as well as contributions of water from regional precipitation during the rainy season. The correlation between area flooded and local precipitation as recorded at the meteorological station closest to the confluence between the Chobe and Zambezi (Kasane, Botswana), as well as TRMM data, is not significant at the 95% confidence interval and only accounts for less than 10% of the areal flooding extent variability throughout the year.

3.2. Inter-Annual Changes in the Flooding Extent in the Chobe River Basin

Figure 2-9 shows the inter-annual spatial extent of flooding as calculated from 16-day MODIS EVI data, showing only the years from 2001 to 2009 and only the pure water class (the mixed pixels class was not included in these maps). We did not show 2000 or 2010 because we do not have the complete data series for the year and the resulting scores for inundation are on a different scale from the other years we have a complete data record for.

Surface water is present in the CRB for more than 8 months of the year only along the main channel of the Chobe and parts of Lake Liambezi, depending on the nature of the year hydro-climatologically. Most of the surface area inundated on an annual basis is usually only inundated for less than three months per year in total, especially in the Zambezi Wetlands where the depth of inundation is generally not very high. There are depressions in the landscape where water remains at the surface for 3 to 5 months of the year, especially along the main Chobe floodplain, areas of the Mamili Wetland and parts of the Zambezi Wetlands in Eastern Namibia. The communities living in these areas are small and usually located on islands in the landscape due to the very nature of the inundation dynamics through the year in that region. Much of the water detected in Mamili during the wettest months of the year (December to February, see Figure 2-8a) is mostly in the mixed pixels category as the water tends to be covered with vegetation and because the discharge remains fairly constant through the year and hence the spatial extent of flooding in Mamili tends to be underestimated when including only the pure water pixels.

Figure 9 shows the lowest spatial extent of flooding in 2005, followed by 2001 and 2002. Even though the flooding in 2010 has been more extensive than the 2009 high flood event, for the data shown 2009 is the year with the most extensive flooding overall. This figure also shows how dependent the entire Chobe system is on the magnitude of the flood pulse from the Zambezi and how negatively affected the entire ecosystem would be if diversions or other water abstraction schemes were to happen upstream along the Zambezi River.

The change in the spatial extent of flooding annually for the period from 2000 to 2010 is closely related to the general flow conditions in the Zambezi River, which accounts for the highest amount of contribution, and the latter correlate fairly strongly with stage data obtained from ENVISAT (Figures 2-10 and 2-11). For the period of interest for this study (1985 to 2009), the driest year in the Zambezi in terms of discharge was 1996, while the greatest floods were recorded in 1989, 2001, 2004, 2008 and 2009. For the 1975-2006 period for example, all 5 major floods (>6,000 m^3/s) were recorded before 1980, while all 5 lowest discharges (< 1,500 m^3/s) recorded after 1990 (Figure 2-10). The overall trend in river discharge for the Zambezi indicates a 7% average reduction in runoff prior to the 2008-2009-2010 floods, associated with the general trend in decreasing precipitations in Southern Africa since the 1970s (Wessels et al., 2004; Gaughan and Waylen, 2011).

Runoff in the Zambezi in turn depends on the overall precipitation trends for the region and the nature and strength of El Niño and La Niña conditions affecting Southern Africa (Figure 2-12). For example, the relatively low spatial extent of flooding in 2001 is related in part to relatively low total annual precipitation rates for that year, although the discharge of the Zambezi was above average and the multivariate ENSO index (MEI) identifies a negative standardized departure from the long-term average, which makes it a relatively wet year by comparison. During the late 1980s rainfall was below the 50-year average, while oscillations between wet and dry years starting with the early 1990s have become more extreme under the influence of stronger El Niño or La Niña years (Wessels et al, 2004). Furthermore, work by Gaughan and Waylen (2011) in the region indicates decreasing precipitation patterns and increased dry years and warm phases of ENSO in the last quarter of the twentieth century. For Southern Africa, 1991-1992, 1994-1995, and 1997-1998 have been the driest El Niño seasons, while 1999-2000 and 1995-1996 the wettest seasons, with the 2001 and 2004 growth seasons being the driest (Figure 2-12). Figure 12 shows the period from 1990 to 1995 to be on average one to two standard deviations positive departure away from the mean and a similar, but less pronounced pattern, for the period between 2002 and 2006, while the years 2008 and 2009 stand out as higher-than-average wet, with a negative anomaly from the mean conditions included in the MEI. These years also exhibit some of the highest spatial extent of flooding.

3.3 Longitudinal (Time-Series) Analysis of the Spatial Extent of Flooding in the CRB Based on AVHRR and MODIS Data: 1985 to 2010

In order to test our hypothesis of whether there has been an overall decreasing trend in the spatial extent of inundation in CRB during the last two and a half decades, we performed a longitudinal time-series analysis of the flooding extent data obtained from both AVHRR and MODIS. We performed a simple linear trend analysis, as well as a moving average trend analysis and a departure from the median calculation. Because the spatial resolution of the MODIS EVI data is different from the AVHRR ones, the two datasets were best plotted individually to show the trend in flooding extent through time for the CRB system. Overall, the analysis of both the AVHRR and MODIS time-series of data indicates a consistent decline in the extent of flooding in CRB in last two and a half decades by ~ 4-6% on average, but this is complicated by the high floods of 2009 and 2010.

The trend analysis of the AVHRR monthly MVC NDVI data reveals a significant decrease in the extent of flooding from 1985 to 2004 for CRB, expressed as area measure at the 1.1 km^2 resolution (Figure 2-13). The 1985-2004 median of area flooded on a monthly basis (solid straight line in Figure 2-13) is 1403 km^2 and mean area flooded is 1415 km^2. An analysis of the number and magnitude of floods above the median for the period shows a slight dampening of the magnitude of floods through time. The dotted line in Figure 14 represents the 2-year moving average of monthly flooded area and, while the r^2 for the linear trend through time is less than .10, there is a 4% decline in flooded area overall.

The trend analysis of the 16-day MODIS EVI data also reveals a decrease in the extent of flooding from 2000 to 2008 for CRB, expressed as area measure at the 250 km^2 resolution. First, we plotted the period 2000 to 2008 separately in order to ascertain what the dynamics of flooding were before the major flood events in 2009 and 2010. The linear trend analysis shows a 6.3% decrease in the area flooded monthly, with an $r^2$of .15. When we included the 2009 and 2010 data into the analysis, the r^2 for the linear trend through time is less than .10, but overall there is a 3.75% decline in flooded area over the last decade (Figure 2-14).

Finally, we aggregated our monthly and 16-day data of the area flooded for the entire CRB into yearly values to determine whether a similar or more consistent trend through time could be observed. While for the AVHRR-based time series the trend in flooded area at a yearly level was not significant ($r^2 < .10$), for the last decade we determined a significant decreasing linear trend (r^2 = .32) in flooded area that probably primarily reflects the generally drier than normal climatic anomalies in Southern Africa (Figure 2-15), consistent with work by Gaughan and Waylen, 2011 and Wessels et al., 2004. The latter finding is slightly confounding however as the general trend in runoff in the Zambezi during the last decade for instance is an increasing one (r^2 = .14, see Figure 2-10) and may indicate more complex lags and feedbacks in the system which are beyond the scope of this paper.

Apart from the complexities introduced by the unusual flow regime and potential climate change and variability impacts, interviews with local informants reveal a decrease in the flooding extent of the Chobe River in the last thirty years. Fieldwork in the Chobe basin and research elsewhere in semi-arid flood-dependent ecosystems indicate a strong relationship between changes in flooding extents and changes in vegetation structure in the floodplain areas (Westbrooke et al., 2005, Ringrose et al., 2007). Both the literature and local informants suggest that there is a link between increasing rates of bush encroachment in the Chobe floodplains in Botswana and Namibia and temporal and spatial modifications of the area flooded annually by the river. However, characterizing the relationship between changes in the flooding regime and vegetation patterns is difficult due to the poor understanding of the present and past spatial extent and dynamics of the floods in the basin and we hope this analysis represents a first step in that direction.

One of the main limitations of this study results from unavoidably underestimating the spatial extent of flooding and possible misclassifications caused by the presence of wildfires which have a similar spectral signature in the visible spectrum bands to water.

The underestimation of burned area is primarily due to the data type used in the analysis, namely vegetation indices as opposed to potentially more sensitive remotely-sensed data, such as thermal imagery which has been shown to better differentiate between surfaces with relatively similar spectral signatures in the visible part of the electromagnetic spectrum, especially the red, blue and near-infrared bands used in deriving the NDVI and EVI products (Cassidy, 2007).

Of importance for water resources management purposes in light of the water abstraction scheme developments planned for the Chobe to start by 2015, as well as for more general natural resource management in the region, is the seasonal and intra-annual distribution of the flooding. By creating maps of the flooding extent index through time for individual years, we determined that the areas most likely to be flooded on a more permanent basis are Lake Liambezi and channels in the Mamili Wetland and parts of the Linyanti channel, as well as the main river channel and low-lying floodplains of the Chobe where waters gets pushed into from the Zambezi or across the eastern Caprivi Strip (Zambezi Wetlands). The main left floodplain of the Chobe-Linyanti and areas in the easternmost part of the Caprivi Strip are likely to experience annual flood pulses that last between five to eight months, depending on the amount of regional precipitation and river runoffs in the Zambezi and Kwando rivers. The areas that are only occasionally flooded during high intensity precipitation or flooding events include bottom reaches of the Mamili Wetland, the densely populated villages spread in the eastern part of the Caprivi Strip in the higher portions of the floodplain, as well as some of the more isolated pans and water depressions in Chobe National Park on the more elevated part of the Chobe floodplain.

4. Summary and Conclusions

The remotely-sensed data and meteorological and hydrological analyses have revealed a decreasing trend in extent of flooding from 1985 to 2009 by approximately 6% and two-week to a one month lag between the highest discharges in Zambezi River and highest extent of flooding in Chobe Basin, thus quantifying for the first time for this system the interconnections between the Chobe and Zambezi systems. Although the main source of water for the Chobe Basin, discharge in the Zambezi upstream from its confluence with the Chobe accounts for only about 39% of the extent in area flooded on an annual basis due primarily to a lag in the movement of the water across the landscape, as well as other factors such as storage in Lake Liambezi and subsequent evaporation, inflows from the Kwando through the Mamili Wetland or regional precipitation. We have also shown how dependent the entire Chobe system is on the magnitude of the flood pulse from the Zambezi. This finding implies that this entire syetem would be negatively affected if diversions or other water abstraction schemes were to happen upstream along the Zambezi River. This paper is the first attempt to perform such an analysis for this particular system. As such, the results of this paper might form a basis for water resources management and ecosystem management in the study area in the future, even though refinements of the present methodology would greatly improve this initial assessment.

Chobe River Basin is a key water resource for Botswana both currently and more so in the future for both domestic and irrigated agriculture, as well as for the subsistence communities of Eastern Namibia. The interest in performing this analysis resulted primarily from key informant interviews during several field visits which revealed changes in the extent of flooding and vegetation structure in floodplain areas, visibly expressed in increasing shrub encroachment. Also, relevant literature on Southern Africa and climate change predictions indicate potentially decreasing annual precipitation values and subsequently decreases in river runoffs that might adversely affect both commercial and subsistence agricultural production, as well as other water resources-related activities in the CRB system in the near future. Future work will include creating inundation maps based on thermal imagery and determining the relationship between changes in flooding extent and grassland to scrubland conversions in the Chobe floodplain.

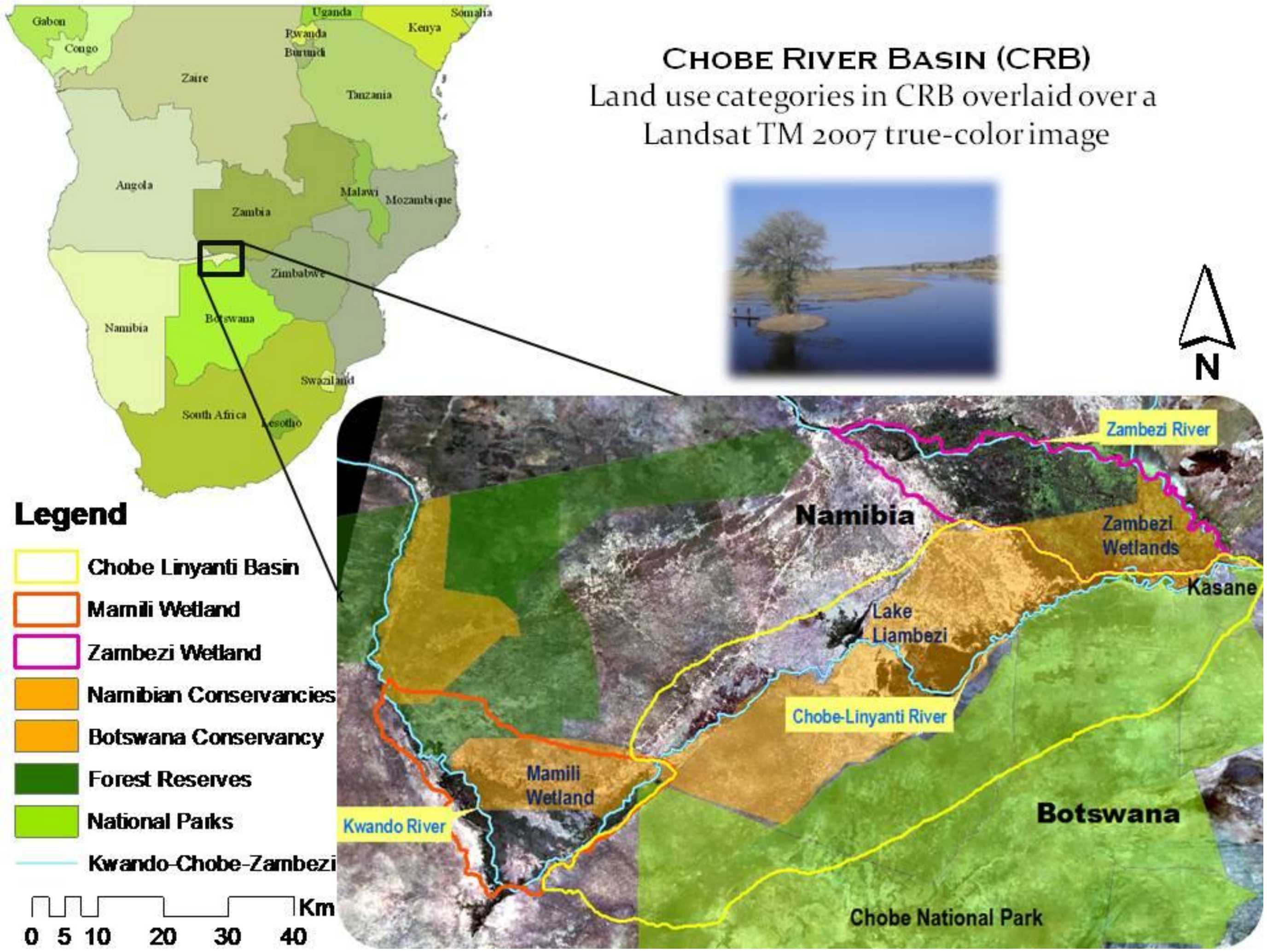
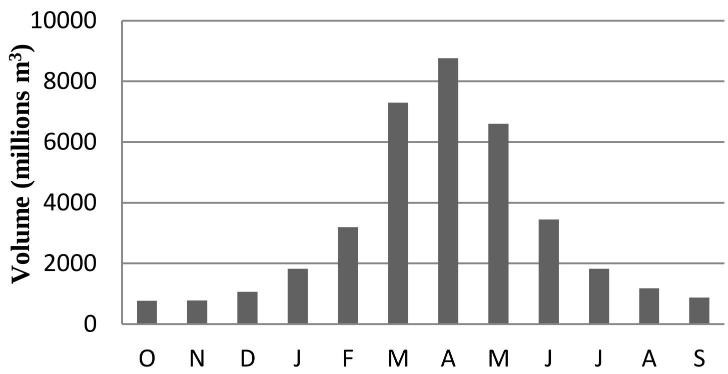
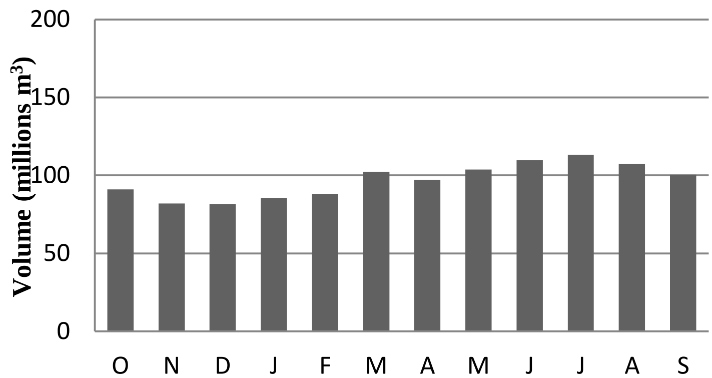


Figure 2-1. Study area showing the Chobe River Basin (CRB) situated in Southern Africa and the main land management categories in the basin. Also shown are the three interlinked river systems: the Kwando River and the Mamili Wetland to the south-west, the Linyanti and Chobe system, and the Zambezi River and Zambezi Wetlands to the north-east. The national boundary between Namibia and Botswana follows the Chobe-Linyanti system.



a)



b)

Figure 2-2. The long-term average monthly discharge of the a) Zambezi and b) Kwando Rivers for the period1965 to 2009 plotted from the beginning of the hydrologic year – October to September (Data source: Department of Water Affairs, Namibia). Such a hydrograph is not available for the Chobe River.

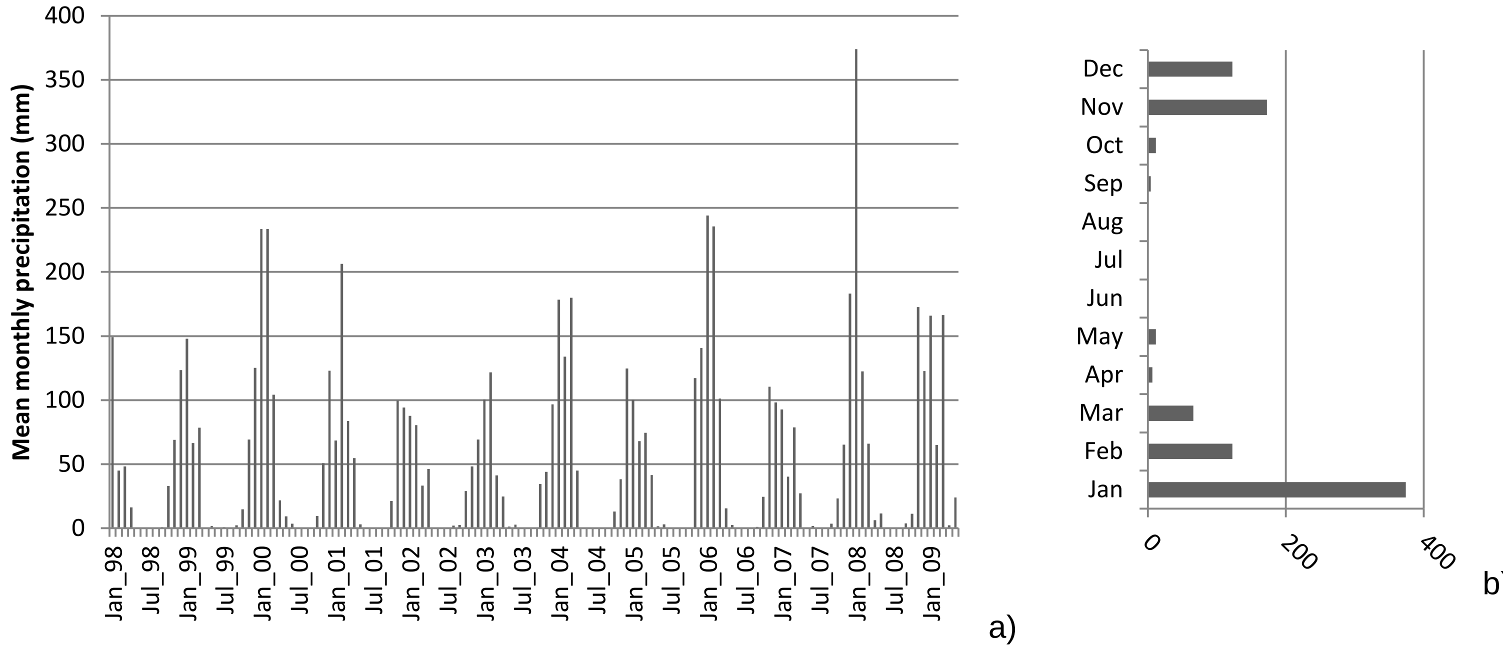


Figure 2-3. a) Mean monthly rainfall data from the Tropical Rainfall Measuring Mission (TRMM 3B43) for the period January 1998 to May 2009 for the Chobe River Basin and b) mean monthly rainfall for 2008 in CRB showing the intra-annual typical distribution of precipitation in mm.

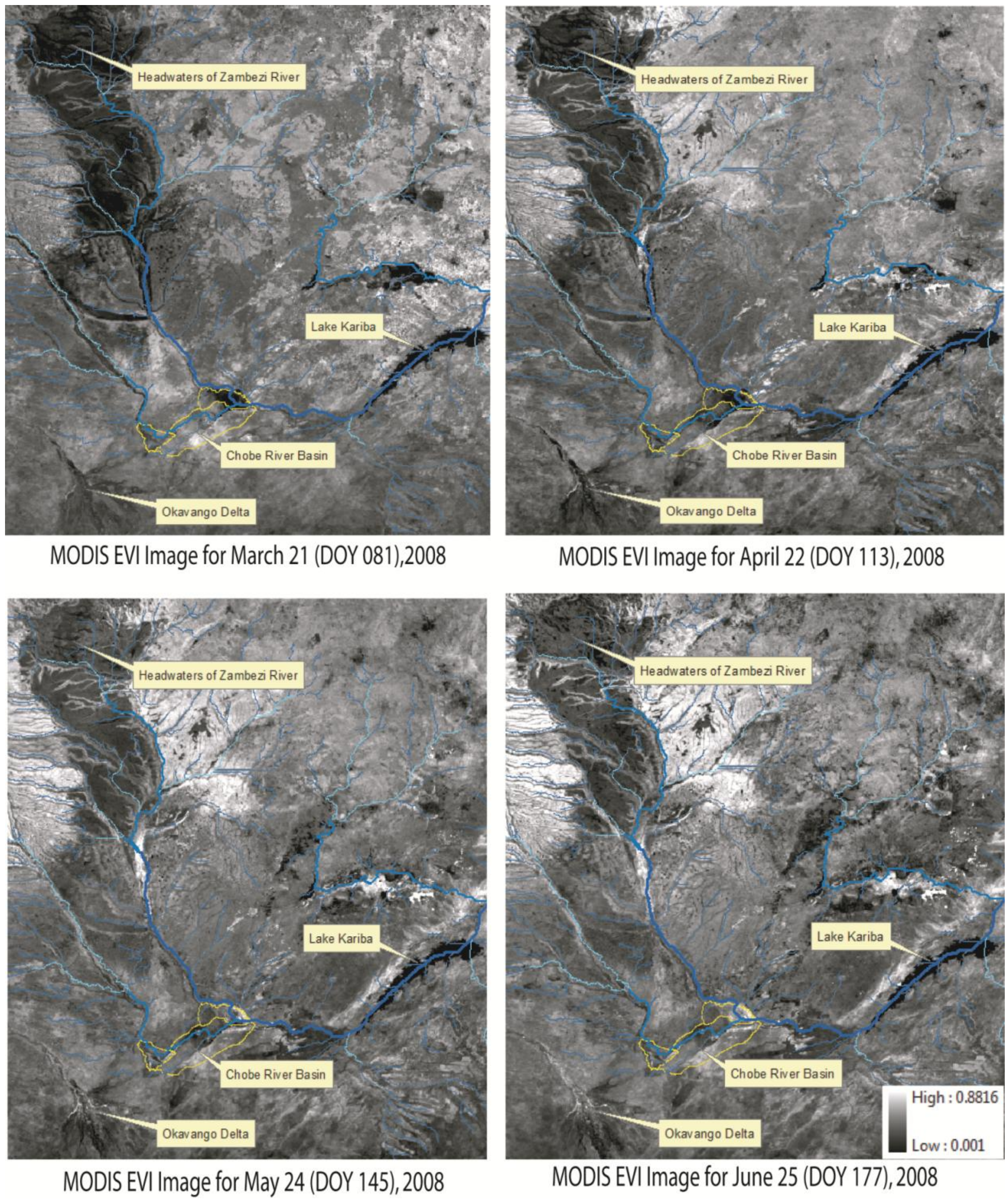


Figure 2-4. Series of MODIS EVI images from March to June 2008 showing the progressive movement of water from the headwaters of Zambezi through CRB. Note Lake Kariba to the north-east of CRB, used as a reference for determining the accuracy of flooding extent delineation in the CRB in a first phase of the analysis. Lighter tones indicate healthy, photosythetically-active vegetation, while darker tones indicate no vegetation (including water). Thicker blue lines for the stream network indicate higher stream order, the main trunk of Zambezi being stream order 5.

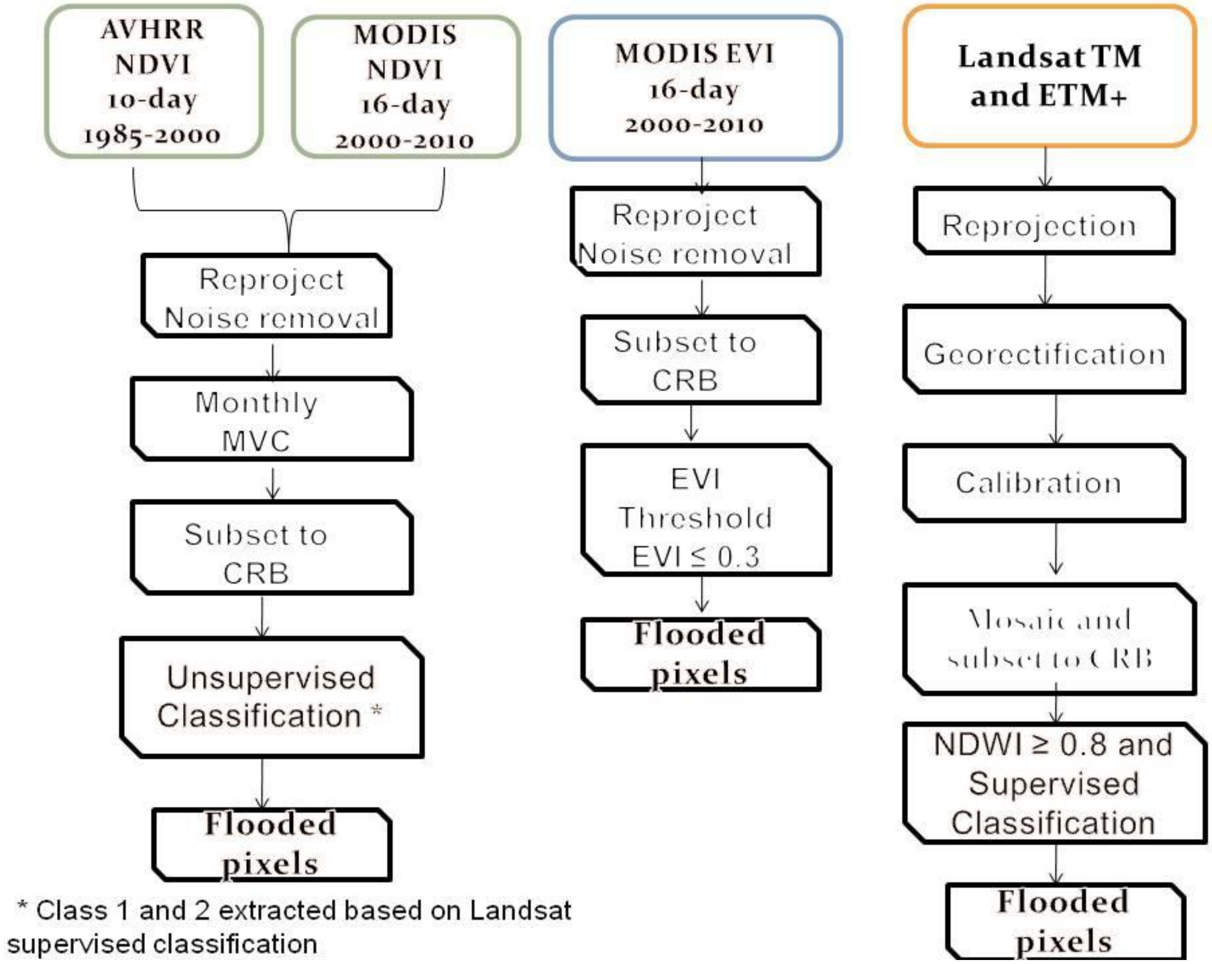


Figure 2-5. Remote sensing workflow showing the pre-processing and processing steps performed to obtain the extent of flooding time-series for CRB. Colored boxes show the three different imagery datasets used in the analysis and arrows indicate the order in which operations were performed.

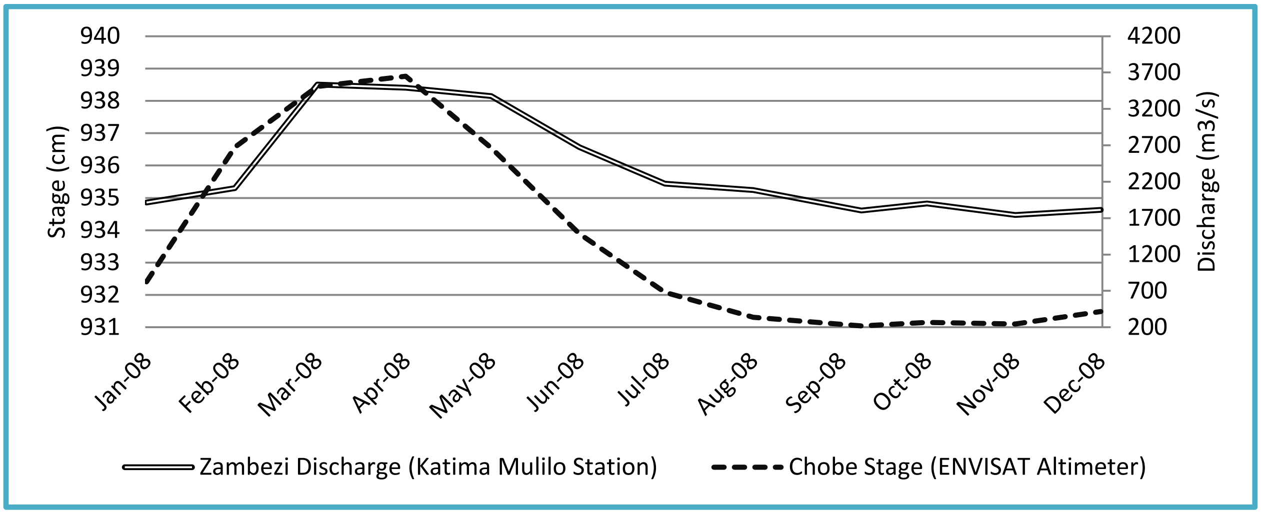


Figure 2-6. The intra-annual Chobe stage-Zambezi discharge relationship for 2008; Chobe stage data upstream from Kasane from the ENVISAT Altimeter and Zambezi mean monthly discharge at Katima Mulilo Station from the Department of Water Affairs, Namibia. The Pearson correlation coefficient (*r*) is 0.91.

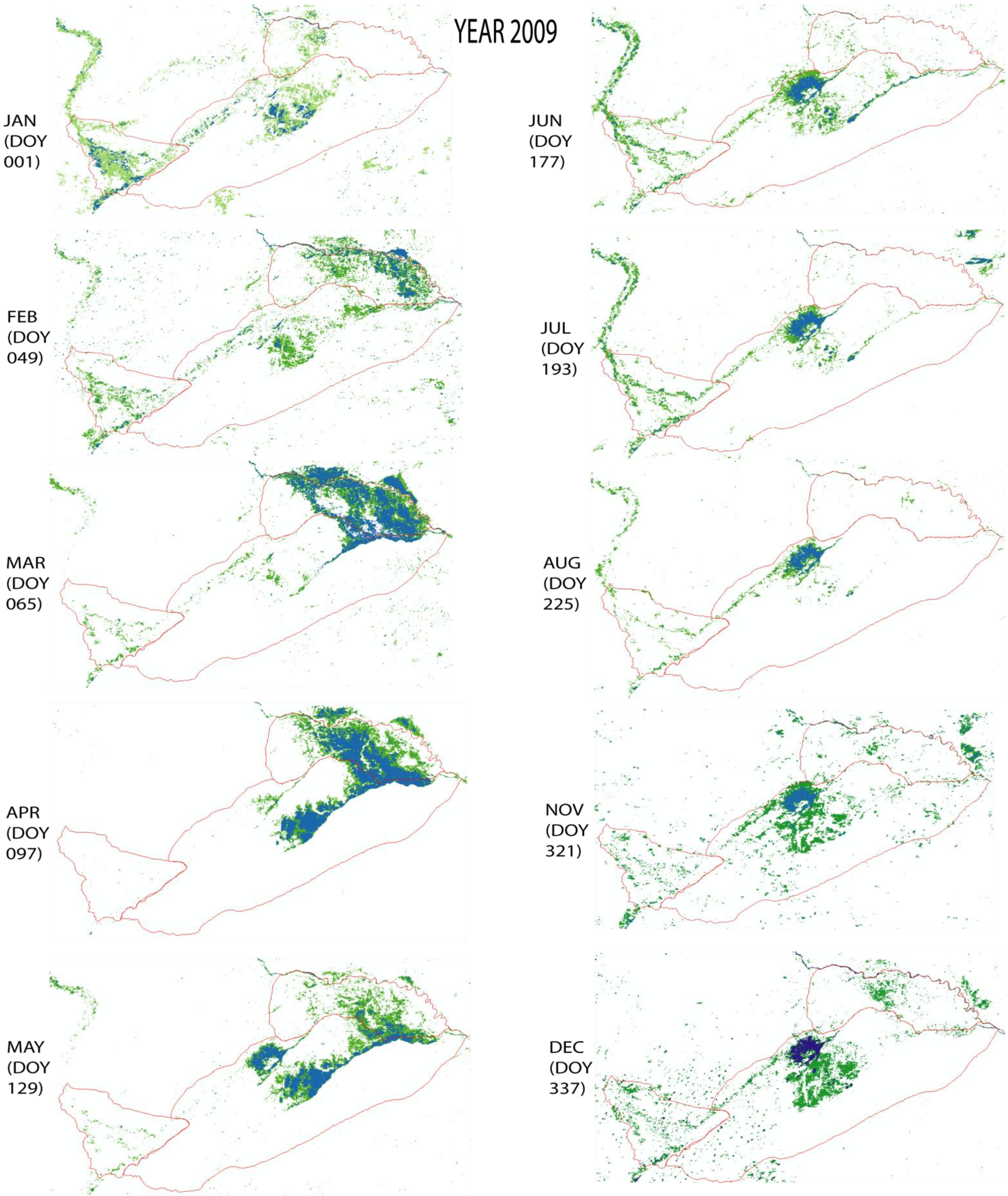
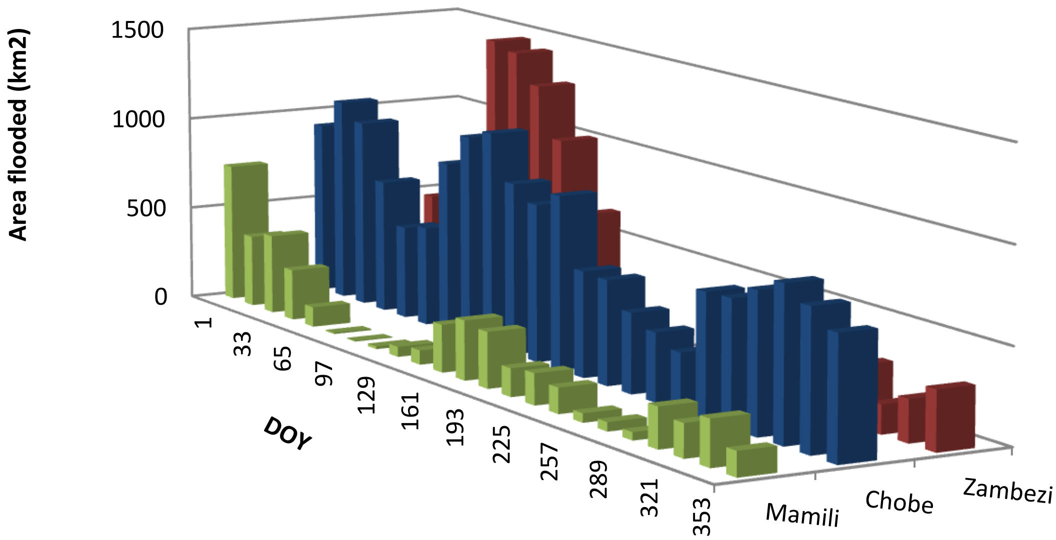
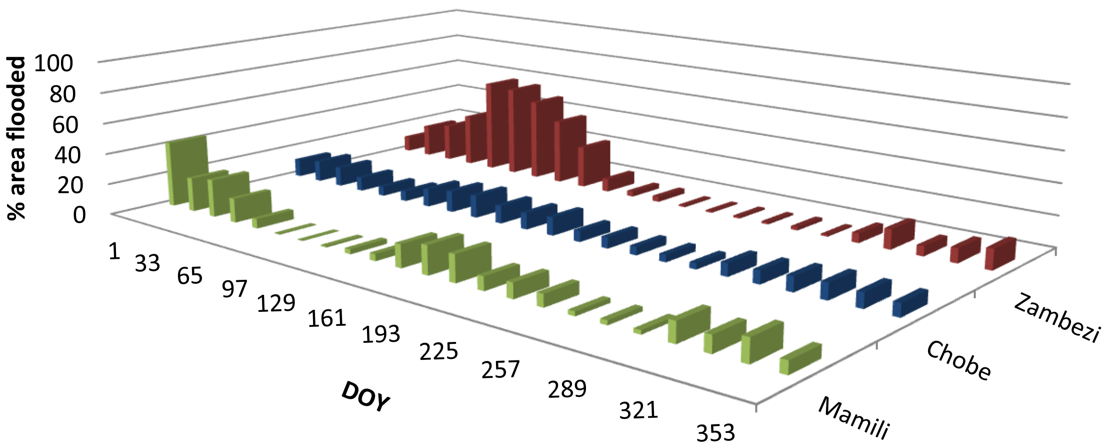


Figure 2-7. The spatial distribution of inundation in the Chobe-Zambezi-Mamili system during 2009, with September and October missing due to low spatial extent of flooding. Areas of blue indicate the distribution of flooded pixels, while areas of green indicate mixed pixels.



a)



b)

Figure 2-8. a) Timing of the flood pulse in the three individual sub-basins of Chobe River Basin, Mamili, Zambezi and Chobe-Linyanti Floodplain, shown in Julian days for 2009 as a function of 16-day flooded area. b) Graph showing the percentage area flooded of the total area (0-100%) for the three sub-basins of CRB in Julian days for 2009.

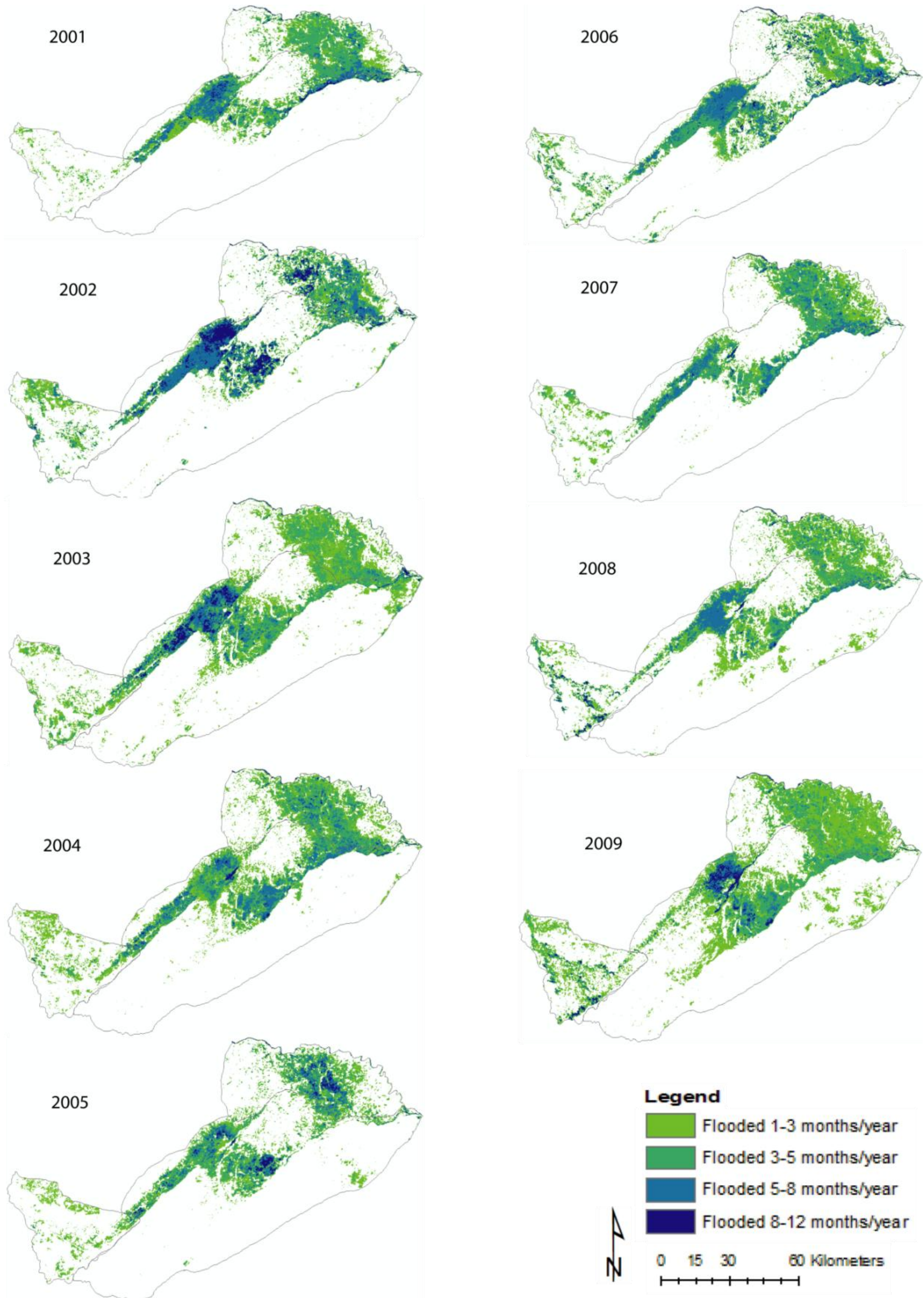


Figure 2-9. The spatial extent of flooding (flooding extent index) calculated for individual years for the Chobe River Basin from MODIS EVI data for the period 2001 to 2009.

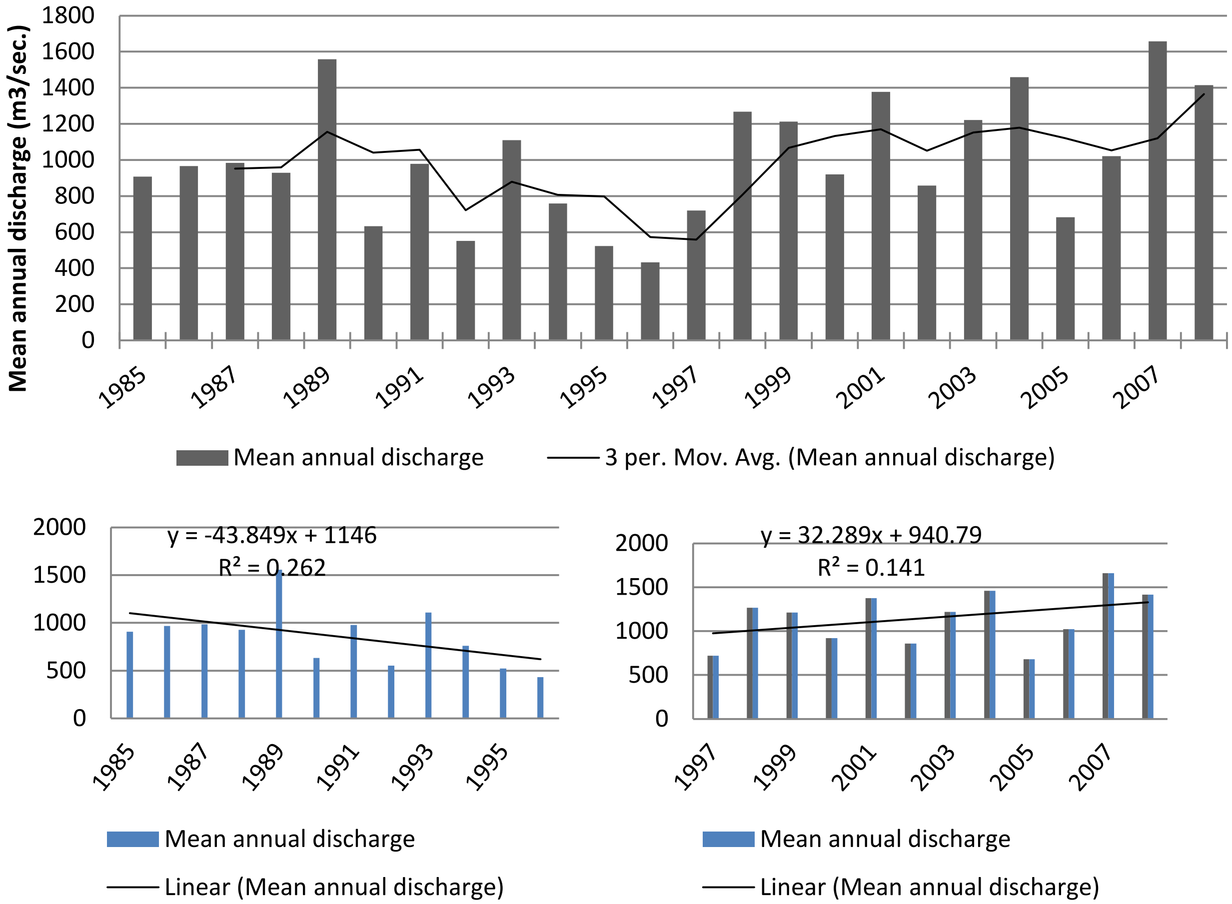


Figure 2-10. Mean annual discharge of the Zambezi River at Katima Mulilo for the period 1985 to 2009 calculated from total daily discharge. The 3-year moving average for the entire time series shows a decrease for 1985 to 1996 and a slight linear increasing trend in discharge for the period 1997 to 2009.

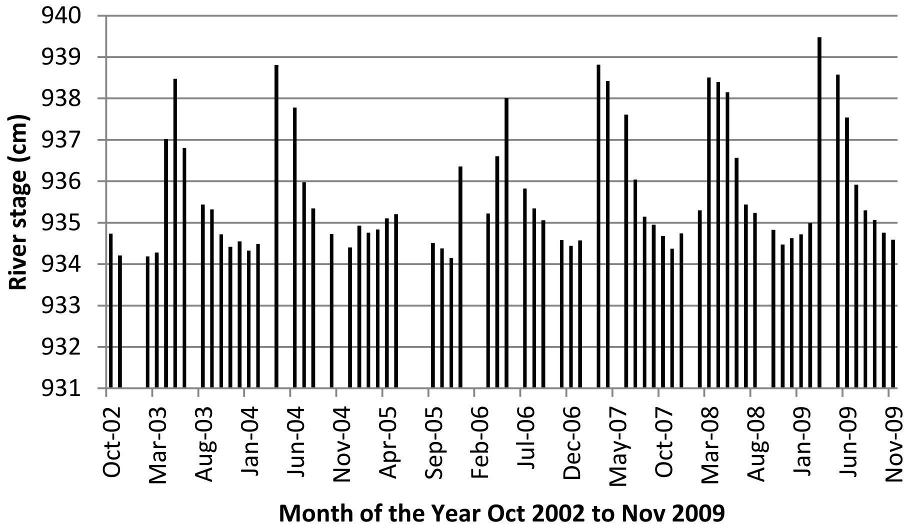


Figure 2-11. The average monthly stage data for a Chobe reach 25 km upstream from the confluence with the Zambezi River retrieved from the ENVISAT altimeter on February 5th, 2010.

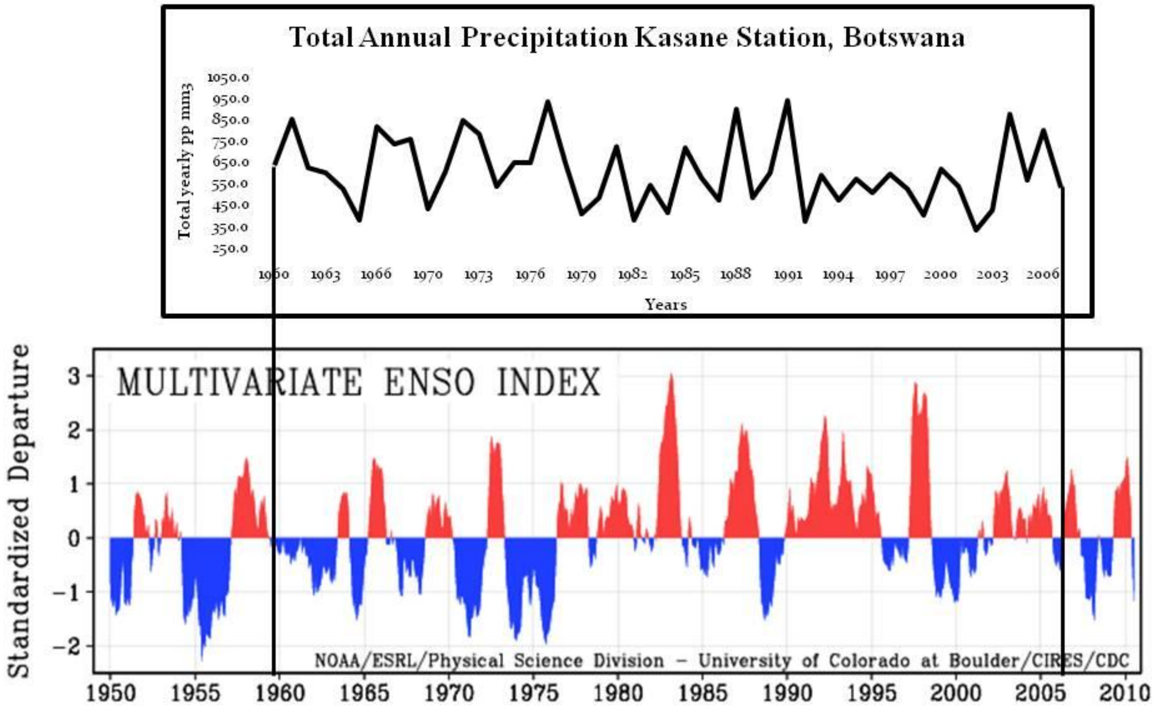


Figure 2-12. Total annual precipitation at the Kasane meteorological station in Botswana between 1960 and 2007 and the Multivariate ENSO Index for 1950 to 2010. Note the correspondence between the dry ENSO conditions between 1990 and 1995 and low annual precipitation values recorded in CRB. (Precipitation data source: Department of Meteorological Services, Botswana; MEI data source: Wolter and Timlin, 1998).

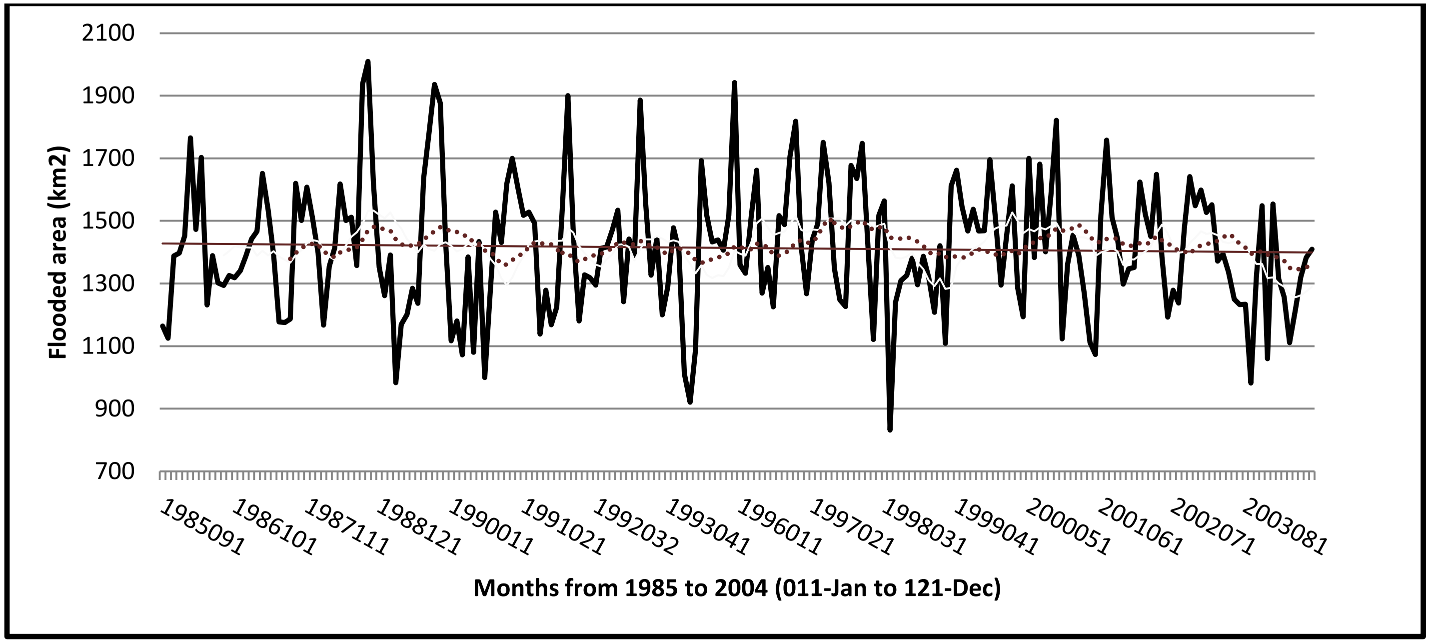


Figure 2-13. Flooded area on a monthly basis in CRB from 1985 to 2004 based on an unsupervised maximum likelihood classification of monthly MVC AVHRR NDVI data. The 1985-2004 median (solid straight line) is 1403 km^2 and mean is 1415 km^2; the dotted line represents the 2-year moving average of monthly flooded area. The R^2 for the linear trend through time is less than .10, but shows a 4% decline in flooded area.

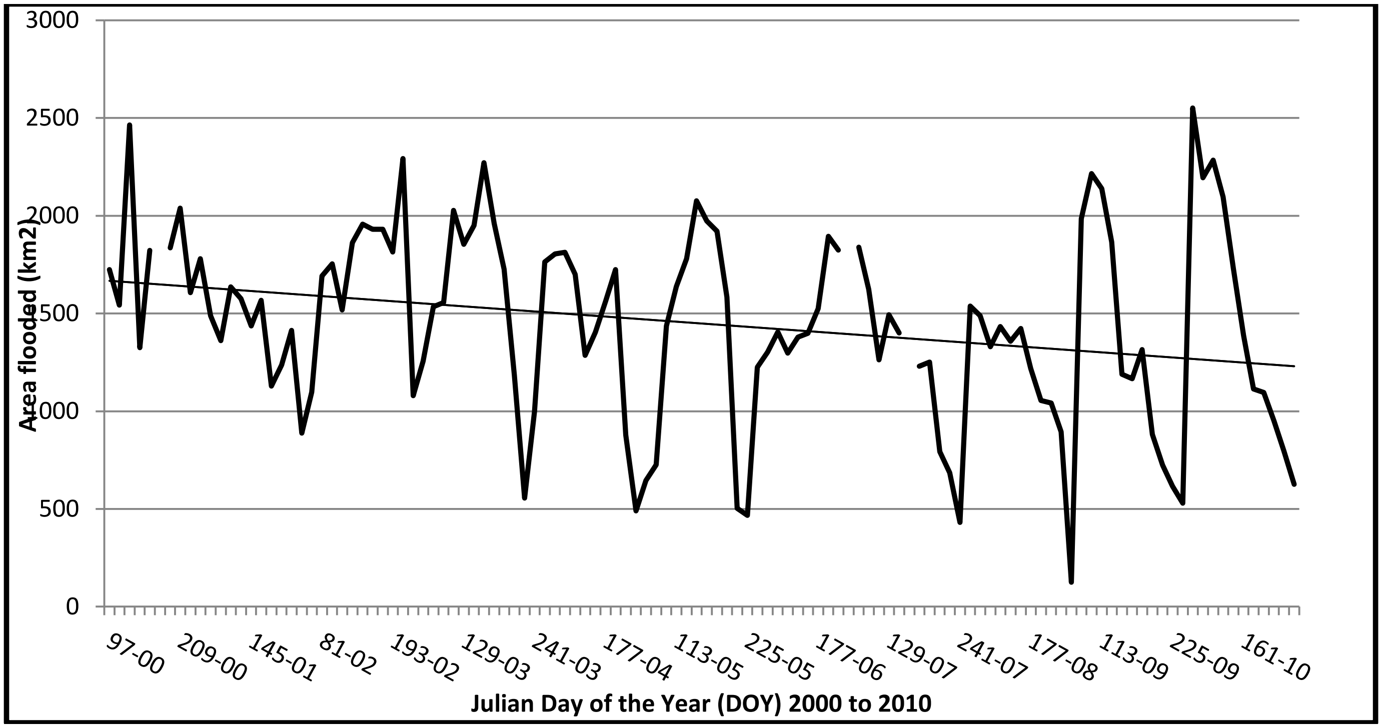


Figure 2-14. Flooded area on a monthly basis in CRB from 2000 to 2010 based on thresholding of 16-day MODIS EVI data. The R^2 for the linear trend through time is less than .10, but shows a 3.75% decline in flooded area over the last decade, even including the last two years of higher flooding.

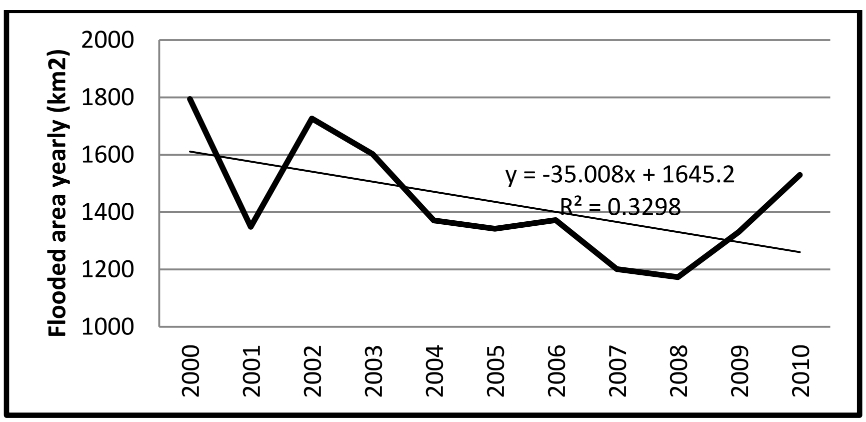


Figure 2-15. Flooded area aggregated to yearly values for the entire from total monthly flooded area Chobe River Basin (including the Zambezi and Mamili Wetlands) aggregated for 2000 to 2010 from MODIS EVI data (includes both pure and mixed water pixels).

Table 2-1. Data types, temporal and spatial resolutions, sources of data and their temporal availability.

Data categories	Data type	Data source	Temporal availability
Remotely-sensed data	AVHRR NDVI 10-day MVC 1.1 km^2 data (AVHRR HRTP)	Coarse Resolution Imagery Database (CRID), South Africa	Sept. 1985 to April 2000
	MODIS EVI 16-day 250 m^2 data (MOD 13QA)	USGS Land Processes Distributed Active Archive Center (LP DAAC)	April 2000 – April 2010
	Landsat ETM+ 30 m^2 multispectral data	USGS Earth Explorer, University of Maryland Global Land Cover Facility, Council for Scientific and Industrial Research, South Africa	April/May 1986, 1990, 1996, 2002, 2003, 2004, 2007, 2009
Climatologic data	Multivariate ENSO Index (MEI)	National Oceanic and Atmospheric Administration	1950-2010
	Station rainfall data	Department of Meteorological Services Botswana	1945-2008
	Tropical Rainfall Measuring Mission (TRMM 3B43) rainfall data	NASA's Goddard Space Center	1998-2009
Hydrologic data	Discharge data Zambezi River, Katima Mulilo	Department of Water Affairs, Namibia	1965-2009
	Discharge data Kwando River, Kongola	Department of Water Affairs, Namibia	1978-2008
	Monthly stage data ENVISAT altimeter	European Space Agency	2002-2009
GIS and other ancillary data layers	Digital Elevation Model (DEM), 10 m resolution	National Planning Commission GIS Division, Namibia	2008
	Orthophotos Caprivi Strip, Namibia, 1-m resolution	Ministry of Lands, Surveying and Mapping, Namibia	2007
	Hydrologic basins of southern Africa	GeoNetwork, Food and Agriculture Organization (FAO)	2009
Field data	Training samples (CIPEC standard protocol)	2007 and 2009 field seasons, Botswana and Namibia; over 100 water/inundation training samples	2007, 2009

Table 2-2. Estimated accuracy of the flooding extent calculated from AVHRR and MODIS data relative to the flooding extent derived from Landsat images for the Chobe River Basin.

Year of acquisition	Landsat 174_72	AVHRR/MODIS (DOY)	R^2
1990	04/16	April MVC	0.70
1996	05/02	May MVC	0.68
2001	08/28	241	0.93
2002	04/09	97	0.95
2003	04/28	113	0.82
2004	05/16	129	0.90
2007	05/01	129	0.94
2009	05/06	129	0.96
2009	05/22	145	0.87

CHAPTER 3
A SPATIO-TEMPORAL FIRE RECURRENCE INDEX FOR SEMI-ARID SAVANNA ECOSYSTEMS IN SOUTHERN AFRICA USING MODERATE RESOLUTION SATELLITE IMAGERY

1. Fire Regimes and Climate Change and Variability: Background

Fires are an intrinsic component of many ecosystems throughout the world, while for the semi-arid savannas of Southern Africa they are one of the controlling factors in maintaining the balance between grassy and woody vegetation (Bond and Keeley, 2005). Understanding the role of fires in driving ecosystem dynamics through the influence of fire on land cover change, atmospheric composition, and the global carbon cycle is a key focus within the global change research community (USCCSP, 2004). Several models project changes in fire regimes, especially increases in fire frequency with climate warming and resulting alteration of plant communities to domination by grasses and fire-tolerant shrub invaders in some ecosystems (Overpeck et al. 1990; Anon., 1996; Bond and Keeley, 2005, Goldammer and Price 1998). The fire regime of a region has six major components: fire frequency, size, intensity, seasonality, type and severity, all intricately linked to ecosystem structure and function and highly dependent on weather and climate oscillations (Gill, 1975; Whelan, 1995; Swetnam and Betancourt, 1998; Flannigan et al., 1998; Flannigan et al., 2000; Bergereon et al., 2004).While extensive research on the potential impacts of global climate change and variability on fire regimes in boreal forests has been undertaken (Stocks et al., 1998; McCoy and Burn, 2005; Flannigan et al., 2005), regional studies that analyze the intra- and inter-annual distribution of fire occurrences and burned area in semi-arid savannas have been sparser (Boko et al., 2007).

The C_4 grasslands, shrubs and woodlands of the savannas of Southern Africa, which are among the most frequently burnt ecosystems in the world, are an expression of fire disturbances at various recurrence rates in the landscape (Bond et al., 2004). Natural fires usually occur in southern African savannas at the end of the dry season – beginning of the wet season, are caused by lightning, and their intensity depends on the physical characteristics of the fuel load (Scholes and Archer, 1997). In terms of fire activity and rates of fire recurrence, two types of vegetation clearly dominate in southern Africa: tree-covered areas containing 40% of total fires observed, and shrub-covered areas, with 19% of total fires (Amraoui et al., 2010). Natural and anthropogenic fire ignition and fire propagation, and their effects on savannas are controlled at local to regional scales by climate, vegetation structure, and land use (Lavorel et al., 2007). Wet years increase fuel availability so that during ensuing dry years the dry fuel burns more strongly and recurring droughts reduce fuel production and subsequent burning activity (Barbosa et al., 1999). In savannas with mean annual precipitation <650 mm, high-frequency fires promote grasses and suppress the recruitment of woody plants because the meristems of grasses are less exposed and can recover much faster in the short term (Watkinson and Powell, 1997). Roques et al., 2001 argue that early dry-season fires, which are usually started by humans as a means of providing additional green stems for cattle, are detrimental to grass meristems, reduce fuel loads, and promote the establishment of undesired woody species. At the opposite end of the spectrum, Bucini and Lambin (2002) suggest that early fire occurrence in savanna ecosystems does not lead to land-cover change but that it fragments the landscape by creating islands of burned and non-burned vegetation, preventing the spatial diffusion of damaging fires later in the season. Alternatively, fire has been shown to lead to reduction of species diversity by differentially affecting younger tree species (Russell-Smith et al., 1998) and to promote landscape heterogeneity (Hudak et al., 2004). These different outcomes of fire regimes alterations indicate how location-specific the effects of fires are.

As the numbers of people living in various ecosystems across the world are increasing, emerging approaches to management tend to focus on maintaining or returning landscape composition and stand structure to those resembling natural ecosystems to maintain biological diversity and essential ecological functions. There has been an increasing interest in the development of management approaches that are based on an understanding of historical natural disturbance dynamics and how those dynamics might be changing through time (Bergereon et al., 2004). One hypothesis put forth by Bergeron et al. (2004) emphasizes that, in fire-dominated landscapes, this approach is possible only if current and future fire frequencies are sufficiently low, compared to historical fire frequencies so that fire can be substituted for by active management. Therefore, we must understand the nature of the current and past fire regimes and the kinds of changes in different aspects of fires regimes, especially fire frequencies, occurring in a given region to assess whether current management approaches are suitable to maintaining essential ecological functions in the future. Serneels et al. (2007) assess the contribution of fire regimes to land-cover changes in various biomes in East Africa and find increasing fire frequencies over time, concluding that, especially for rangelands, the impact of fires translates more in changes in vegetation phenology than in vegetation productivity.

This paper analyzes changes in several components of fire regimes in Africa's largest transfrontier conservation area, the Kavango-Zambezi Transfrontier Conservation Area (KAZA), during the last decade using two fire products derived from Moderate Resolution Image Spectroradiometer (MODIS) data. Specifically, we ask whether fire management is expressed in the landscape in the form of changes in the annual extent of burned area in protected areas managed differently in the five countries of KAZA. Secondly, we tested whether the seasonality, extent and frequency of fires has changed through time in a specific area of KAZA (the Caprivi Strip of Namibia and northern Botswana) with a mosaic of land uses. The two areas are actively managed in different ways, one to prevent fires (Botswana) and one with seasonal prescribed burns (Namibia). The primary method of the paper is to create a fire recurrence index (FRI) map for the central KAZA region for the last decade; secondarily, we wanted to understand the general trends in fire frequency and seasonality between two neighboring countries with different fire policies and management and to test whether there is an increasing trend in fire occurrences irrespective of expressed fire policies and management regimes. Ultimately, this analysis can contribute to understanding whether and how these changes in fire regimes translate into changes in vegetation productivity and phenology.

1.1. Fire Regimes and Fire Policies in the Central Kavango-Zambezi Transfrontier Conservation Area.

The Kavango-Zambezi Transfrontier Conservation Area (KAZA) is a vast multi-nationally managed network of national parks, game management areas, and community-based wildlife management communal lands that encompasses an area of approximately 300,000 km^2 of Botswana, Namibia, Zambia, Zimbabwe, and Angola.

The expressed purposes for the creation of KAZA by the member countries are tri-fold: to improve the cooperative management of shared resources, to increase the area available for wildlife and plant populations, and to bring economic benefits to the local communities adjacent to protected areas (Peace Parks Foundation, South Africa, 2010). The largest and most important protected areas of central KAZA used in this analysis were the following: for Botswana – Chobe National Park, the Okavango Delta RAMSAR site and Moremi and Linyanti Game Reserves; for Namibia – Bwabwata, Mamili and Mdumu National Parks; for Zimbabwe - Victoria Falls, Hwange, and Kazuma Pan National Parks; for Zambia – only Sioma Ngwezi National Park; and, finally, for Angola – Luiana Partial Reserve (Figure 3-1).

We chose to include these various protected areas into the analysis of changes in the annual extents of burned area from 2000 to 2010 primarily because they form the central nucleus of KAZA and are in very close proximity to each other. Secondly, despite their proximity and the expressed common management goals of KAZA, each country has a different and more or less specific policy on fire management and/or fire suppression. To some degree, all member countries have fire suppression policies within their protected areas originally setup as ‘green conditionality” for aid and loan disembursement (Eriksen, 2007); however, in reality, there is a large disconnect between official fire policies and indigenous de facto fire practices. For example, social research in the savanna woodlands of West Africa by Hough (1993) predicted an increase in the incidence of human-caused bush-fires in and around national parks as a “revenge tool” or to deter wild animals and increase the supply of certain forest products, in addition to the common reasons for setting bush-fires: tradition, clearing fields, hunting, and improving dry season grazing. In the protected areas of Angola for instance, although information on official government policy on fire management is difficult to surmise, a 2006 assessment report performed by United States Forest Service highlighted the increasing extent of uncontrolled burning for subsistence agriculture and hunting, as well as an increase in anthropogenic mid-dry season fires (USDA, 2006). They also found that the mid-dry season repeated burns have adverse effects on vegetation composition and forest integrity and have begun an official fire management training program in the region starting from 2008. The situation is somewhat similar in Zambia, where fire suppression and early-dry season prescribed burns intended to reduce the fuel-load for later, more destructive fires are common practice in protected area, while uncontrolled, late dry-season bush fires are common in wildlife management and communal areas (Eriksen, 2007). In Zimbabwe, the policy on complete fire suppression across all land use categories is strict. In 2007, a new statutory regulation regarding fire ignition by humans was voted into law. It provides for large fines and imprisonment, puts the burden of fire prevention on individual land owners, and specifies that between July 31 to December 31 fire ignition outside residential areas is prohibited (ZELA, 2010).

The study area is located in the region of subtropical dry climates characterized by an alternating dry and wet season. Thus, precipitation is seasonal, influenced by the movement of the InterTropical Convergence Zone (ITCZ), with the wet season occurring during the summer between November and April (Figure 3-2). The variability in precipitation patterns is also related to El Niño Southern Oscillation (ENSO) events. Annual average rainfall is approximately 640 mm. The period from May to October represents the dry season, when the mean maximum and mean minimum monthly temperatures during October (hottest month) of 39 ◦C and 14 ◦C respectively are reached. The coldest month is July, with a mean max temperature of 30 ◦C and a mean min monthly temperature of 4 ◦C (Barnes, 2001).

The focus of the second part of the paper is on changes in the fire frequency, extent and seasonality in northeastern Botswana and the Caprivi Region of Namibia, primarily because we have conducted extensive fieldwork in the region. Secondly, we zoomed in on this area because of the relative uniformity of biophysical conditions and similar environmental histories punctuated by specific changes in fire policy during the last decade, thus different fire management policies. These latter considerations make for an interesting case study in disentangling changes in fire regimes induced by environmental variability from land management decisions. Verlinden and Laamanen (2006) used Landsat imagery to determine the amount of area burned annually in Northern Namibia between 1989-2001, showing that between 27 to 51% of the area burned annually, while only 10% of the area did not burn during the same period (settlements and permanent wetlands). Trigg (1998) and Mendelsohn and Roberts (1997) showed that 60% of the Caprivi region burned during 1996, the year when formal fire management began in the Caprivi Strip. The 1996 Namibia Forestry Strategic Plan (MET-DoF, 1996) stated that the occurrence and severity of uncontrolled and accidental fires needs to be reduced. The initiative consisted of building firebreaks and holding awareness programs to remedy some of the perceived environmental and economic consequences induced by uncontrolled burning. However, starting in 2006, fire managers in the Caprivi Region of Namibia initiated a program of annual, early dry-season prescribed burning to promote grass regeneration for cattle and wildlife grazing (WWF/IRDNC Project Technical Progress Report, 2006). This program is set up as a patch-mosaic early-dry season Verlinden and Laamanen (2006) did not include fire scars detected on Landsat Quicklooks between May and July as they could represent controlled early dry season fires, which are now part of the fire management regime (they only observed 10 such fires for the period 1989 and 2001). As such, there has been no effort up-to-date to determine the extent of change in these early dry-season burns (in effect a change in fire seasonality) for the Caprivi region.

In Botswana, on the other hand, fires have been actively suppressed in all land use categories over the last two decades and extensive efforts and resources are put into creating and maintaining an increasingly extensive network of firebreaks, especially aimed at containing the spread of wildfires from neighboring Zimbabwe (Mr. R. Mafoko, Director of Botswana Department of Forestry and Range Resources, personal communication, 2007 and 2009). Fires of lower intensities and frequencies than currently taking place in Namibia have positive effects on woodland regeneration after species pass the sapling stage (Stahl et al., 2002), while annual burning of woodlands, even at low intensities, can damage many species regeneration and growth (Smit et al., 1999). Vegetation composition and structure in semi-arid savannas can therefore be affected by fires and land use changes, as well as by changes in precipitation regimes, either part of the natural variability regime for the region or intensified by global climate changes (Frost, 1996; De Luis et al., 2001).

1.2. Moderate-Resolution Fire Products and Their Applicability in the Southern African Savannas

Our main goals were:

(1) To determine whether fire management is expressed in the landscape in the form of changes in the annual extent of burned area in protected areas in different countries of KAZA and create a fire recurrence index for the region;

(2) To determine whether the seasonality and frequency of fires has changed through time between areas actively managed to prevent fires (Botswana) and regions with seasonal prescribed burns (Namibia).

Firstly, we hypothesized that protected areas with low fire management and with annual prescribed burning experience much higher fire recurrence rates than areas managed to prevent fires. The product used to test this hypothesis was the MODIS Burned Area data – MOD45A1 – (2000-2010) for the larger area of central KAZA to assess annual fire patterns in protected areas. Some of the results we expected to see were that highest fire recurrence rates occurred in the protected areas of Angola, Zambia and northeastern of Namibia where fire management is not well regulated and that fires affecting Botswana originate mainly from Zimbabwe, as key informants interviews with officials in charge of fire management had suggested. Secondly, we hypothesized that there has been an increase in the fire frequency and a change in fire seasonality in northeastern Botswana and the Caprivi in the last 10 years and that communal lands have higher fire recurrence rates than protected areas. We tested this hypothesis using, apart from the Burned Area product, the MODIS active fire data – MOD14GD – (2000-2010) and accounted for changes in fire policy in Namibia (policy on early-dry season mosaic prescribed burns that went into effect in 2006). We expected to see an increase in fire frequency in both countries and a change in the timing and seasonality of fires in Namibia driven by increasing human-induced early dry-season fires. We chose to used both of these fire products because Serneels et al. (2007) used the MODIS (MOD14A2/MYD14A2) active fire frequency data and concluded that understanding the impact of fires on short-term land cover changes in semi-arid regions would be greatly enhanced by using burnt area data instead of only the active fire frequency data supported by the MODIS platform at the time. Thus, analyzing both the frequency of fires, as well as the spatial extent of seasonal fires can give us a clearer understanding of the relationship between fire regimes, land management decisions and environmental variability for this region of Southern Africa.

Our study area is characterized by very high annual percentages of landscape burning, with a minority of fires that could start and stop over the year. The accuracy of the active fire and burned area products for this area is good compared to other products and other regions of the world (Roy and Boschetti, 2009). For example, MODIS active fire products provide a valuable source of data about fire activity that capture spatial and temporal patterns not represented in other fire data. Hawbaker et al. (2008) have found that overall detection rates of fires by the MODIS active fire products were high (82%) when data from both the Aqua and Terra sensors were combined but that small fires were less likely to be detected than large fires. According to Morisette et al. (2005), the MODIS active fire product has substantially improved fire detection capabilities in comparison to the similar AVHRR product as it creates a pixel-resolution fire mask, while the increased saturation temperatures of the sensor decrease the ambiguities related to false alarms or omission errors characteristic for the AVHRR fire product. The active fire product detects fires using a contextual algorithm that exploits the strong sudden emission of mid-infrared radiation from fires as opposed to the non-fire background response using a set of relative thresholds of detection, usually based on mid-infrared brightness temperatures greater than 320º K (Dozier, 1981). Each pixel in an image therefore is assigned to one of the following classes: missing data, water, cloud, non-fire, fire, and unknown (Giglio et al., 2003). For most fire regimes however, the timing and spatial extent of burning cannot be estimated reliably from active fire detection alone, as the satellite may not overpass when burning occurs and because clouds may preclude active fire detection (Justice at al., 2002).

Previous to the creation of the MODIS Burned Area product, Perreira (1999) used the near-infrared (0.725-1.10 µm) and mid-infrared (3.55-3.93 µm) channels on the AVHRR platform for burned vs. non-burned area discrimination, and Roy et al. (1999), based on work by Kaufman and Remer (1994), similarly used the an index (called VI3) calculated as the near-infrared minus the reflective component of the mid-infrared divided by their sum to create a burn scar detection algorithm for an area near the Okavango Delta. They find that by using the VI3 index as opposed to an NDVI adds stronger discrimination between the burned and unburned areas. Visually, burned areas appear dark because of low post-burn soil moisture and vegetation levels, while the unburned areas appear bright as they are moist and highly vegetated (Roy et al., 1999). Further, Alleaume et al. (2005) created an index called the Normalized Burned Index (NBI) based on changes in radiometric values in bands 5 (1230-1250 nm) and 7 (2105-2155 nm) of MODIS before and after a fire; while surface reflectance for band 5 decreases post-fire, it increases for band 7. The algorithm used to create the MODIS burned area product takes advantage of the spectral, temporal and structural changes that occur post-burning in a landscape, such as removal of vegetation, deposits of charcoal and ash, and changes in vegetation structure (Roy et al., 1999). Specifically, the current burned area algorithm is based on a bidirectional reflectance model-based change detection in daily surface reflectance time series data at 500 m resolution (Roy et al., 2002; Roy et al., 2005b). A comparison between the burned area and active fire products by Roy et al. (2008) highlighted that for low percent tree cover and leaf area index values, the MODIS burned area product defines a greater proportion of the landscape as burned than the active fire product and that in reality burned areas tend to be orders of magnitude more extensive, especially for the savannas of Southern Africa and Australia than both algorithms can detect. Overall, for Southern Africa, the MODIS burned area product has been validated in several studies using independent reference data collected by the Southern Africa Fire Network (Roy et al., 2005a) and has detected approximately 85% of the true area burned (Archibald et al., 2009).

2. Data Analysis and Methods

2.1. Data Sources

We used a combination of remotely-sensed, spatial, climatological, and field-collected data in this analysis, as summarized in Table 3-1. The data layers used in the delineation of protected areas of KAZA were downloaded from the World Database on Protected Areas (WDPA; data available at: http://www.wdpa.org/). The MODIS fire datasets for the region became available in February 2000. For this study we acquired two separated products, both available through the University of Maryland. Upon acquisition, all the data were reprojected to the Universal Transverse Mercator (UTM), WGS84 coordinate system using nearest neighbor resampling.

The MODIS Active Fire Data (MOD14GD) contains daily 1 km fire pixel locations that are most appropriate for determining the spatial distribution and seasonality of burning. The data is available from November 2000 to April 2010 for our study region. The active fire data were acquired from the University of Maryland MODIS ILUCI Fire Dataset for 2000-2010. It consists of spatially-explicit and georeferenced (WGS 1984, UTM 34 South) point layers for every year with the following attributes: mid-infrared brightness value, acquisition date, time of day of fire detected, and the confidence level for every active fire detected (Giglio et al. 2003).There is data missing from the end of June to the beginning of July in 2001, 2002 is missing some data throughout the data set, 2007 has some missing data from mid August and data is missing for part of 21 April 2009, and missing for 22 April 2009 (Justice et al., 2002; Davies et al., 2009).

The MODIS Burned Area Product (MCD45A1) is a monthly Level 3 gridded 500 m product available from April 2000 to April 2010. The Burned Area product was downloaded from the University of Maryland Global Land Cover Facility (GLCF) in HDF-EOS and GeoTIFF format and pre-processed according to the accompanying user manual. The data for June 2001 is not available due to prolonged sensor outage; because of the June 2001 outage, the May and July 2001 products are also affected, and some burned areas might not have been detected.Additionally, we acquired a set of Landsat Quicklooks-derived fire scars for Namibia for 1989 to 2007 from the National Remote Sensing Center of the Government of Namibia that we used to compare to the burned area product as an initial validation step, but, given the relatively unreliable nature of the Landsat-derived scar data from Quicklook images, our level of confidence in the analyses was low and they were not included in the final analysis.

To gain an initial understanding of the dynamics of dry and wet years for the southern African region in relation to larger-scale sea-land teleconnections, we used the Multivariate ENSO Index for the period 1950 to 2010 (Figure 3-3), (data available at: http://www.esrl.noaa.gov/psd//people/klaus.wolter/MEI/). MEI is calculated based on six major variables measures over the Tropical Pacific Ocean: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky (Wolter, 1987; Wolter and Timlin, 1998).

Mean monthly and annual total precipitation data between 1945 and 2008 for several stations, including Kasane meteorological station, in the basin were obtained from the Department of Meteorological Services Botswana. Secondly, monthly averages of rainfall calculated from daily rainfall values for the basin were obtained from the Tropical Rainfall Measuring Mission (TRMM) for the period between January 1998, when the mission started, and May 2009 (Figure 3-2), (data available at: http://mirador.gsfc.nasa.gov). Finally, we conducted a series of semi-structured key informant interviews with fire managers in the field, as well as Department of Forestry officials in both Namibia and Botswana during our 2007 and 2009 field seasons (Bernard 2000).

2.2. Data Analysis Methods

2.2.3. MODIS burned area product processing methods

After we subset the MODIS burned area GeoTIFF product to our study area that includes all the protected areas in central KAZA (Figure 3-1), we used ESRI ArcGIS 9.3 to eliminate the missing, cloud, or no data values, and reclassified each layer containing the Julian date of burning to monthly layers, making sure we addressed the 8-day overlap between consecutive months (Roy and Boschetti, 2009). Once we obtained a layer with the number of burned pixels for every month, we multiplied by the sensor's spatial resolution (0.25) to obtain the total area burned for every month in the time series from 2000 to 2010. Then, to determine the influence of land use and management regimes in the five countries included in the analysis (Angola, Botswana, Namibia, Zambia, and Zimbabwe), we grouped the land use units into 5 major categories and subset the burned area monthly products to each land use type: 1. National parks (Chobe in Botswana, Bwabwata, Mudumu and Mamili in Namibia, Hwange in Zimbabwe, and Sioma-Ngwezi in Zambia); 2. Game reserves (Moremi in Botswana); 3. Forest reserves (Chobe, Kasane, Maikaelo, and Sybuyu in Botswana and the state and community forest reserves in the Caprivi, Namibia); 4. Partial reserves (Luiana in Angola and the Okavango Delta RAMSAR site in Bostwana); and 5. Wildlife management areas (several across all five countries). To create graphs of the total annual burned area for each protected area for each year, we added the individual months together and obtained a score indicating areas that burn more than once every year. Finally, to obtain a fire recurrence index for central KAZA for the last decade, we recoded the total annual burned area layers into binary values (1 = burned and 0 = non-burned). All monthly scenes for individual years were added together, so areas that are burned, for instance, on a yearly basis received a score of 10 and areas that are burned only during some of the years in our 10-year data series received a score that indicates the number of times each pixel was burned from 2000 to 2010.

2.2.4. MODIS active fire product processing methods

Because the MODIS active fire data is released to the user as a single geospatially referenced point layer for the entire time period requested (in our case, from November 2000 to April 2010), we retrieved monthly and yearly active fires for every land use category in the study area, focusing in particular on northeastern Botswana and the Caprivi Region of Namibia. The data were then exported into a statistical package where we analyzed them first at a regional level (Namibia vs. Botswana) to determine trends in fire occurrences and seasonality for the last decade quantified as mean monthly numbers of active fires detected, standard deviations of the mean monthly fire detections, and a percent change in the mean monthly number of active fires between 2001 and 2010 between the two countries to determine the potential impacts of the change in fire policy in Namibia in 2006. Subsequently, we further analyzed the data at a land use category level (national parks, forest reserves, and communal lands) between the two countries of primary interest to understand whether the increasing trends in fire occurrences are constant throughout the differentially-managed land use categories and throughout the year. We also conducted statistical significance tests of difference in the mean monthly number of active fires detected in the Caprivi for the period 2000 to 2006 (prior to the introduction of the early-dry season, mosaicked prescribed burns program) and 2006 to 2010.

McCoy and Burn (2005) performed a series of multiple regressions of annual fire incidence, area burned, and burn severity with mean temperatures, total precipitation rates, mean relative humidity, and mean wind velocity and concluded that the strongest associations for area burned were with temperature and precipitation rates, therefore we used precipitation data (both station rainfall data and TRMM rainfall, as well as the MEI data) to check our burned area analysis against. TRMM data has been used successfully in previous studies and has been shown to perform well for these latitudes, comparing well with measured rainfall stations throughout the region (Huffman et al., 1997; Kummerow et al., 2000; Nicholson et al., 2003).

3. Results and Discussion

Changes in fire regimes are best analyzed in conjunction with hydro-climatic data (Carcaillet et al., 2001). Work in this region on long-term changes in flooding extent has shown a decrease in the annual spatial extent of flooding, which may translate into a potential for fire incidence increases (Ringrose et al., 2007). Climatologically, work by Wessels at el. (2004) have shown that rainfall for the late 1980s was below the 50-year average, while oscillations between wet and dry years starting with the early 1990s have become more extreme under the influence of stronger El Niño or La Niña years. They also found that for Southern Africa, 1991-1992, 1994-1995, and 1997-1998 have been the driest El Niño seasons, while 1999-2000 and 1995-1996 the wettest seasons, with the 2001 and 2004 growth seasons being the driest (Figure 3-3). Figure 3-3 shows the period from 1990 to 1995 to be on average one to two standard deviations positive departure away from the mean and a similar, but less pronounced pattern, for the period between 2002 and 2006, while the years 2008 and 2009 stand out as unusually wet, with a negative anomaly from the mean conditions included in the MEI. The period from 1999 to 2003 was a relatively wet period in Southern Africa, whereas the preceding three years before 2006 (when fire incidence in central KAZA was greatest across protected areas of the five countries analyzed, Figure 3-4) were, by comparison, dry which contributed to creating the conditions for the unusually extensive fires of 2006 throughout KAZA.

3.1. Analysis of Changes in the Spatial Extent of Area Burned for Central KAZA Using the MODIS Burned Area Product (MOD45A1)

Our analysis of the burned area product for the protected areas of central KAZA reveals that between 15,000 and 35,000 km^2 of these ecosystems burns on an annual basis, depending on the climatologic conditions, fuel load availability and condition, ignition and other factors (Figure 3-4). A complete explanation of the main direct (ignition frequency, fuel load, continuity, and moisture) and indirect (lightning frequency, population density, land management, topography, road density, dry season length, relative humidity, tree cover, rainfall, soil fertility and grazing, and wind speeds) drives affecting burnt area in Southern Africa is offered by Archibald et al. (2009) and is beyond the scope of this paper. The year 2006 experienced the highest degree of burning throughout all protected areas included in this study, probably as a result of the preceding three years being unusually dry and experiencing below average precipitation (see also Figure 3-3). Such an assumption is supported by findings by van Wilgen et al. (2003), who showed that there is a significant positive correlation between fire extents and the amount of rainfall for the preceding two years in a similar ecosystem in South Africa, irrespective of the fire management and interventions.

The following section breaks down the area burned annually for each individual protected area in every country and compares the proportion of the total area of the protected area that is burned for every year of the analysis (Figure 3-5). Mudumu National Park in Namibia, a relatively small (727 km^2) park created after the Namibian independence in the 1990s and located in an area surrounded by communal lands on all sides, experiences, of all seven protected areas included, the highest proportion of area burned every year, with some years, such as 2006, experiencing a 98% of the total area burned (Figure 3-5). Second and third after Mudumu by proportion of total area burned are Luiana Partial Reserve in Angola and Sioma-Ngwezi National Park in Zambia, both experiencing fires for more than 40% of their area annually. That fact is, most likely, a direct result of the lack of explicit fire management regulations and also enforcement of existing fire prevention and suppression policies in the two countries. Interestingly, a slight decrease in fire extents seems to be occurring in Luiana after 2006 (approximately 10%) which coincides with the beginning of the USDA fire training and prevention programs in that region of Angola (USDA, 2006). In Zimbabwe, exemplified here by Hwange National Park, despite the history of active and effective fire prevention and management programs in the last few decades prior to 2000, the extent of area burned annually as a function of the park's area (14,651 km^2) has been significantly increasing for the last decade (r^2 = 0.40), making that the largest and most significant increasing trend in burned area across the central KAZA region (see also Figure 3-7). Similarly significant but opposite in trend is the case for Mamili National Park in Namibia, also a small park created around the wetlands of the Kwando River (344 km^2) after the 1990s, which is experiencing a decrease (r^2 = 0.37) in annual burned area, most likely as a result of increasing extents of annual flooding by the Kwando River (key informant interviews, Caprivi Strip, Namibia)

The following four figures show comparisons between the different protected areas analyzed for the last decade as a function of the proportion of the area that is burned every year. For instance, Figure 3-6 shows a comparison between Luiana in Angola and Sioma-Ngwezi in Zambia; Luiana (with an area of 8,400 km^2) burns on average between 40 and 84% of the area and shows a slight decrease in area burned through time, while Sioma-Ngwezi (area of 5,276 km^2) burns on average between 30 and 60%, with no remarkable increasing or decreasing trend in the area burned annually.

Chobe National Park in Botswana, established in 1967, with an area of 10,566 km^2, is Southern Africa's second largest national park after Kruger National Park in South Africa and home to an impressive number of wildlife species, but famous in particular for the largest elephant density in the world (Department of Wildlife and

National Parks, Botswana, 2009, personal communication). The vegetation of the park, along the river on the alluvial soils, consists of a thin strip of riparian forest followed by shrublands dominated by *Capparis tomentosa* and *Combretum mossambicense.* This area has slowly transitioned to shrubland on the alluvial soils that earlier had large *Acacia* and *Combretum* trees. Further away from the river woodlands dominated by the economically-important *Baikiaea plurijuga* species occur (Makhabu, 2005). The park is very actively managed to prevent fire spread from neighboring countries and communal lands it adjoins to, with a robust network of firebreaks maintained and continuously expanded. Despite these fire suppression efforts in line with the official fire policy, the park has been experiencing an increasing linear trend in the annual extents of fire for the last decade (with an r^2 of 0.23 for the entire period and $r^2 = 0.43$ if we exclude the unusually high 2006 fire season from the time series). Hwange, where fire management has not seen much attention during the last decade as a result of Zimbabwe's general economic situation, has also seen a significant increasing linear trend in the area burned yearly for the last decade ($r^2 = 0.40$), (Figure 7).

The three national parks created in the Caprivi Strip of Namibia at the end of the Namibian war of independence, Bwabwata, Mudumu and Mamili, were managed according to a fire suppression program starting in 1996 and have been undergoing prescribed early-dry season burning programs since 2006 with the primary purpose of grass regeneration for wildlife and, secondarily, prevention of more extensive late-dry season wildfires which could endanger the ever increasing human population living in the region. The largest of the three parks is Bwabwata with an area of 6,334 km^2, home to several extensive villages and divided by a major road; between 15 and 59% of its area burns every year, similar to findings by Verlinden and Laamanen (2006) who used fire scar mapping and Landsat Quicklooks imagery to determine the annual extents of burning (Figure 3-8). From the analysis of the MODIS burned area product, a slight decrease in fire extents through time in all three parks is recorded. That may be an indirect result of increasing human populations living in the Caprivi and therefore increasing numbers of cattle which remove a larger percentage of the fuel load in grasslands or woodlands with a grassy understory, as human settlements exist and grazing occurs especially in Bwabwata (Archibald et al., 2009).

Finally, focusing the analysis on understanding the differences in fire regimes between Botswana and Namibia, a comparison between Bwabwata and Chobe National Parks, which are relatively similar in size and vegetation composition, reveals a striking difference that occurs mainly as a result of park management (Figure 3-9). While Bwabwata burns on average between 15 and 59% annually, the average area burned in Chobe is only between 2 and 18%, with an exceptional 38% of area burned during the 2006 fire season. Key informants in Botswana indicated that the extensive 2006 burns in Chobe were mainly fires crossing over into Botswana's forest reserves from Zimbabwe to the east and possibly Namibia to the north. As a result, retroactively, fire managers are increasing their fire prevention efforts along the eastern and northern sections of the park, primarily by expanding and improving the firebreaks network (G.J. Mafoko, Department of Forestry and Range Resources, Botswana, personal communication). However, our spatial analysis indicates that the southwestern part of the park, which also experienced a severe burn in 2006, is also vulnerable from fires originating in the communal lands to the west and as such fire prevention efforts should be equally focused in that region (Figure 3-10). Also, there seems to have been an intensification of the extent of area burned in Chobe in the second half of this decade, despite increasing fire prevention efforts which may be an indirect result of overall increasing temperatures and decreasing precipitation in the region (Wessels et al., 2004).

The spatial distribution of areas burned for central KAZA from 2000 to 2009 reveals the pattern of most recurrent burning in the region described above using the proportion of total area burned for each protected area (Figure 3-10). We chose to show only four years from the time series analysis, namely 2001 and 2009 which were both unusually wet years preceded by two years of wet conditions as well (Figure 3-3) and 2005, the year with the lowest total area burned for the region and 2006, the year with highest total area burned in central KAZA for the period of analysis (Figure 3-4). Figure 3-3 shows that, according to the MEI 2005 was preceded by two very dry years and therefore 2006 was preceded by three anomalously dry years, also illustrated in the precipitation record from both station and TRMM precipitation data (Figure 3-2). Parts of the Caprivi region in Namibia (especially Mudumu National Park), Angola and Zambia burn repeatedly, while more rare but more spatially extensive fires occur in the protected areas of Botswana, such as the extensive fire in the Nxai-Pan and Magkadikgadi Pans National Parks in 2001, or the fires in Chobe National Park and eastern Okavango Delta in 2006, both of which have been documented through key informant interviews and ground data from park and forestry officials in Botswana. Also, fairly extensive fires burn on a regular basis in the communal lands to the north of

Chobe National Park and Okavango Delta, as well as in the central and eastern regions of the Caprivi in Namibia (Figure 3-10).

Our main objective for using the MODIS burned area product (MOD45A1) was to be able to create a spatial fire recurrence index (FRI) for the central region of KAZA for the period 2000 to 2010 (Figure 3-11). All land use categories in Namibia and Botswana that are part of the central region of KAZA have been included in this analysis and only the protected areas for the other three countries because we were unable to obtain adequate spatial data for other land use categories in these latter three countries. The FRI we calculated shows, as expected from the discussion above, that parts of the two protected areas in Angola and Zambia experience high fire recurrence intervals for the last decade ranging from 6 to 10 years out of 10 years in approximately 30 to 40% of their total area. Mudumu National Park in Namibia also experiences very high fire recurrence intervals for more than 50% of its total area, followed by some communal areas in the Caprivi (Figure 3-11). The Caprivi region of Namibia for instance, with the exception of areas along the main roads crossing the region and areas adjacent to human settlements, experiences relatively high fire recurrence throughout. In previous research, proximity analyses have shown that slightly more early-dry season burning is undertaken close to roads, and at greater distances from settlements but that there are no proximity differences for fires later in the season (Russel-Smith et al., 1997). However, in this paper and for the burned area product, we have not differentiated between early and dry season burning as we were primarily interested in creating a fire recurrence index for the entire region and in documenting the differences in proportion of area burned annually among the protected areas in the region.

In Botswana, with the exception of the forest reserve to the east of Chobe National Park and the communal areas in the northern part of the country, to the north of Chobe and adjacent to the communal areas of Caprivi, fires generally have low recurrence intervals of less than 3 years on average. Surprisingly in Botswana, the wildlife management areas to the south of Chobe National Park also have lower fire recurrence rates than the two national parks at the southernmost tip of central KAZA: Nxai-Pan and Makgadikgadi National Parks. Although overall in Zimbabwe's Hwange National Park a significant increase in fire extents has occurred in the last decade, only a small proportion of its area experiences fire recurrences higher than 3 years for the last decade, and most all those fires originate in the communal or wildlife management areas to the east and north of the park. This represents a first attempt in the literature to map the spatial and temporal distribution of fires in the form of an FRI for this increasingly important, ecologically and economically, conservation region in Southern Africa.

3.2. Analysis of Active Fire Detections, Fire Seasonality and Changes in Active Fire Detections from 2000 to 2010 for Northern Botswana and the Caprivi Strip of Namibia Using the MODIS Active Fire Product (MOD14GD)

In order to test the hypothesis that there has been an increase in fire frequencies and a different change in fire seasonality between areas managed primarily through complete fire suppression in all land use categories (Botswana) and areas where early-dry season burning programs have been initiated with different intensities in different land use categories for the last decade, we used the MOD14GD (active fires) product made available from November 2000 onwards. Figure 12 shows the temporal distribution of total active fires detected by MODIS for the Caprivi in Namibia (all land use categories included) and northern Botswana, aggregated from daily fire detections at the 1 km^2 pixel size. A simple linear trend analysis of the data for Caprivi shows a 266% increase in total fire detections for the entire period from 2000 to 2009, with an r^2 = 0.71, whereas the same kind of analysis for northern Botswana reveals an 88% increase in total fire detections (r^2 = 0.30). Because 2006 was such an anomalously high year for fire activity in northeastern Botswana (see also our analysis of the burned area data), if we eliminate 2006 from the trend analysis, the increase in fire frequencies is by 82%, with an r^2 of 0.65.

To further determine if the trends observed in the total fires detected were consistent and could give us an indication of the changes in fire regimes for the last decade, we analyzed the intra-annual distribution of the mean monthly number of active fires detected for each region (Figure 3-13). In the Caprivi region, Figure 3-13 shows the intra-annual distribution of fires during both the rainy and dry seasons, indicating a consistent increase in the mean number of fires detected overall throughout the year, as well as an increase in the mean number of fires occurring during the early-dry season, which was expected given the initiation of the early-dry season burning program from 2006. We used the mean number of fire detections for every month to get an indirect idea of the relative size of a fire based on the number of fires detected in one km^2 pixel.

In northeastern Botswana, on the other hand, while the fire season of 2006 clearly stands out similarly to the data obtained from MODIS burned area product, there is no noticeable change in the mean number of fires detected in the early-dry season except for a slight increase in fires in June 2002 and 2005 (Figure 3-14). However, there is an overall increase in fires during the later part of the dry season, especially during the months of September and October and especially after 2006. The monthly average number of fires detected outside of the normal fire season is rarely higher than 10, while for the fire season it can be as high as 30 to 50 fires.

Because, on the one hand, 2001 and 2009 are at either end of our analysis period temporally, but also, on the other hand and more importantly, because they are comparable climatologically as shown by the MEI and precipitation conditions for the previous two years, we compared the means and standard deviations of the monthly numbers of fire detections for 2001 and 2009 (Figure 3-15). Firstly, for northern Botswana, there is a statistically significant difference in the standard deviation range between 2001 and 2009 from August to November and a significant positive increase in fire detections for September in particular. This indicates that, as the standard deviations get higher, the fires are more frequent and possibly larger either in size or temporal extent (i.e. they can continue for more than one day). In the Caprivi, there is a statistically significant increase in fire detections throughout the year between 2001 and 2009, with a marked increase in standard deviations of fires during the early-dry season in May and June (probably due to the introduction of the early-dry season burning policy in 2006), as well as a similar trend towards the end of the dry season, in August and September when more natural fires generally occur (Figure 3-15).

Finally, we performed a change analysis of the mean monthly number of active fires detected in both regions between different years relative to 2001. Specifically, in northern Botswana our data shows a 53% increase in active fire detections during September between 2001 and 2009 and a consistent above 50% increase in fire detections from July to September between 2001 and 2008 (Figure 3-16). In the Caprivi, where fire suppression is not practiced throughout all land use categories as it is in

Botswana, between 2001 and 2009 for example, there is an above 100% increase in active fire detections beginning with May and up to almost a 400% increase in the month of June. Because 2008 was preceded by a very dry year in 2007 and a relatively dry season in 2006 and overall experienced high total numbers of fires, the increases from 2001 to 2008 for June are above 400% and as high as 800% in November (Figure 3-16), due in part to a later onset of the rainy season during 2008 for this region.

Overall, the analysis of the active fire data for the period 2001 to 2009 for the two regions in central KAZA which are managed very differently in terms of fire suppression and policies on early-dry season burning, has revealed consistent increasing trends in active fire detections in both regions and a shift in fire seasonality primarily in the Caprivi consistent with a transition to active fire management based on early-dry season burns. Because we aggregated all land uses into a single category for this analysis, for the next part of the paper we separated out the different land use categories to test whether the increasing trends in fire frequencies we observed are primarily anthropogenically-driven and the result of differential fire management practices or the result of increasing environmental variability in the form of increasing temperatures and decreasing precipitation trends for this region in Southern Africa (Boko et al., 2007).

3.3 Analysis of the Trends in Fire Frequency and Seasonality for Different Land Use Categories in Northern Botswana and the Caprivi Region of Namibia from 2000 to 2010 Using the MODIS Active Fire Product

While the analysis of active fires in the previous section indicated a significant increase in fire frequencies in both regions situated in the center of the KAZA region that is consistent with predictions of the impacts of climate changes on fire regimes in semi-arid savannas as suggested in the fourth IPCC Assessment Report (Boko et al., 2007), this section presents an analysis of specific intra-annual distribution of active fires for selected land uses in the two regions. From a land use and management perspective, both the Caprivi Strip of Namibia and the Chobe District of northern Botswana are organized into a mosaic of units of protected areas, forest reserves, and communal lands. This study therefore can uniquely analyze the intra-annual distribution of fire frequency detections by MODIS per land management category for adjacent regions which are managed very differently. If the trends in fire detections are similar across regions with different management regimes, then we can assume we are detecting an underlying variability driven most likely by climatic factors. We plotted the total number of active fires detected by MODIS on a monthly basis for each of the three land use categories for each region from 2001 to 2009 and determined which months were more likely to have significant increases or decreases in fire occurrences and whether these trends were consistent across land use units (Figure 3-17). This analysis also helped reveal in more detail the monthly temporal distribution of fires throughout the year for dry and wet years, showing that the month with the highest fire incidence and recurrence is September almost in all land use units.

Even though overall September has the highest number of active fires detected for most land use categories for the nine years of this analysis, usually followed by August, Bwabwata and Mamili National Parks in Namibia consistently experience the most burning during August, followed by September, July and June. For Mamili National Park, which is a terminal wetland of the Kwando River, the phenomenon may be explained by the fact that the flood pulse from the Kwando River arrives into the park by the end of August, thus reducing the amount and quality of the fuel load. We had hypothesized there was a change in fire seasonality in Namibia vs. Botswana driven by the early-dry season mosaic burn policy instituted after 2006 and our analysis at the aggregated level in section 3.2 revealed such a change. When analyzed at the land use category level, the active fire data shows a series of significant increasing trends in fire occurrences for the month of June only in the land uses in Caprivi Strip, Namibia (Figure 3-17). Specifically, in Bwabwata National Park for the period 2001 to 2009, an increase in fires of 29% (r^2 = 0.76) was recorded in June, with a similar increase of 28% in September (r^2 = 0.46) and 19% in July (r^2 = 0.33), while for Mudumu National Park, the most significant increase in fire occurrences was also recorded in June, by 12% (r^2 = 0.56). The communal lands in Eastern Caprivi of Namibia, including both areas managed for wildlife conservation (conservancies) and areas primarily used for agriculture and cattle grazing, show an increase in fire frequencies in September of 74% from 2001 to 2009 (r^2 = 0.80) and of only 4.6% (r^2 = 0.17) during June (Figure 3-17). This may be explained by more aggressive early-dry season burning program implementation in the two main protected areas of Caprivi for wildlife viewing and tourism promotion in the region (Bwabwata and Mudumu national parks). The largest state forest reserve in Caprivi located just east of Bwabwata also shows a significant increasing linear trend in fire frequencies during September of 23% (r^2 = 0.71).

In northeastern Botswana, the increasing trends in fire occurrences are consistent across all three land use categories for the month of September, namely by 101% (r_2 = 0.20) in Chobe National Park, by 16% (r^2 = 0.32) in the two forest reserves adjoining the national park, and by 24% (r^2 = 0.62) in the communal lands to the north of the park and across the border from Namibia (Chobe Enclave Conservation Trust). This analysis, therefore, shows that fire frequencies have increased across all land use categories of Eastern Caprivi and northeastern Botswana during the last decade, with the most significant increases occurring in September irrespective of the fire management policy of each country. This may indicate that the underlying cause for the changes documented can be attributed to climatic changes and variability.

4. Summary and Conclusions

Increasing climatic and environmental variability add to the already high uncertainty and difficulty of assessing and understanding fire regime changes (Thompson and Calkin, 2011). As outlined in the latest IPCC report, rainfall change and variability is very likely to affect southern African savanna vegetation by reducing cover and productivity in response to the observed drying trend of about 8 mm/yr since 1970 and also to affect the timing and distribution of fires throughout these fire-controlled ecosystems (Bond et al., 2005; Woodward and Lomas, 2004). Furthermore, increasing human populations in southern Africa and the tendency towards stricter fire suppression policies lead to a need to assess the potential effects of changes in fire regimes before introducing new fire management policies (Sheuyange et al., 2005). In response to these perceived needs, we analyzed changes in several components of fire regimes in Africa's largest transfrontier conservation area during the last decade using two fire products derived MODIS platform data in conjunction with climatological data.

We were specifically interested in whether fire management is expressed in the landscape in the form of changes in the annual extent of burned area in protected areas managed differently across the five countries of KAZA and we used the MODIS burned area product to test this hypothesis. We concluded that protected areas in Angola and Zambia have highest rates of fire recurrence (most frequent burning), with anywhere between 30 and 84% of their total area burned every year, followed by Namibia.

Mudumu National Park in Namibia, a small park, not managed very effectively, for example, averages between 58-99% of its area burned annually. The two national parks in Botswana and Zimbabwe, on the other hand, are characterized by fairly low rates of fire recurrence and low, between 0 and 15%, proportions of their total area burned in any given year.

The end objective of using the MODIS burned area product was to create a fire recurrence index (FRI) map for the central KAZA region for the last decade, showing the areas most likely to burn most frequently in the region. This represents a first attempt in the literature to map the spatial and temporal distribution of fires in the form of a spatio-temporal index for this transfrontier conservation region in Southern Africa which is becoming increasingly important, ecologically and economically for all the five member countries.

Secondly, we wanted to understand the general trends in fire frequency and seasonality changes between two neighboring countries (Namibia and Botswana) with different fire policies and management and to test whether there is an increasing trend in fire occurrences irrespective of expressed fire policies and management regimes. We determined that approximately 29-55% of area in Caprivi burns every year, with only approximately 1-10% of the area in Northern Botswana experiencing the same fire frequencies. We also observed significant increase in fires in Caprivi before and after the introduction of the early-dry season burn program, and, consequently, a significant change in fire seasonality in Caprivi. Finally, we showed that fire frequencies have increased across all land use categories of Eastern Caprivi and northeastern Botswana during the last decade, with the most significant increases occurring in September irrespective of the fire management policy of each country. This may indicate that the underlying cause for the changes documented in fire frequencies in this region can be attributed to climatic changes and variability.

Ultimately, our analysis provides an example of the applicability and usefulness of the MODIS fire products to land management officials and practitioners in southern Africa in response to some of the issues we detected in our key informant interviews and concerns documented in the literature regarding the relatively low adoption of these fire products for applied fire management interventions (Trigg and Roy, 2007).

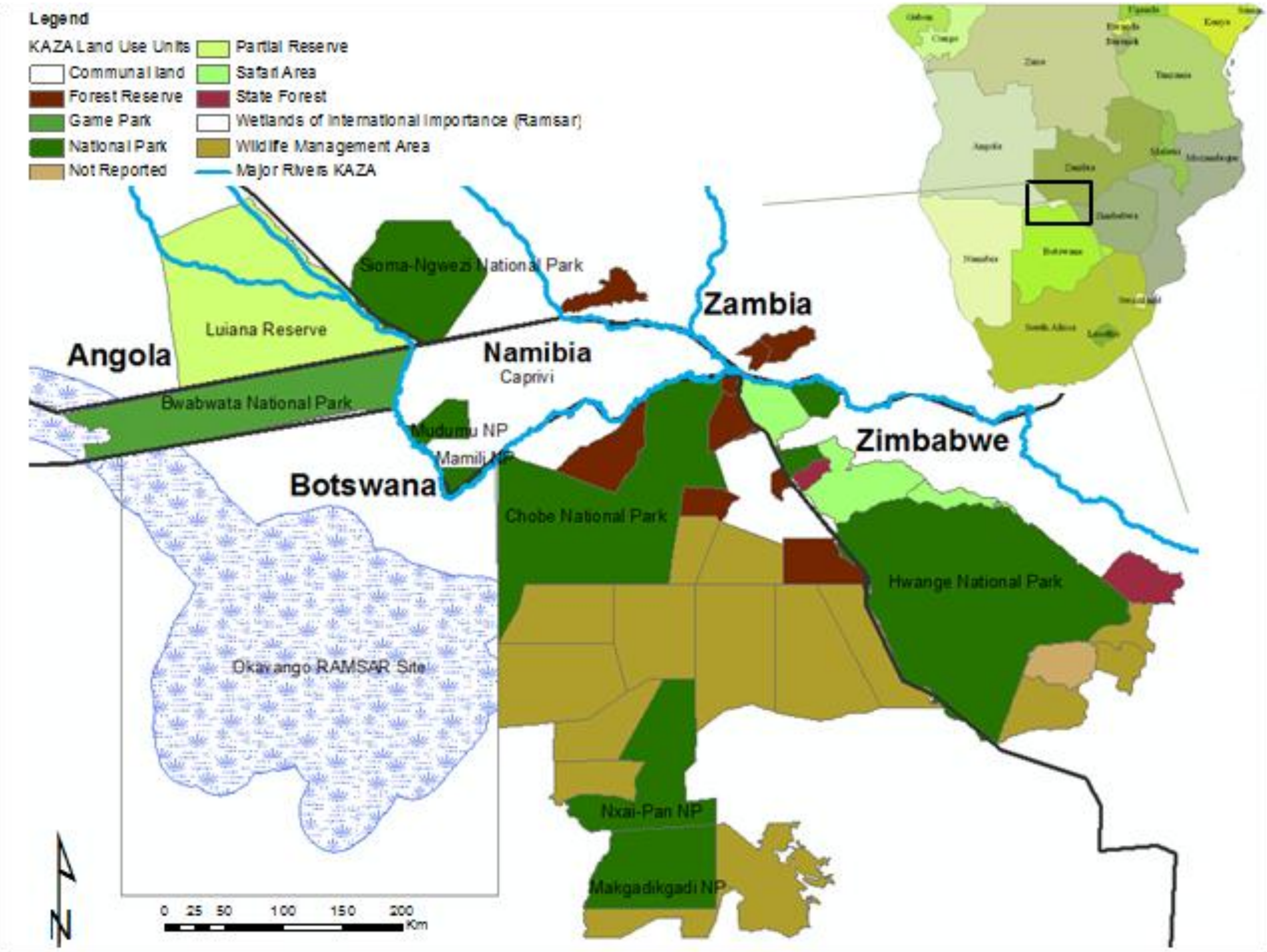


Figure 3-1. Study area of the central Kavango-Zambezi Transfrontier Conservation Area (KAZA) in Southern Africa, showing the protected areas and other land management categories as designated by the World Database on Protected Areas (WDPA).

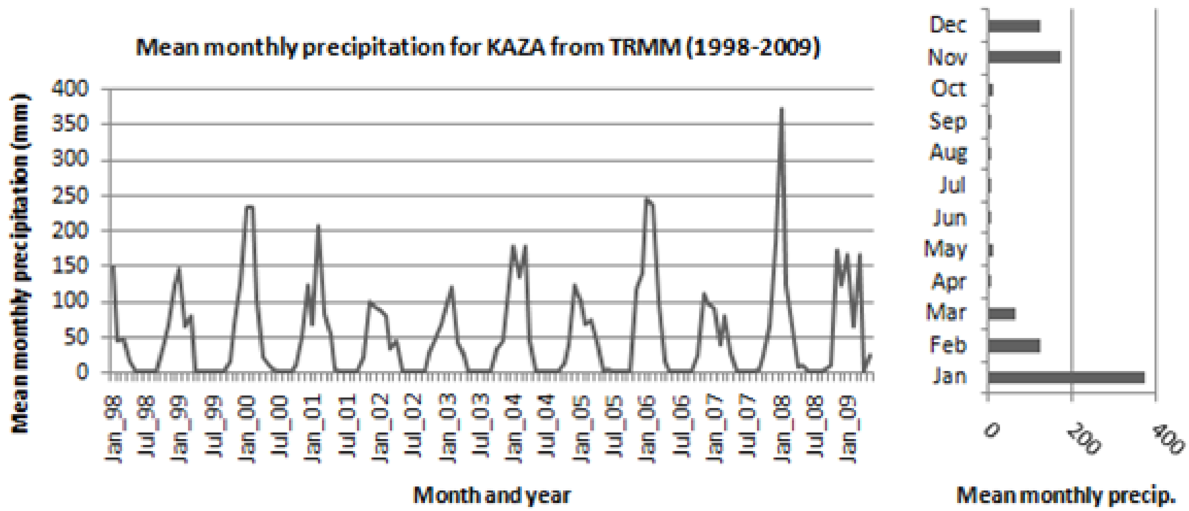


Figure 3-2. a) Mean monthly rainfall data from the Tropical Rainfall Measuring Mission (TRMM) for the period January 1998 to May 2009 for the central KAZA region and b) mean monthly rainfall for 2008 showing the intra-annual typical distribution of precipitation in mm.

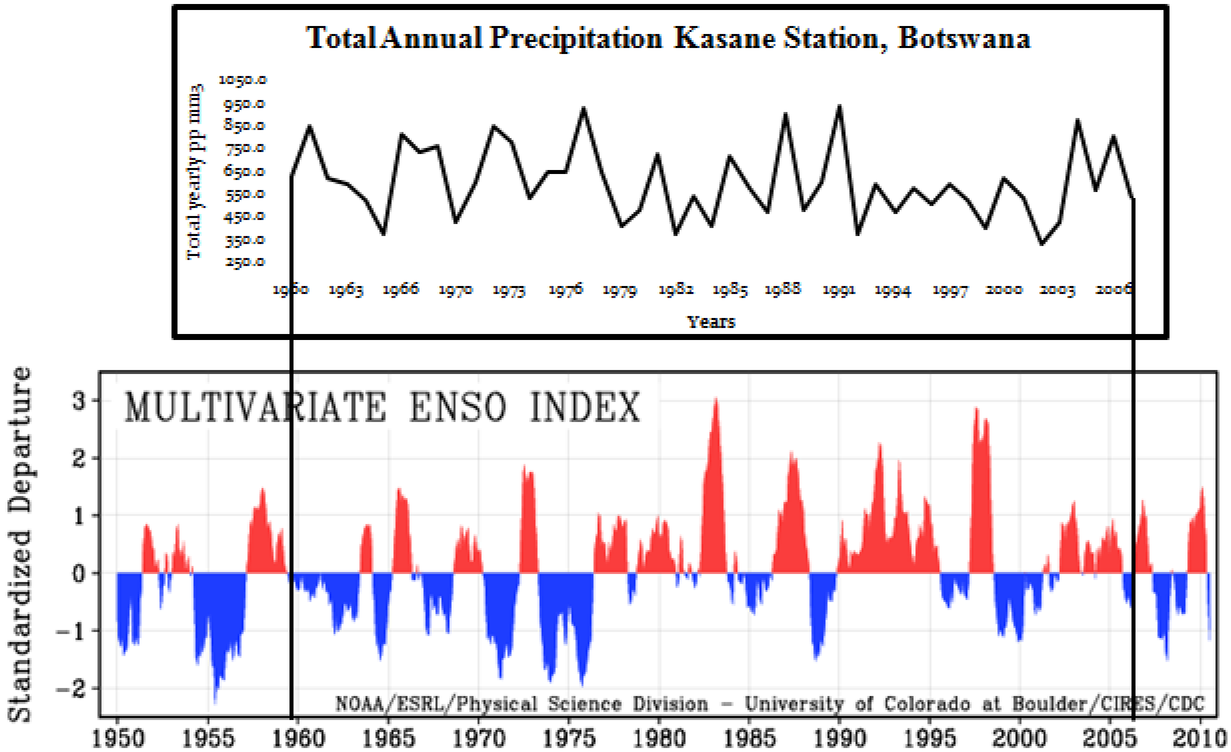


Figure 3-3. Total annual precipitation at the Kasane meteorological station in Botswana between 1960 and 2007 and the Multivariate ENSO Index for 1950 to 2010. Note the correspondence between the dry ENSO conditions between 1990 and 1995 and low annual precipitation values recorded in central KAZA (Precipitation data source: Department of Meteorological Services, Botswana; MEI data source: Wolter and Timlin, 1998).

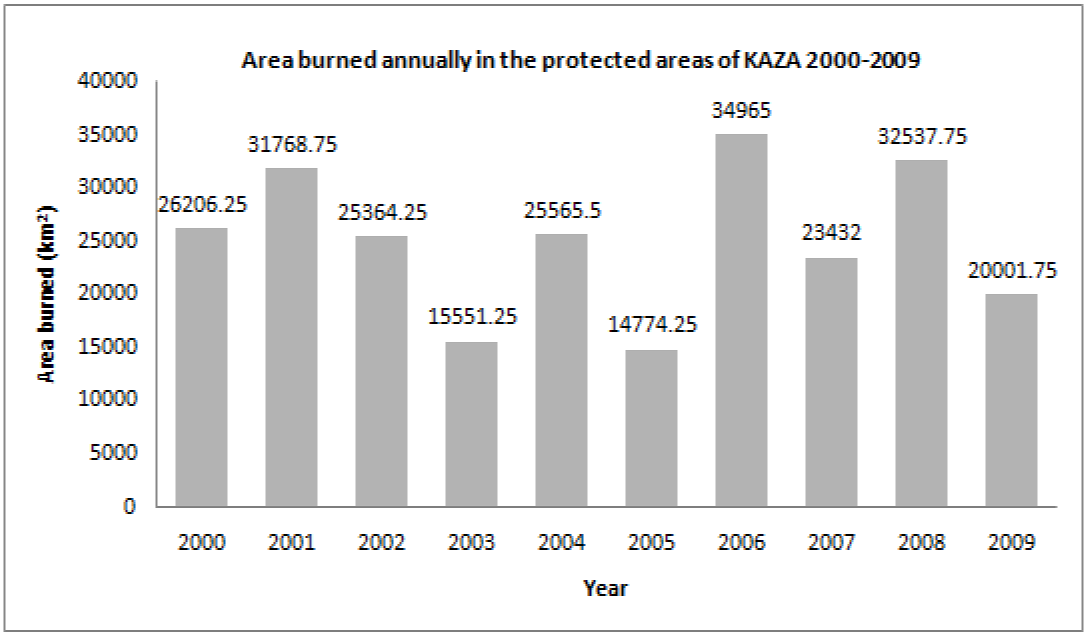


Figure 3-4. Total area burned annually in the protected areas of the central KAZA region from 2000 to 2009 in km^2 based on the MODIS Burned Area product data.

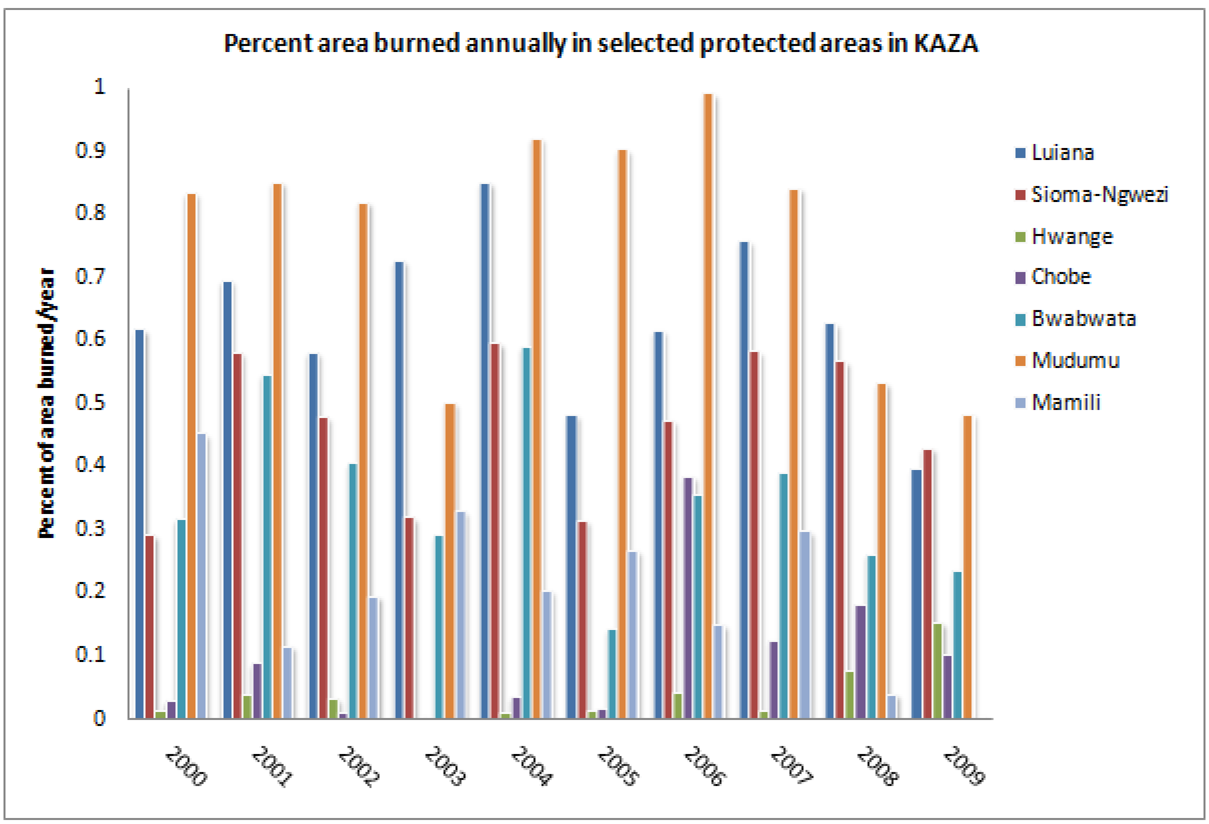


Figure 3-5. The proportion of area burned on an annual basis in the protected areas of central KAZA from 2000 to 2009.

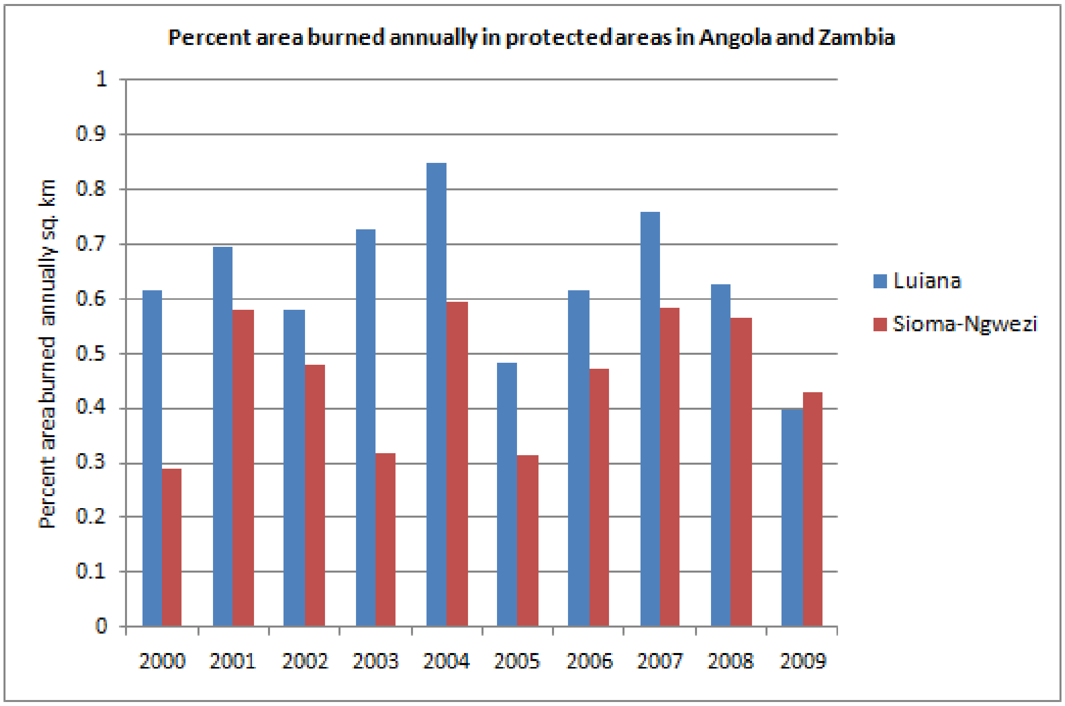


Figure 3-6. Percent area burned annually as a function of total area in the protected areas of Angola (Luiana Partial Reserve) and Zambia (Sioma-Ngwezi National Park) from 2000 to 2009.

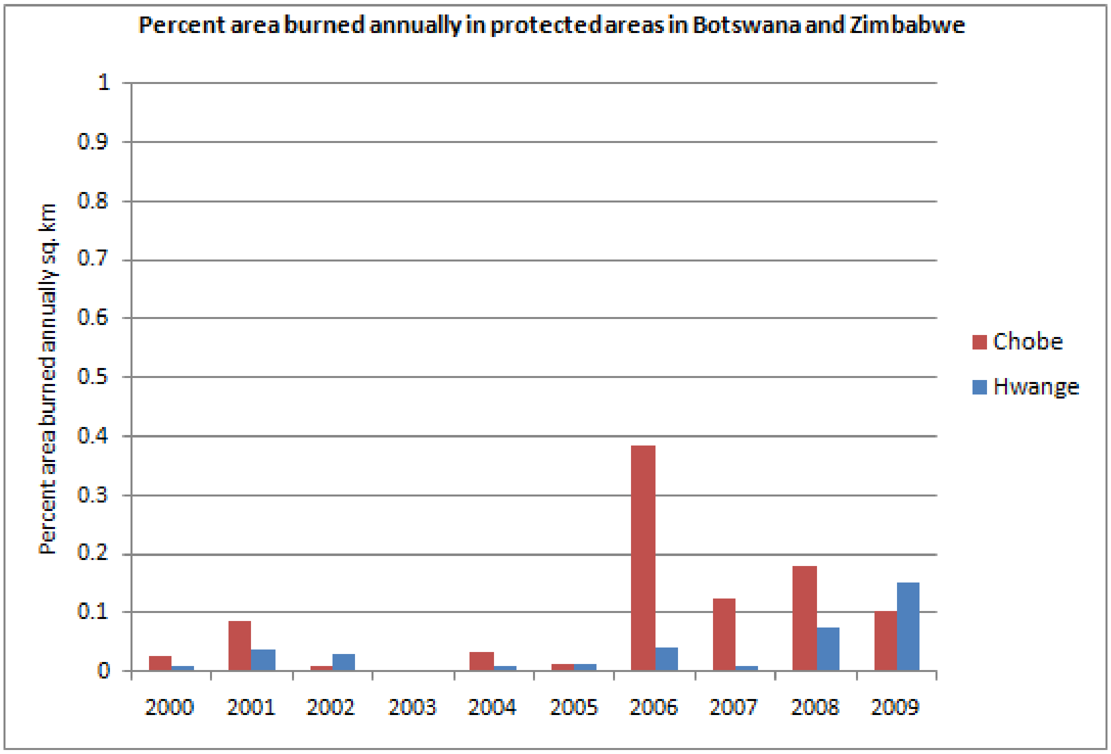


Figure 3-7. Percent area burned annually as a function of total area in the protected areas of Botswana (Chobe National Park) and Zimbabwe (Hwange National Park) from 2000 to 2009.

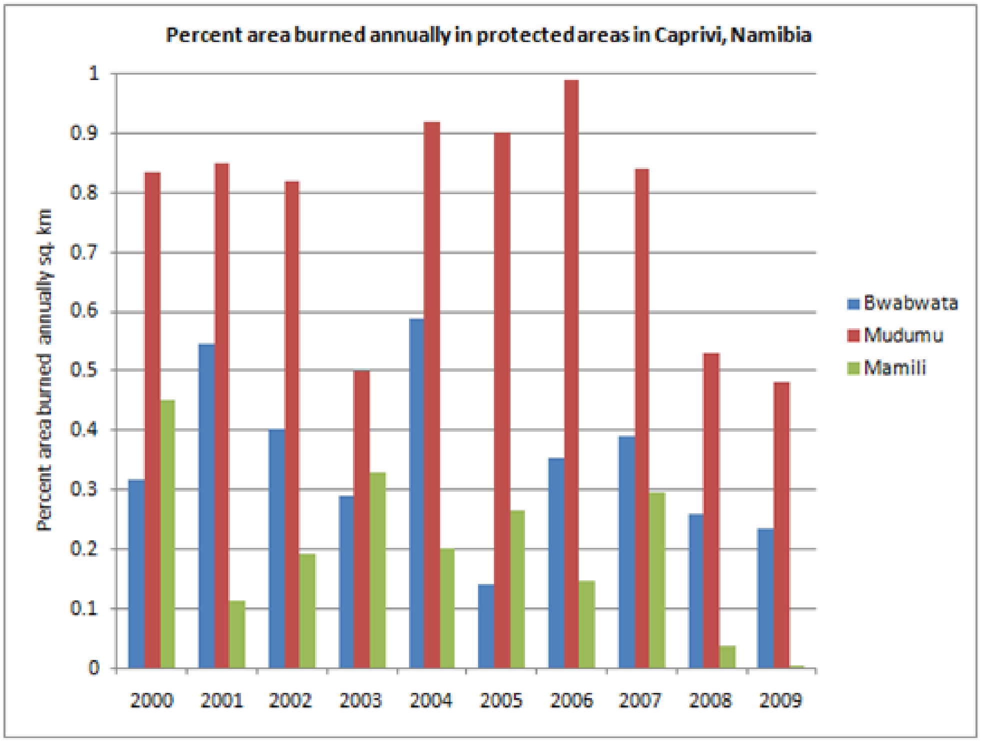


Figure 3-8. Percent area burned annually as a function of total area in the three protected areas of the Caprivi Region, Namibia (Bwabwata, Mudumu and Mamili National Parks) from 2000 to 2009.

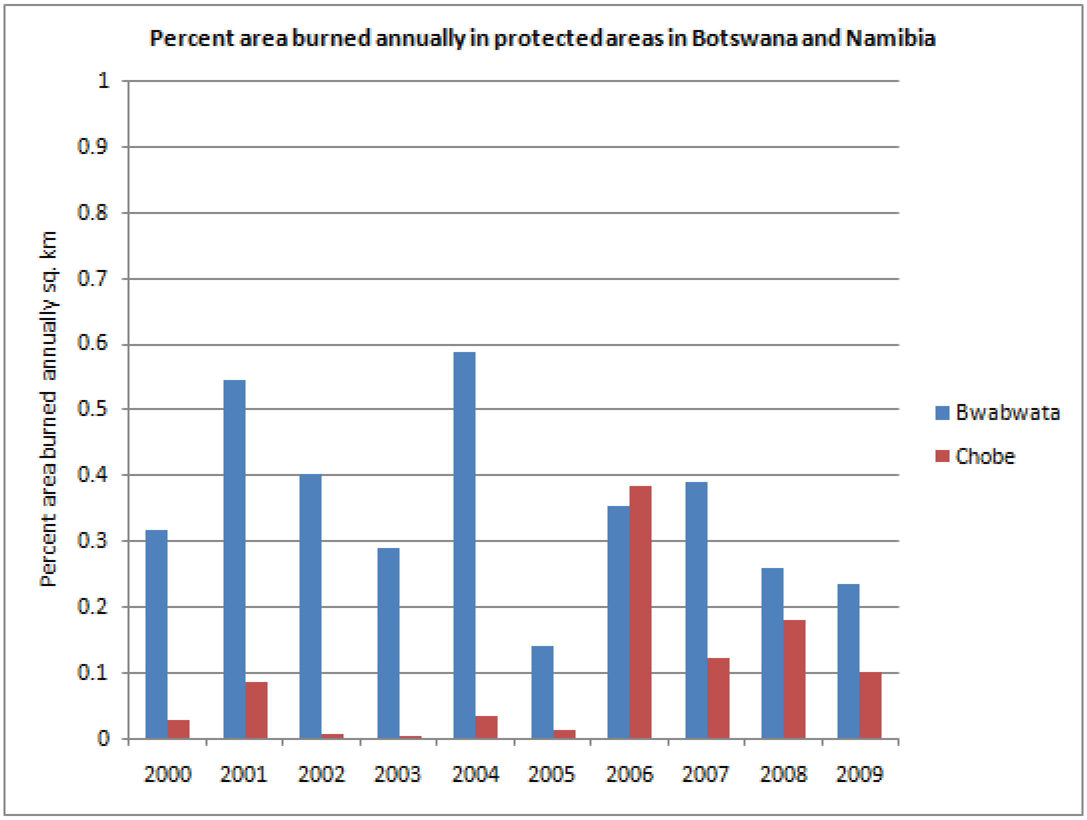


Figure 3-9. Percent area burned annually as a function of total area in Namibia's Bwabwata National Park and Botswana's Chobe National Park from 2000 to 2009.

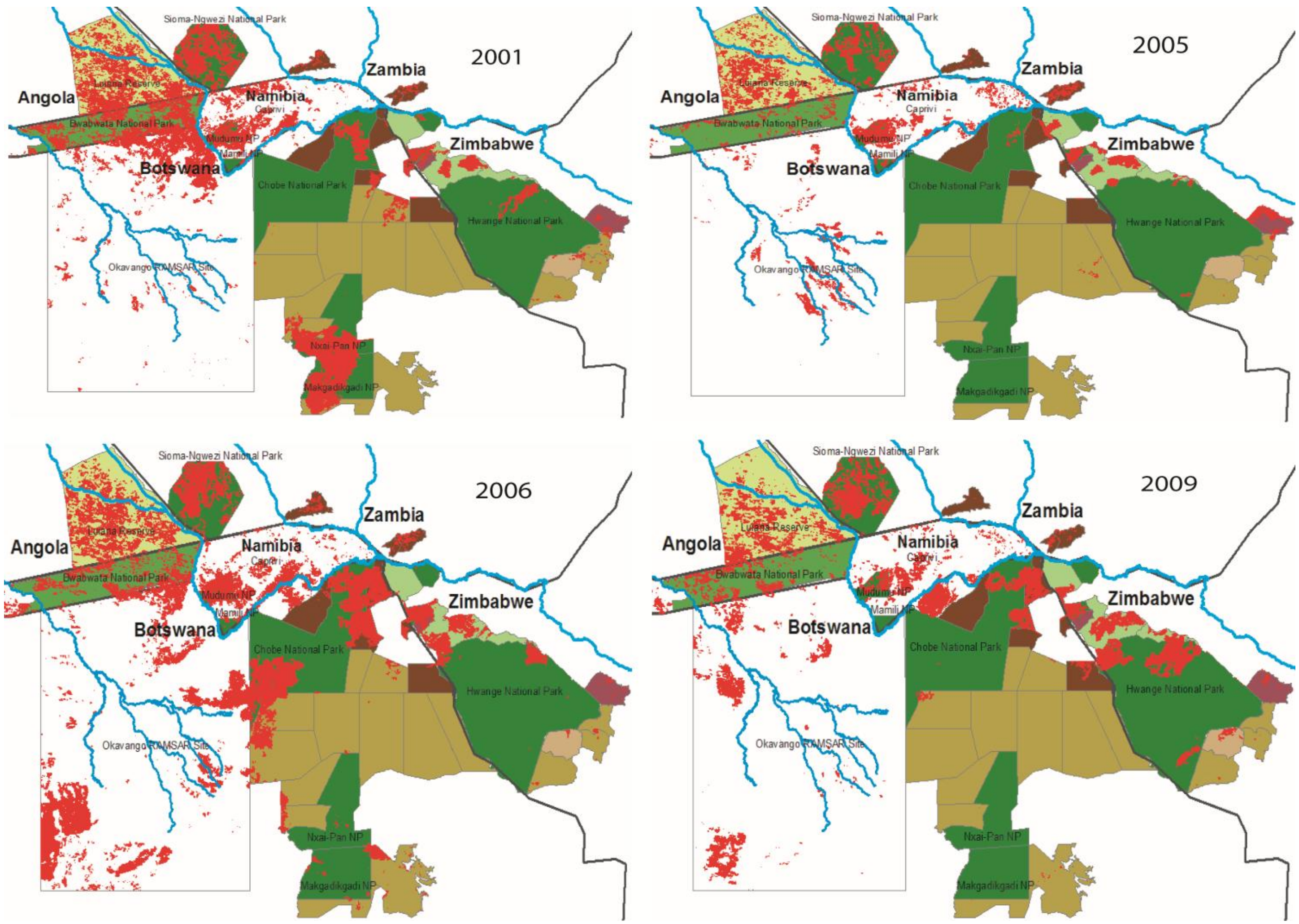


Figure 3-10. Burned area derived from the MODIS MOD45A1 product for selected years in our analysis: 2001 and 2009, both wet years preceded by 2 wet years (based on MEI data) and 2005, the smallest extent of burned area for the region and 2006, the largest extent of area burned. The land management categories are the same as in Figure 1.

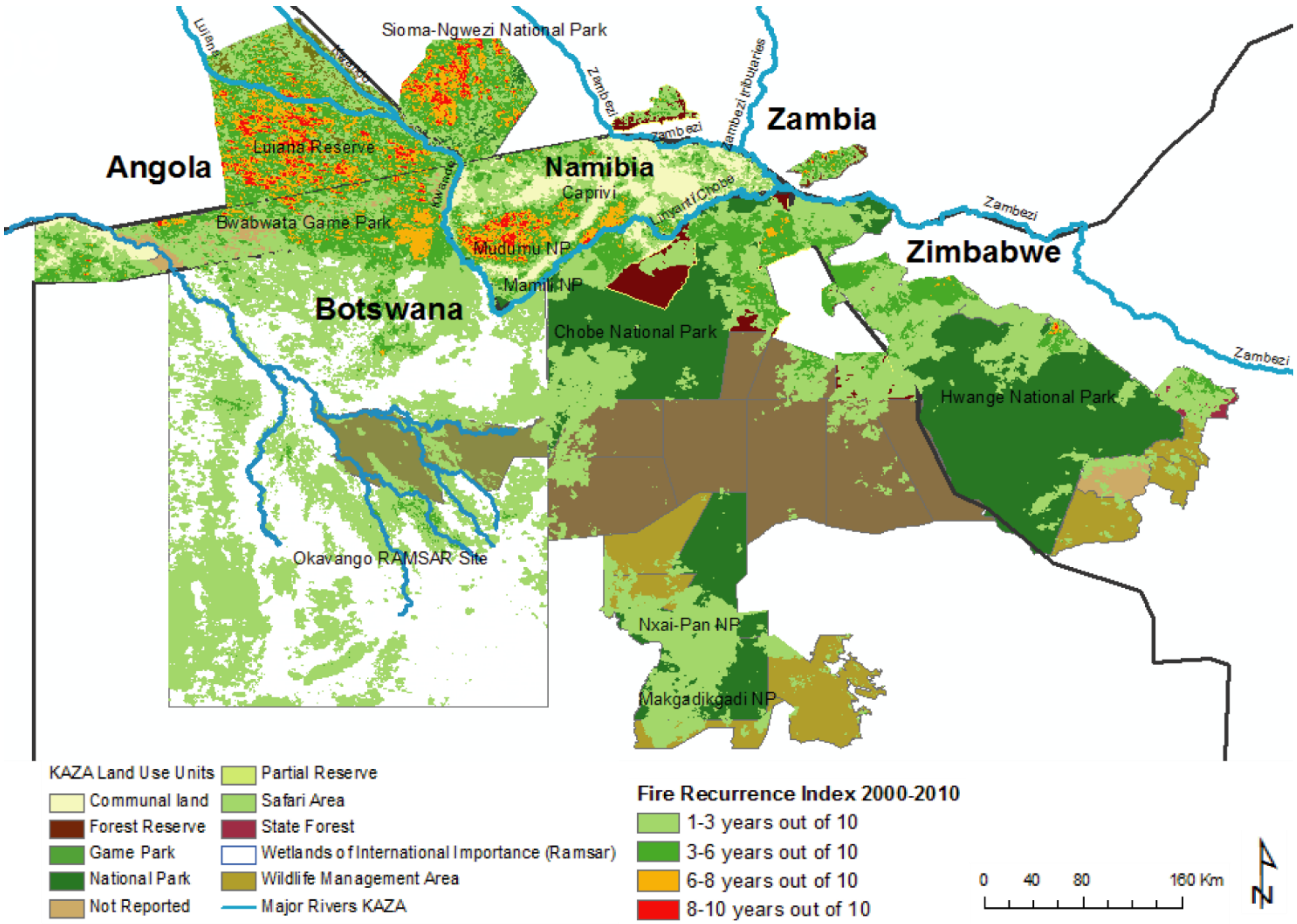


Figure 3-11. Map of central Kavango-Zambezi Transfrontier Conservation Area (KAZA) showing the spatial extent of a fire recurrence index (FRI) calculated using monthly MODIS Burned Area data from 2000 to 2010 for all land use categories in the region. The scores which make up the FRI represent the number of years an area is burned aggregated from monthly spatial extents of burning.

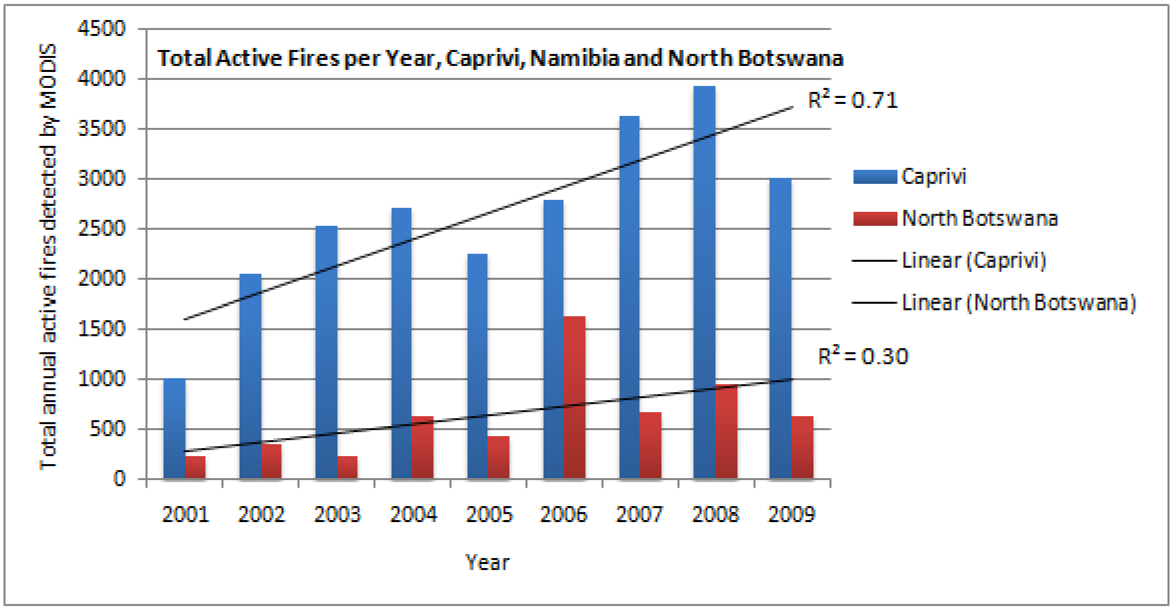


Figure 3-12. Total annual active fires detected by MODIS from 2001 to 2009 for the Caprivi Strip of Namibia.

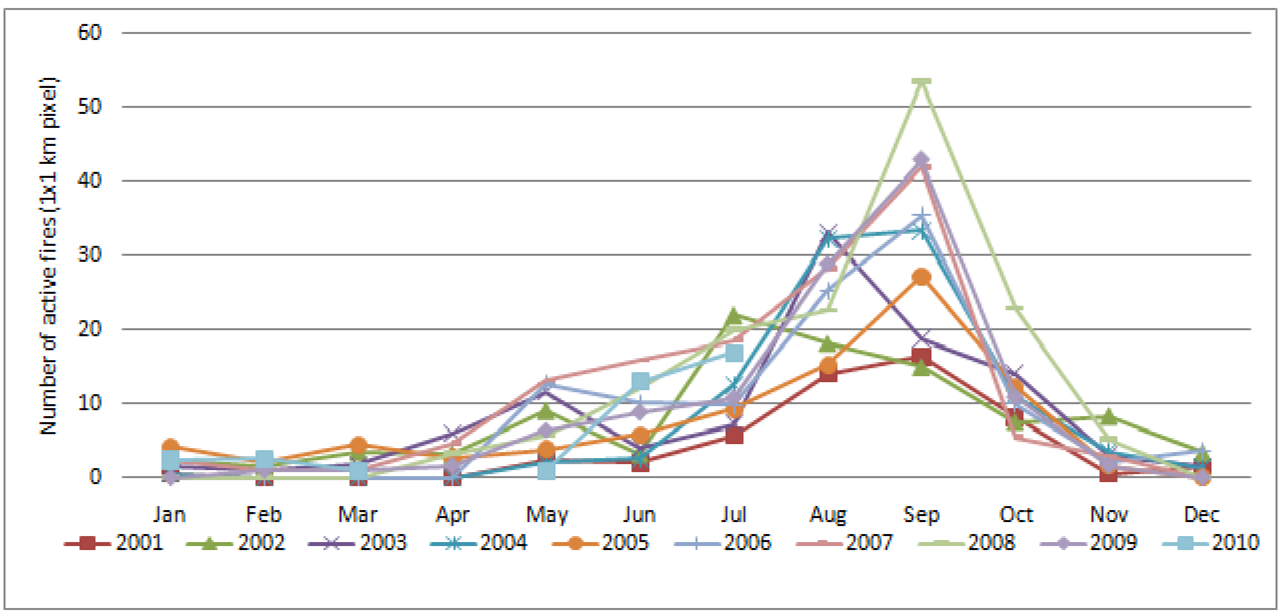


Figure 3-13. Mean monthly number of active fires for the Caprivi Strip, Namibia from 2001 to 2010, calculated using the MODIS Active Fire product.

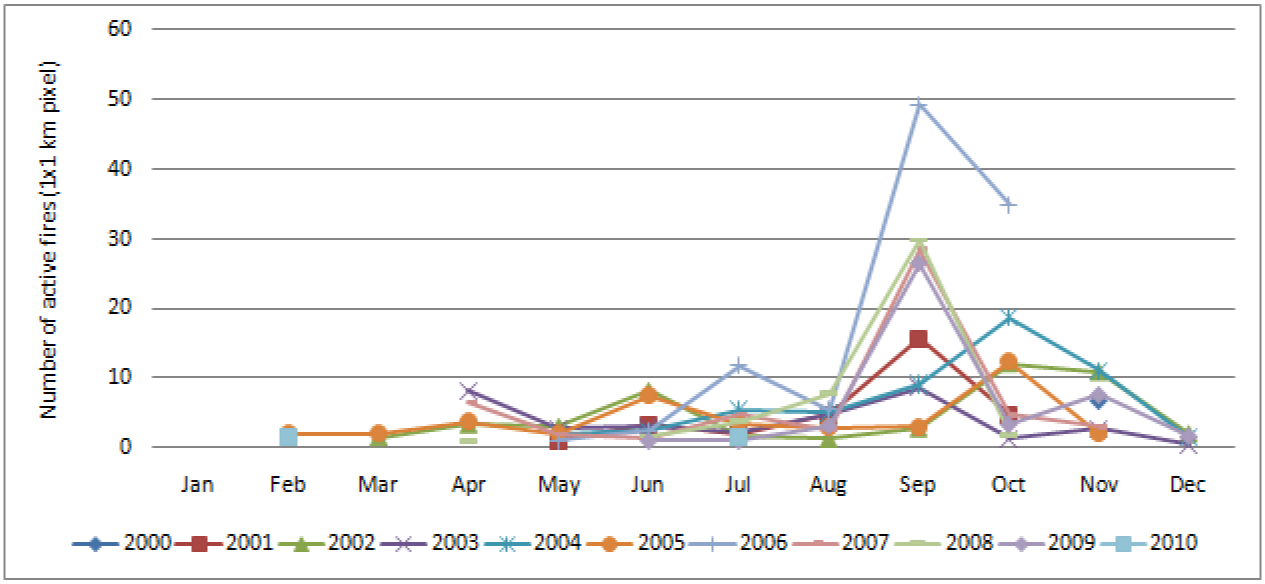


Figure 3-14. Mean monthly number of active fires for the Northern Botswana from 2001 to 2010, calculated using the MODIS Active Fire product.

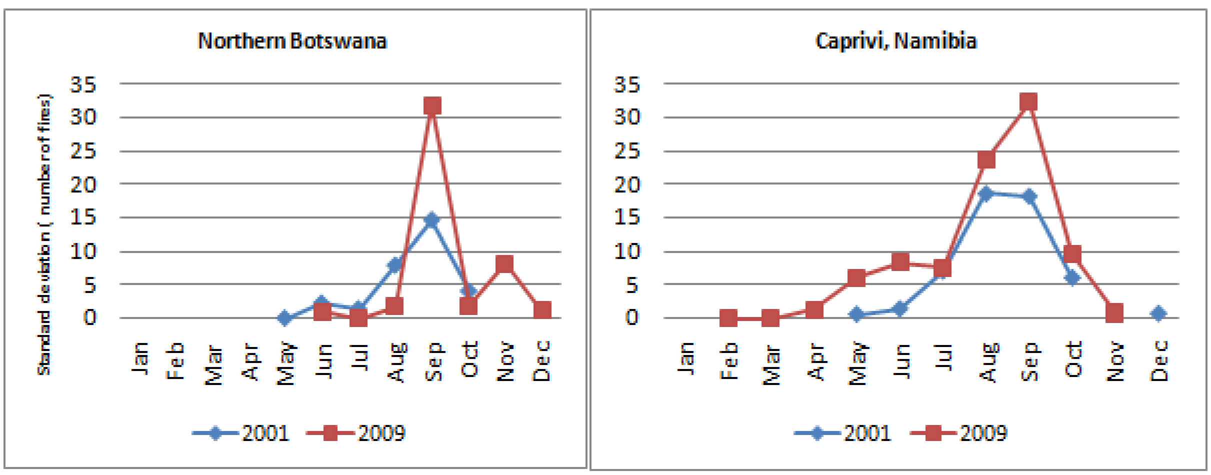


Figure 3-15. Intra-annual standard deviation ranges for the aggregated land uses of northern Botswana and the Caprivi Strip in Namibia for 2001 and 2009 based on MODIS active fire detections data.

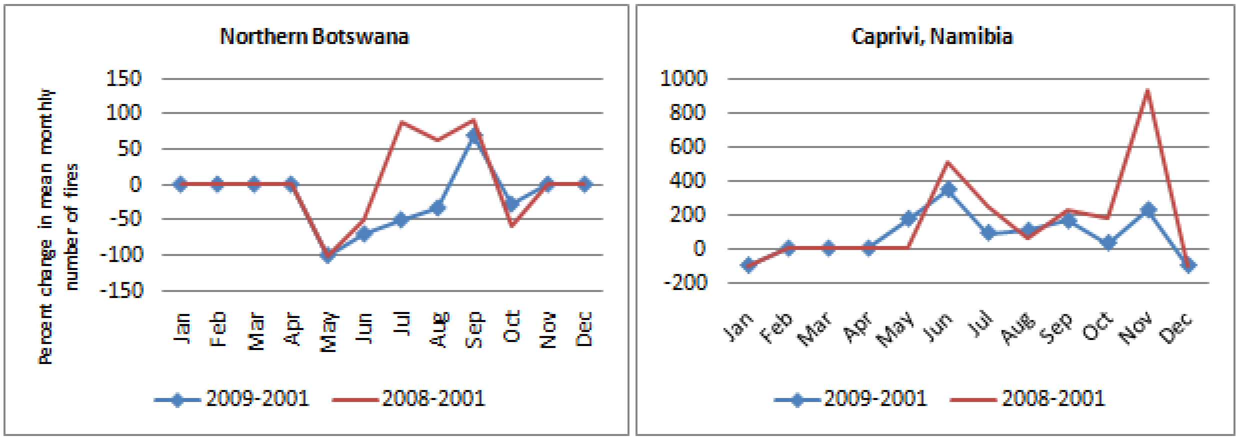


Figure 3-16. Intra-annual changes in fire frequency and seasonality for northern Botswana and Caprivi, Namibia between 2001 and 2008 and 2001 to 2009.

Figure 3-17. Monthly distribution of total active fires detected by MODIS between 2001 and 2009 for eight different land use categories (protected areas, forest reserves, and communal lands) in Botswana and Namibia, central KAZA. The liner trend line shown is for the month of September for all units except for Bwabwata and Mudumu National Parks in Namibia which experienced the most significant increases in total active fires detected during June.

Table 3-1. Summary of the data types, sources and temporal extent of data used in the analysis.

Data categories	Data type	Data source	Temporal availability
Land use and protected area data	2009 protected area data-layer	World Database on Protected Areas (WDPA)	2009
	2008 GIS land use units layers	National Planning Commission, Namibia	2008
Remotely-sensed data	MODIS Active Fires (MOD15GD)	MODIS ILUCI Dataset (U of Maryland)	Nov. 2000 – April 2010
	MODIS Burned Area (MOD45A1)	U of Maryland Global Land Cover Facility	April 2000 – April 2010
	Landsat Quicklooks	National Remote Sensing Center (Namibia)	1989 to 2007
Climatologic data	Multivariate ENSO Index (MEI)	National Oceanic and Atmospheric Administration	1950-2010
	Station rainfall data	Department of Meteorological Services Botswana	1945-2008
	Tropical Rainfall Measuring Mission (TRMM) rainfall data	NASA's Goddard Space Center	1998-2009
Field data	Semi-structured key informant interviews	2007 and 2009 field seasons, Botswana and Namibia	2007, 2009

CHAPTER 4
SPATIAL AND TEMPORAL ANALYSIS OF VEGETATION DYNAMICS IN A TRANSBOUNDARY SOUTHERN AFRICAN SAVANNA WATERSHED

1. Vegetation Dynamics and Global Environmental Change

After decades of research and improved change-detection capabilities, it continues to be extremely important to monitor vegetation dynamics using long-term, repetitive satellite-derived data in the sensitive semi-arid savanna and drylands regions of the world. That is important not only to asses states and trends, but particularly to improve the prediction capabilities of climate models and to enable them to capture vegetation variations induced by large-scale climate teleconnections such as El Niño Southern Oscillation better (Kandji et al., 2006). The warming trend recorded in southern Africa over the last several decades, consistent with the global rise in temperatures starting with the 1970s, has also been accompanied by a warming of the adjacent Indian Ocean of more than 1^{o}C since the 1950s (NCAR, 2005). This period, particularly since the 1980s, has also seen declines in overall precipitation amounts, increasing spatial and temporal variability of rainfall, and an increase in the frequency and intensity of El Niño episodes (Nicholson et al., 2001; Gaughan and Waylen, 2011). Such a decreasing trend in precipitation and increasing climatic variability can have direct impacts on vegetation productivity and in turn lead to the creation of a positive feedback mechanism between decreasing vegetation cover and a further decrease in precipitation due to increasing albedo, corresponding radiative cooling of the overlying air and a subsequent enhancement of large-scale atmospheric subsidence leading to less precipitation (Oyama and Nobre, 2003). Furthermore, ongoing clearing and degradation of savannas increases temperatures and wind speeds and decreases precipitation and relative humidity, thus creating warmer and drier climates, which, in turn, substantially increase fire frequencies and leads to tree cover loss and vegetation degradation (Hoffmann et al., 2002).

More specifically, the last decade has experienced a decrease in net primary productivity (NPP) associated with large-scale droughts primarily in the southern Hemisphere and specifically in the southern African region (Zhao and Running, 2010). Decreases in NPP associated with natural climate variability are exacerbated in this region by land use and management decisions and are further accentuated by changes in wildfire and flooding regimes, changes and increases in wildlife herbivory and livestock grazing.

The research question in this paper is "What is the general trend of vegetation in the Chobe River Basin (CRB), a transboundary, differentially-managed watershed shared between Namibia and Botswana, and how is the trend linked to regional inundation pulses and interannual fire regimes." We analyze changes in patterns of annual and multi-date vegetation indices as a function of changes in patterns of fire and flooding for the last decade in a spatial coincidence analysis framework. We use vegetation indices measured from satellite imagery data in the form of a normalized difference vegetation index (NDVI) from 1985 to 2010, specifically emphasizing 2000 to 2010. Secondly, based on indices of flooding and fire recurrence regimes for this region, we determine the level of correlation of the spatial patterns of NDVI variability with the patterns of vegetation change through time.

The effects of rainfall variability on vegetation dynamics especially in relation to ENSO phases by using satellite-derived NDVI data has been thoroughly documented (with reported strong positive relationships between rainfall and NDVI), particularly for southern Africa (Nicholson et al., 1990; Anyama and Eastman, 1996; Barbosa, 2004). Generally, ENSO events (El Niño) cause droughts which lead to decreases in NDVI which is a proxy for both the amount of standing biomass and controlled by antecedent and concurrent rainfall conditions in semi-arid regions (Barbosa et al., 2006). NDVI has been successfully used in similar ecosystems as a proxy for mean monthly rainfall, apart for also being well correlated with the amount and seasonality of above-ground net primary production and vegetation biophysical parameters such as leaf area index, green leaf biomass, and leaf photosynthetic activity (Tucker et al.; 1985; Curran, 1980; Barbosa et al., 2006). We use NDVI as a proxy for rainfall and do not directly account for rainfall in our analyses, emphasizing instead patterns of vegetation productivity in relation to changes in flooding and fire regimes.

1.1 The Interaction between the Main Drivers of Change in Semi-Arid Savanna Ecosystems

The semi-arid savannas in southern Africa have been disturbed by human-induced changes, both directly and indirectly (climate change and variability and associated effects) and have been recognized by Geist and Lambin (2004) to be among the systems in the world most susceptible to continued and increasing degradation and even desertification. Many different factors interact in driving vegetation conversions and changes in semi-arid savannas, such as the temporal and spatial distribution of precipitation, natural and anthropogenic fire regimes, grazing and herbivory by both livestock and wildlife populations, inundation regimes in flood-adapted ecosystems, increasing human populations and a suite of land management decisions and practices.

Higher human population pressures in our study region (especially in the Caprivi Strip of Namibia) led to an intensification of land uses. Fire remains the most viable land management tool for the large numbers of subsistence farmers (Hoffmann et al., 2002). Grazing, similarly to fire, has been a factor of change in savanna ecosystems for millennia; however, with increasing human population and demands on savanna productivity, the impact of both is becoming increasingly important. Van Langevelde et al. (2003) demonstrated the positive feedback between grazing intensities (directly affecting biomass availability and fuel loads) and fire intensity and frequency. More grazing leads to reduced fuel loads, thus less intense fires with a less damaging impact on trees and, consequently, an increase in woody vegetation. In the absence of fires, semi-arid savanna grasslands would become closed forests (Swaine et al., 1992; Bond et al., 2005). Therefore, grazing, through its negative effect on fire frequency, when coupled with droughts and high scrub density is one of the primary factors determining vegetation alterations, particularly woody species encroachment (Roques et al., 2001, Moleele et al., 2002, Fensham et al., 2005). Increased shrub densities have negative effects on livestock carrying capacity, biodiversity, and soil moisture availability (Tews et al., 2006, Kutt and Woinarski, 2007). Increasing elephant (*Loxodonta africana)* populations in southern Africa are also constantly modifying the dynamics of savanna ecosystems by conversing woodlands to shrublands at a rapid pace in some regions (Nellemann et al., 2001, Rutina et al., 2005). Also, while initially wood-clearing practices were employed as a means of restoring the grazing potential of savanna rangelands, more recently commercial harvesting of larger trees for charcoal and fire has become more prevalent (Milton et al., 2001).

While the interaction between precipitation, drought, fire, and grazing on arid environments has been the subject of considerable research, less is known about the effects of flooding or its lack in flood-adapted ecosystems, and how it interacts with other factors in driving landscape-level vegetation dynamics (Westbrooke and Florentine, 2005). Westbrooke et al. (2005) have shown that flooding was the most important factor for determining changes in vegetation composition in an arid basin in Australia, while fire and grazing were of much less importance, as water availability directly affects rooting depth for grasses vs. shrubs. For example, Ringrose et al. (2007) concluded that water-table lowering, driven by localized desiccation, and resulting in increased soil salinization lead to invasions by relatively shallower-rooted woody vegetation in the semi-distal areas of the Okavango Delta in Botswana. Westbrooke and Florentine (2005) also showed that perennial grass and perennial shrubs are the most likely to be influenced by rare flooding events which means that water availability is a significant control in grassland-to-scrub transitions. As surface layers become drier, the density of shrub species increases and species are selected based on their ability to access water in deeper layers of the soil horizon.

1.2 Study Area and Background

CRB (Figure 4-1) is part of the Kalahari Desert, and is characterized by a relatively flat terrain with a relatively small relief (Field, 1978). In the Chobe National Park region, elevations range only from 910 to 1050 m (Omphile and Powell, 2002), while for the rest of the study area from the range is approximately 830 to 980 m. CRB is located in the region of subtropical dry climates characterized by an alternating dry and wet season. Precipitation in the Chobe Basin is seasonal, influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), with the wet season occurring during the summer between November and April. The variability in precipitation patterns is also related to El Niño Southern Oscillation (ENSO) events. Annual average rainfall is approximately 640 mm. The period from May to October represents the dry season, when the mean maximum and mean minimum monthly temperatures during October (hottest month) of 39 ◦C and 14 ◦C respectively are reached. The coldest month is July, with a mean max temperature of 30 ◦C and a mean min monthly temperature of 4 ◦C (Child and Von Richter, 1968; Barnes, 2001; Nelleman et al., 2002).

The predominant vegetation types in the communal lands along the Chobe River are *Acacia tortilis* woodlands along the river (actively being ring-barked or pushed-over by elephants), grasslands in the lower floodplain areas, and mixed woodlands of *Combretum eleagnoides, Lonchocarpus nelsii,* and *Acacia erioloba* on the higher-elevation ridges. Bush encroachment by species such as *Dichrostachys cinerea*, *Terminalia seriscia*, *Combretum hereorense*, and *Acacia erioloba* has been recorded during the training sample collection process especially in areas that maintain signs of recent overgrazing by cattle (abandoned corrals) or areas that appear to be less moist than they used to be in the past (personal observations, 2007 and 2009). In Chobe National Park, along the river on the alluvial soils is a thin strip of riparian forest followed by shrublands dominated by *Capparis tomentosa* and *Combretum mossambicense.* This area has slowly transitioned to shrubland on the alluvial soils which earlier had large *Acacia* and *Combretum* trees. Farther away from the river, on Kalahari sandridge, woodlands with *Baikiaea plurijuga* occur (Makhabu, 2005). The vegetation structure in the forest reserves is most similar to the sandridge regions in Chobe National Park. It consists mainly of an overstory of *Baikea plurijuga* of different heights and densities, and an understory made up of *Combretum eleagnoides* and/or *apiculatum* and *Croton gratissimus* (personal observation, 2007 and 2009).

The study area is a mosaic of land-use and management units: subsistence communal lands predominantly utilized for livestock grazing (Chobe Enclave Community Trust, CECT) or agricultural lands (Salambala Conservancy), two differently-managed forest reserves (Chobe and Kasane Forest Reserves), three national parks (Chobe National Park in Botswana, and Mudumu and Mamili National Parks in Namibia), and an urbanizing area, the town of Kasane (Figure 4-1). Significant vegetation changes have occurred in this region in the last thirty years, possibly caused by significant increases in wildlife populations, decreases in rainfall and river inundation extent, and increasing human population and utilization by cattle (Mosugelo et al., 2002; Skarpe et al., 2004; Rutina et al. 2005).

Chobe National Park (CNP), established in 1967, is the second largest park in Southern Africa with a total extent of 10,566 km^2 and one of the largest elephant populations in Africa (over 120,000 individuals, CSO 2004). Significant vegetation degradation is occurring in the park, especially in the areas adjacent to the river where most wildlife is concentrated during the dry season. Work along the Chobe floodplain in the park indicates severe vegetation degradation: tree species loss and a shift in tree species composition from predominantly *Acacia nigrescens* to an overwhelming dominance by *Croton megalobotrys*, a fast-growing tree species (A. Wolf, Masters' Thesis, 2008). While in 1965 nearly 47% of riparian trees were untouched by elephants or had few healed scars, there were no trees observed without elephant damage recently (Wolf, 2008). Mudumu NP (only partially included within the boundaries of

CRB) and Mamili NP are much smaller by comparison and were established in the 1990s.

Chobe and Kasane Forest Reserves were established in the 1980s for the protection of economically-important tree species (*Baikea plurijuga* especially) and are currently managed by the Department of Forestry and Range Resources, Botswana. They are both separated from the park and adjacent land use units by an extensive network of firebreaks and are being actively managed for prevention of anthropogenic fires, usually originating from Zimbabwe (especially for Kasane Forest Reserve). Evidence of elephant damage abounds in both forest reserves, especially in areas originally cleared in the 1990s by a Zimbabwean logging company (personal observations through fieldwork, 2007 and 2009).

The communal lands (organized and managed as community-based organizations in Botswana and conservancies in Namibia) in both countries are primarily used for subsistence agriculture, cattle grazing, and photographic and hunting safaris. The potential effects of grazing and fire suppression in these communal areas, especially in and around mobile cattle posts, are expressed in areas of thick scrub. Key informant interviews with locals have revealed growing concerns about the disruption of agriculture by increasing elephant numbers no longer constrained to the park boundaries, expansion of bush encroachment due to an increased emphasis on cattle grazing, and drought-induced risks. Salambala Conservancy for instance, the largest community-managed area in the Eastern Caprivi of Namibia, is one of Namibia’s most biologically diverse areas despite significant decreases in wildlife numbers during the prolonged war of independence in Namibia (1968 to 1989).

1.3 Research Question and Objectives

We asked the overall question of what the general state of Chobe watershed's vegetation trajectory is as measured by multi-temporal NDVI analyses and how is it linked to regional inundation pulses and interannual fire regimes and designed a three-step research design in trying to answer it.

Our main objectives were to:

(1) To describe vegetation dynamics in CRB over 25 years in relation to general climatic conditions for the region by using mean-variance analysis, a form of graphical dynamical systems analysis previously used successfully in drylands ecosystems by Washington-Allen et al. (2008);

(2) To determine how much of the variability in vegetation productivity during individual growing seasons is explained by a) variations in the annual flooding extent in CRB and b) variations in the total amount of area burned in the CRB during a year; and

(3) To supplement mean-variance analyses with an analysis of the spatial patterns of vegetation productivity in relation to two important drivers of change (flooding and fire) to provide an initial assessment of the relationship between these factors of change and spatial patterns of vegetation productivity and change.

2. Methods and Data Analysis

2.1 Data Sources and Datasets

Despite drawbacks of using NDVI in savanna systems (Qi et al., 1995; Huete et al., 2002), we use this satellite-derived product because it was the only dataset available starting from the 1980s. We used Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Index (NDVI), the Moderate Resolution Imaging Sprectroradiometer (MODIS) NDVI MOD13Q1A products, and the MODIS Net Primary Productivity (NPP) MOD17A3. The latter dataset was used primarily as a check for the basin-scale MODIS NDVI analysis data.

A continuous series of 623 AVHRR high-resolution picture transmission (HRTP) images from 1985 to 2004 were acquired in atmospherically and spectrally calibrated maximum value composite (MVC) 10-day normalized difference vegetation index (NDVI) form from the archive of the Coarse Resolution Imagery Database (CRID) of the Institute for Soil, Climate and Water, Agricultural Research Council of South Africa. The data for 1994 and 1995 are missing from our record due to an AVHRR failure.

The first MODIS image available for the region is for February 2000. The MODIS VI (Vegetation Indices) 250-m spatial resolution, 16-day data (MOD13Q1A) were acquired from USGS's Land Processes Distributed Active Archive Center (LP DAAC) from February 2000 to October 2010.

Chapters 2 and 3 of this dissertation explain the derivation of the flooding and annual burned area datasets used as two distinct indices in this analysis: a flooding extent index (FEI) and a fire recurrence index (FRI), both derived products shown in Appendices 4 and 5, respectively. We used the inundation and fire datasets both on an individual, year-by-year basis, as well as in aggregated index form (created by addition as one composite layer from 2000 to 2010). The FEI, derived from MOD13Q1A EVI (16-day, 250 m spatial resolution) data for 2000 to 2010, quantifies the number of months in a given year an area is inundated and was reclassified into three classes: areas flooded for 1 to 3 months/year, 4 to 6, and for more than 7 months during a year (Appendix 4). The FRI, derived in Paper 2 from MCD45A1 data (MODIS Burned Area Product, originally 500 m resolution but resampled to 250 m to match the NDVI data resolution) for 2000 to 2010, quantifies the number of times a given area burned in the interval analyzed. It has also been reclassified into three classes: areas that burned between 1 and 3 times, 4 to 6 times, and areas that burned during more than 7 out of the 10 years (Appendix 5).

2.2 Data Analysis Methods

This analysis has three distinct parts: first, we investigated the temporal dynamics of vegetation productivity using different statistical parameters for the entire time period from 1985 to 2010, using AVHRR NDVI data until 2000 and MODIS NDVI data after 2000. The second and third parts of the analysis incorporated a spatially-explicit component to the temporal dynamics analysis. Because the annual fire extent data (derived in Chapter 2 of this dissertation from the MODIS Burned Area Product) are available only for the 2000 to 2010 period, we focus only on the last decade to be able to incorporate both the fire and the spatial inundation extent layers (derived in Chapter 1 of this dissertation based on both AVHRR and MODIS EVI data) into the analysis.

2.2.1 Long-term vegetation dynamics analysis using AVHRR and MODIS NDVI data in CRB from 1985 to 2010

Prior to statistical and spatial analyses, all the data were georectified and reprojected to the Universal Transverse Mercator (UTM), WGS84 coordinate system using nearest neighbor resampling. We created spatially-averaged monthly maximum value composites (MVC) from both the AVHRR and MODIS NDVI data. These data were then added together to create a growing season MVC NDVI value for each year from 1985 to 2010 which included only seven months of the year (from March to September). Growing season MVC NVDI was plotted through time and analyzed to determine whether there was a statistically-significant trend in the data at the temporal scale of growing season. We then calculated a spatially-averaged coefficient of variation

(CV) for each monthly MVC value as a means to capture the basin's vegetation responses to rainfall variations (droughts and wetter years) and disturbances which may not be obvious solely in mean NDVI value (Kogan, 2000). In other words, the CV values were used as a measure of NDVI variability relative to the mean-monthly and the growing season NDVI values (Weiss et al., 2001) and were calculated as:

$$CV = (s.d.NDVI \, / \, meanNDVI)*100 \qquad (1)$$

where meanNDVI is the mean for the entire image during a given growing season and s.d.NDVI standard deviation for the whole image for that growing season.

In the second step, due to the strong correlation of precipitation and NDVI and because we used a multi-sensor dataset (both AVHRR and MODIS), we standardized NDVI values across the study period (1985 to 2010) using the following formula:

$$(g.s.NDVI - meanNDVI)/s.d.NDVI, \qquad (2)$$

where g.s.NDVI is spatially averaged NDVI for the entire CRB for a given growing season.

These growing season NDVI standard normal deviates were used to remove the seasonal signal and to record NDVI variations across an area with respect to the mean. In other words, higher NDVI standard normal deviate values show regions with higher vegetation productivity, while lower NDVI standard normal deviate values show areas with lower vegetation productivity. Standardized NDVI values track changes in the degree of wetness or dryness of ground vegetation, so that negative values indicate below normal vegetation conditions indicative of drought and vice versa. In addition, we smoothed the standardized monthly MVC NDVI values with different-interval running averages to isolate partially the inter-annual variability in CRB: a three and a seven-year moving average (based on work by Nicholson (2000) who identified two to seven-year wet and dry cycles in southern Africa associated with ENSO). Even though the period considered in our analysis (25 years) is not long enough to reflect long-term trends (which happen on roughly a 20-year time span, Nicholson et al., 2001), it does provide for some interesting insights into the trend and directionality of change in vegetation dynamics.

In the third step of the temporal analysis, we used mean-variance analysis, originally developed by Pickup and Foran (1987), to characterize the spatio-temporal behavior of NDVI through time for the entire data series. Such a mean-variance plot is generally used to describe the seasonal and interannual response of vegetation to climate and disturbances as a function of the mean greenness (which is a proxy for the degree of vegetation cover in an area) and the coefficient of variance (CV) of the NDVI, which measures the degree of heterogeneity in vegetation cover, as illustrated in Figure 2 (Washington-Allen et al., 2003; Zimmermann et al., 2007; Washington-Allen et al., 2008).

In the mean-variance plots, each sector describes the state of a landscape's trajectory at a given time, in our case both annual growing season NDVI and the April MVC NDVI for each year from 1985 to 2010. We chose the April MVC NDVI to capture the end of the growing season associated with the dry season peak in this region. Thus, sector 1, encompassing vegetation with low mean and low variance, is considered the most degraded state of a landscape. Sector 2, with a low mean and high variance, suggests that a higher proportion of the landscape gravitates toward bare ground and increased susceptibility to wind and water erosion. Sector 3, characterized by a high mean and high variance of NDVI indicates a higher proportion of vegetation cover in the landscape but also that some portions of the landscape are susceptible to erosion, most likely as a function of local topography (see discussion above). Finally, sector 4, characterized by high mean and low variance indicates the most ideal and stable vegetation conditions at a given time (Figure 4-2). We created mean-variance plots that include all the monthly MVC's through time for both datasets, plots that focus only on the April MVC NDVI for each time period, and plots that compare the monthly MVC NDVI for two communal areas that are managed differently in terms of fire regimes and where intensive grazing occurs, one in Botswana (fire suppression) and one in Namibia (controlled early dry season burns, see chapter 3 for more details).

Because of the high correlation between NDVI and rainfall and to check our NDVI dataset against measured rainfall data, we used the mean monthly rainfall data from the Tropical Rainfall Measuring Mission (TRMM 3B43) from January 1998 to June 2009 (A-1). The data were downloaded from the NASA Mirador Earth Science database. We also used the Multivariate ENSO Index (MEI) (Wolter and Timlin, 1998). In general, there is a strong association between dry ENSO phases (identified as positive standardized departures from the mean) and drought conditions in southern Africa, especially when the dry ENSO phase occurs during a year with lower overall precipitation (A-2) (Nicholson et al., 2001; Mason, 2001).

2.2.2 Spatial dynamics in vegetation productivity in response to inundation patterns and the amount of area burned annually in CRB from 2000 to 2010

To analyze the vegetation dynamics in CRB from a spatially-explicit point of view, we used the annual growing season (March to September) NDVI normal standard deviate values derived using Equation (2) as proxies for vegetation health and productivity. We reclassified the normal standard deviates for each individual year (growing season) to create maps of the distribution of lower and higher vegetation productivity with the assumption that areas that display greater departures from the mean NDVI are areas with more heterogeneous vegetation cover, as identified by the mean-variance plots. We particularly focused on the years our mean-variance analysis identified as representative for each of the sectors of the plots.

Secondly, we calculated Pearson's product-moment correlation coefficient (*r*) correlations to identify, from a spatial point of view, the strength of association (or the magnitude of the linear relationship) between the standardized NDVI score representative of vegetation productivity and the FEI (number of months an area was inundated during each year) and the area burned for each individual year from 2000 to 2010. The main interest was to identify how much of the spatial patterns of vegetation productivity during each growing season can be explained by the mapped patterns of inundation and burned area.

2.2.3 Two-date image differencing, vegetation dynamics and the FEI and FRI in CRB from 2000 to 2010

To determine the general patterns of change in vegetation health and productivity through time based on our continuous NDVI data-series, we performed two-date image differencing on the growing season NDVI between each consecutive year (2000 to 2001, 2001 to 2002, and so on). We recorded change above a 25% threshold to determine which years and specifically which regions of our study area showed the most variability from year to year to compare against the mean-variance analyses. In general, the incorporation of both spatial and spectral information into land-cover change analyses greatly improves the amount of information obtained (Southworth et al., 2004). For example, Lambin and Strahler (1994) found that changes in the spatial extent are more likely to reveal longer-lasting and longer-term land-cover changes, while spectral differences are more sensitive to shorter-term fluctuations e.g., inter-annual variability in climatic conditions.

The last step in the analysis consisted of performing an image change detection on the growing season NDVI values specifically from 2001 to 2009. We chose 2001 and 2009 as our before and after image in the change detection both because they were the first and last complete record of data for MODIS, but also primarily because both years were climatically comparable, despite 2001 being slightly drier, but both preceded by two wet periods (A-1 and MEI in A-2). After the change detection, we created standard normal deviates of the 2001-2009 difference image and reclassified it into five classes of standard deviations from the mean ranging from above and below 2 and -2 SD, respectively to a class of no significant change (see A-3). We then correlated this standardized difference image with the multi-annual FEI (number of months an area was under inundation aggregated from 2000 to 2010) and the multi-annual FRI (the number of times an area was burned during the 10-year time interval), both classified into three classes as described in section 2.1. We interpret our results in light of regional precipitation and the multivariate ENSO index conditions as described above and not in relation to precipitation on a pixel by pixel basis (done extensively in the literature).

3. Results and Discussion

3.1 Temporal Analysis of Vegetation Productivity and Variability in CRB from 1985 to 2010 Using AVHRR and MODIS NDVI Data

3.1.1 Temporal patterns of NDVI variability

We plotted the AVHRR growing-season NDVI (March to September) from 1986 to 2000 and the MODIS growing season NDVI from 2000 to 2010 (Figure 4-3 a and b). Growing season NDVI varied closely as a function of rainfall distribution and the alternation between dry and wet ENSO events (A-1 and A-2). During 1988 and 1992 period for instance, over 15 drought events were reported in various areas of southern Africa, as well as an increase in the frequency and intensity of El Niño episodes (Kandji et al., 2006). El Niños are associated with droughts in southern Africa and generally lead to decreases in NDVI. Prior to the 1980s, strong El Niños occurred on average every 10 to 20 years, and after the 1990s they occurred on average every 7 to 10 years (Glantz et al., 1997). During our period of analysis, strong El Niño events occurred in 1991/1992, 1994/1995, and 1997/1998, the latter being considered the most intense during the last century (Wessels et al., 2004; NCAR, 2005 and MEI data in A-2). Figure 3a shows low growing season NDVI values in 1987, possibly as a result of the strong dry ENSO events during the 1986/1987 growth season, as well as low values in 1996 and 1997/1998 following the droughts cited in the literature and the correspondingly high standardized departures in MEI (A-2). The lowest growing season NDVI value is recorded during 1996, following a 5-year positive standardized departure from the mean in the MEI. The three-year moving mean of the 1985-2000 time series shows a slight increase in NDVI before 1993, continued by a decline during the second half of the 1990’s decade probably associated with the strong dry ENSO events of that period.

There is no linear trend in growing season NDVI from 2000 to 2010 (the regression is not statistically significant, $R^2 = 0.14$), driven primarily by above-average rainfall beginning with 2008 in this region. There have been several dry spells over this region of southern Africa starting in 2001, the 2002/2003 drought for instance resulted in high food deficits in many countries of southern Africa (Kandji et al., 2006). Wessels et al. (2004) also identified the 2001/2002 and 2002/2003 growth season to be very dry. Our analysis highlights the 2002/2003 drought in particular, showing a subsequent fairly stable increase in vegetation productivity since the end of the major dry spell in 2006 and particularly starting in 2008 (Figure 4-3b and A-2). Higher-than-average precipitation amounts have been recorded in this region in 2008, 2009, and 2010 (and more recently in 2011) and they account for the slight increase in NDVI starting in 2008.

Finally, we plotted the growing season NDVI coefficient of variation (CV) measured from 1985 to 2010 showing no linear trend ($R^2 = 0.10$) and a three-year moving average and varying degrees of variability through time (Figure 4-4). The 2003 growing season displays the most variability in NDVI, followed by 1987 and 1998 (associated with drought conditions in southern Africa once more), while 2009 and 1992 show the least amount of variance in NDVI.

The overall trend in vegetation productivity in CRB over the last decade is one of slightly increased vegetation cover and fairly stable variance of the vegetation cover (Figure 4-4). Similar increases in NDVI in other locations where the temporal and spatial variability of precipitation are increasing and overall precipitation amounts are decreasing (Gaughan and Waylen, 2011 for this region) have occurred as a result of increased agricultural production, plantation forestry, etc (Kausman et al., 2008).

3.1.2 Mean-variance analyses of NDVI

In this section, we created a plot that include all the monthly MVC's through time for both datasets (Figure 4-5a and b), a plot that compare the monthly MVC NDVI for two communal areas that are managed differently in terms of fire regimes and where intensive grazing occurs, one in Botswana (fire suppression) and one in Namibia (controlled early dry season burns) (Figure 4-6), and plots that focus only on the April MVC NDVI for each time period (Figure 4-7a and b). Figure 4-5 a and b shows decreasing CV with increasing monthly MVC NDVI values as a function of the long-term mean NDVI value for every month and long-term CV calculated for the entire period of analysis for both the AVHRR and MODIS time series. Figure 4-5 shows increasing variability in NDVI in the second period of our analysis, 2000 to 2010, from an average variance of 4 to 17% for the 1985 to 2000 period to a CV ranging from 15 to 23% for the second period.

In Figure 4-6, we plotted the mean monthly NDVI values vs. the CV for 2 subsets of the communal lands in the basin on either side of the Chobe River in order to determine whether there are any differences in trajectories given the two countries have different management approaches towards fire management and livestock and population densities also differ between the two countries (higher and increasing population and livestock densities in Namibia vs. Botswana). While the trajectories of the mean-variance plots for the first 15 years of our analysis in the two countries follow similar patterns of decreasing CV with increasing monthly NDVI values (Figure 4-6 a and b), for the last 10 years of the analysis the pattern between the two countries is markedly different (Figure 4-6, c and d). Although the communal lands in Namibia for the last decade show a less strong relationship between CV and monthly NDVI values

(R^2 = 0.22), it is still a negative relation of decreasing CV with increasing mean value (Figure 4-6 c). For Botswana, it appears that during the last decade the relationship between CV and monthly NDVI values is beginning to reverse, while both the long-term monthly MVC NDVI value and CV values are lower than in the Namibian case (Figure 4-6 d). As the two sites are characterized by nearly identical climatic conditions, this difference might be the result of differential fire policies and grazing pressures. Research by van Leeuwen et al. (2010) has shown increases in post-fire vegetation productivity and declines in vegetation heterogeneity after fires, while Bond et al. (2006) have demonstrated that less burning in fire-prone systems lead to more closed canopies, thus higher vegetation productivity and cover but with increased heterogeneity. Even though we do not specifically test this hypothesis in this paper, the long-term suppression of fires in Botswana and less frequent (but more intense fires, Chapter 3) fires there might partially account for the different trajectory noted in Figure 4-6d.

Figure 4-7a and 4-7b shows that mean-variance analyses (Washington –Allan et al., 2008) shows the relationship between vegetation dynamics in CRB over a 25-year time span and general climatic conditions for the region. Thus, sector 1 in Figure 4-7a (bottom left quadrant), shows the year with the most variance in vegetation out of the 15-year time series being 1992. Despite 1997/1998 standing out as the strongest El Niño in the last three decades, the 1991/1992 El Niño, which was statistically a moderate event, caused a major drought throughout southern Africa, and was considered one of the worst during the last century in southern Africa (Glantz et al., 1997; Kandji et al., 2006). Interestingly, this plot identified 1992 as the year with a highly variable vegetation state (potentially degraded) as a function of lower greenness (vegetation cover) and higher heterogeneity (see also A-2 to note 1992 being the third year in a row with above average standardized departures from MEI, indicative of drought in southern Africa). The years 1986, 1987 and 1998, also characterized by drought conditions, fall in sector 2 (low mean and high variance), suggesting that a higher proportion of the landscape gravitates toward bare ground and increased susceptibility to wind and water erosion (Washington-Allan et al., 2008).

Figure 4-7 b shows the most recent decade MODIS NDVI time-series data for April, the end of the growing season in this region. The year 2007 falls in sector 1 of the plot which suggests high vegetation heterogeneity and low cover density. Apart from being characterized by relatively low annual rainfall (A-1), 2007 follows after four dry ENSO phases (A-2) which might explain the degraded landscape-level vegetation state indicated by Figure 4-7 b. 2002 and 2003, identified both in the literature and in Sections 3.1.1 and 3.1.2 as representative of dry growth seasons for this region, fall into Sector 2 of the mean-variance plot, which represents a less degraded state of vegetation with lots of bare ground which introduces high spatial heterogeneity. Finally, 2000, 2001, and 2006 fall into Sector 4 of the mean-variance plot which is characterized by high mean and low variance and, in theory, indicates the most ideal and stable vegetation conditions at a given time. This is logical given that the 1999/2000 growth season rainfall was the highest until 2008 (Wessels et al., 2004) and that 2006 growth season rainfall was higher than the preceding four years and was also associated with a low-intensity wet ENSO phase (A-2).

3.2 Spatio-Temporal Analysis of Vegetation Productivity in Relation to Annual Flooding and Fire Extents in CRB from 2000 to 2010

Vegetation cover and pattern are some of the most important parameters for assessing ecosystem and landscape functioning and trajectories over time (Kéfi et al., 2007). Section 3.1.3 and Figure 4-7 b identified 2007, 2002, 2004, and 2001 representative for sectors 1 through 4 of the mean-variance plots that describe the vegetation trajectory through time in CRB. We mapped spatial patterns of growing season standardized NDVI values for CRB for each of these years (Figure 4-8). Higher NDVI standard normal deviate values show regions with higher vegetation productivity, while lower NDVI standard normal deviate values show areas with lower vegetation productivity. Areas that display greater departures from the mean NDVI are, in theory, areas with more heterogeneous vegetation cover, as identified by the mean-variance plots. In general, the patterns in Figure 4-8 show reveal higher vegetation productivity in the seasonally-inundated parts of both the eastern Caprivi Strip of Namibia and of Mamili National Park in the south-western part of CRB, as well as in much of the Chobe Forest Reserve and the interior parts of Chobe National Park. Consistently low vegetation productivity areas in CRB are in the communal lands of both countries and particularly in areas adjacent to Lake Liambezi on the Namibian side of the river where population densities are relatively high.

We correlated these spatial patterns of the standardized NDVI score representative of vegetation productivity and annual flooding and fire extents for each individual year (Figure 4-9). The main interest was to identify how much of the spatial patterns of vegetation productivity during each growing season can be explained by association with the mapped patterns of inundation and burned area (summarized for each year in Table 4-1). The areas in the eastern part of Namibia with high vegetation productivity are areas that are flooded to different degrees during the growing season, while many of the areas generally characterized by lower vegetation productivity (Figure 4-8) are areas that burn during a given year (Figure 4-9). While the spatial coincidence between current year flooding extent and area burned and low and high vegetation productivity are generally between 17 and 32% of the total area in CRB, the actual spatial patterns of these associations are of primary interest in this analysis. Additionally, we also calculated how the previous year area burned in CRB is correlated with areas of low and high vegetation productivity and that explains another 5 to 20 percent of the association patterns we observed for a given year (Table 4-1). The years with higher than 40 percent correlations are years characterized by a large percentage of the basin area experiencing burning (see A-5 and A-6).

Finally, in terms of the spatial patterns of vegetation productivity and area burned annually in CRB, it is interesting to note that much of Mudumu National Park in Namibia burns extensively during each year (see also A-6 for a comparison of area burned in each of the three protected areas).

3.3 Two-Date Growing Season NDVI Change Detection in Relation to Multi-Annual Flooding Extent (FEI) and the Multi-Annual Mean Fire Return Interval (FRI) for CRB

Most of the year-to-year changes occurred in the communal areas identified in Figure 4-8 to be characterized by overall lower vegetation productivity during individual growing seasons. Secondly, the years that recorded significant (above 25 percent of the image) decreases in NDVI from year to year, were those characterized by drought conditions, specifically 2005 and 2002 (A-1 and A-2). Similarly, the slightly higher 2004 growing season rainfall led to a significant increase in NDVI from the conditions in 2002 and 2003 when the basin vegetation recovered from low NDVI and high CV values (sector 2 in Figure 4-7 b) to higher vegetation cover (sector 3 in Figure 4-7 b and Table 4-2). A second significant increase in NDVI occurred between the 2005 and 2006 growing seasons (Table 4-2). Referring back to Figure 4-7 b, 2005 falls in the mean-variance plot in the sector of moderately low NDVI values (indicating more homogeneous cover) and CV and is on the border between sectors 1 and 4. 2006 falls clearly into sector 4, with more homogenous and higher vegetation cover probably as a result of the wet climatic conditions for that year. Interestingly and probably a direct result of the increased vegetation cover and resulting fuel loads, 2006 is also characterized by a high proportion of the basin affected by wildfires (A-5), as well as the highest proportion of area burned in Chobe and Mudumu National Parks (A-6).

Appendix 3 (A-3) shows the standardization of the 2001 to 2009 image difference, displaying most change once more in the communal lands in both Namibia and Botswana. Above the 25 percent threshold, 6.63 percent of CRB has recorded an increase in NDVI between the two dates, with a much smaller percentage recording a net decrease (Table 4-2). This result is interesting when analyzed against the mean-variance plot in Figure 4-7 b that shows 2009 to be characterized by an overall lower mean NDVI and higher CV (thus higher vegetation heterogeneity) in 2009 vs. 2011. In 2009 and 2010, the vegetation cover in CRB moved towards increasing spatial heterogeneity and higher NDVI, from more homogeneous conditions in 2001. This could also be partially explained by increases in the area burned post-2006 (A-5 and chapter 3 of the dissertation) in CRB and supported by research (van Leeuwen et al., 2010; Swaine et al., 1992; Enslin et al., 2008). Vegetation cover can be related to vegetation productivity, phytomass, and susceptibility to soil erosion but it does not provide information about changes in species composition over time. No change may occur in the NDVI response for an area, but changes in species composition within a pixel may occur undetected (Schindler 1987). As such, we do not attempt to explain the compositional changes in vegetation highlighted in the image differencing procedure but were interested in understanding whether the NDVI changes detected are spatially linked with multi-annual flooding and fire regimes (FEI and FRI presented in Appendices 4 and 5 respectively).

Figures 4-11 and 4-12 show the spatial coincidences between the 2000 to 2009 FEI (defined as the number of months an area was under inundation per year during the 2000 to 2009 interval), FRI (defined as the number of times an area burned during the 2000 to 2009 interval) and the standardized 2001 to 2009 growing season NDVI image difference. Areas in green indicate increases in vegetation productivity, while areas in shades of red indicate lower vegetation productivities in 2009 as compared to 2001. Figure 4-11 suggests that the multi-annual FEI is related to vegetation productivity in both a positive and negative way. Areas in the eastern Caprivi of Namibia that are usually flooded for less than 3 months out of the year tend to be associated with lower vegetation productivities and these are also the areas that, later within the growing season when the flooding recedes (see chapter 2 for details on the intra-annual flooding dynamics in CRB), tend to burn quite frequently (between 1 to 6 years out of the 10 included in the computation of the FRI) (Figure 4-11 and 4-12). A longer fire return period can often be beneficial to woody recruitment and lead to increased woody plants densities, while at the same time suppressing the general height of trees (Enslin et al., 2008).

The fact that the pattern of association between flooding and fire extents and higher vegetation productivities between 2001 and 2009 tends to be relatively similar for the communal areas in both Botswana and Namibia around Lake Liambezi is interesting. The pattern could be related to more flooding in that region beginning with 2004 (and especially starting with the large floods in CRB after 2008) and frequent burning primarily during the years prior to 2004 when, for the first time since the 1980s, the flood waters from the Chobe and Kwando rivers joined and Lake Liambezi partially filled once more (chapter 2 and Piotr Wolski, personal communication). Understanding this pattern will require more detailed investigations and will be part of the future work based on this exploratory analysis of spatial patterns of association between changes in continuous vegetation indices through time and multi-annual flooding and fire regimes in this region.

4. Implications of Findings

This paper investigated the general state of Chobe watershed's vegetation trajectory as measured by multi-temporal NDVI analyses and explored how the spatial patterns of vegetation productivity through time are linked to regional inundation pulses and inter-annual fire regimes. Based on temporal and mean-variance analyses of growing season NDVI, we reconstructed the vegetation dynamics in CRB since 1985, primarily highlighting the strong correspondence between climatic conditions in this region, such as the major droughts of 1987, 1991/1992, 1997/1998, 2001/2002, and 2002/2003, and variations in statistical parameters that describe vegetation productivity and health. We specifically demonstrate the usefulness of mean-variance analyses in describing the overall dynamics of vegetation through time and how they can potentially inform analyses of spatial patterns of vegetation productivity. We found that 1992 and 2007 are placed by the mean-variance analysis in the sector of low vegetation cover and high variance of the surface cover, which are indicative of an overall degradation of vegetation.

Our spatial coincidence analysis revealed that for CRB, on an annual basis, the areas with higher vegetation productivity are the seasonally-inundated parts of both the eastern Caprivi Strip of Namibia and of Mamili National Park in the south-western part of CRB, as well as in much of the Chobe Forest Reserve and the interior parts of Chobe National Park. We found that the areas of consistently low vegetation productivity are the communal lands of both countries and particularly areas adjacent to Lake Liambezi on the Namibian side of the river where population densities are relatively high. The spatial coincidence analysis also revealed that the association between the current year flooding extent and area burned and low and high vegetation productivity is generally between 17 and 32% of the total area in CRB, with that percentage being as high as 40% when we factor into the analysis the spatial extent of burning that occurred during the previous dry season.

As long as population pressure in this region continues to intensify land use, anthropogenic fire ignitions are unlikely to limit fire frequencies, permitting fire frequency to respond to future climates (Hoffman et al., 2002). This in turn might translate in further increases in vegetation cover and especially heterogeneity that could have serious implications for vegetation structure and functionality in the future (Bond et al., 2005; van Leeuwen et al., 2010). We did not compare species level vegetation quality between dates and the different sites in our study area but, instead, we used NDVI standard normal deviates as a proxy of vegetation health and productivity. While the study design of this paper does not allow us to identify the exact causal factors for the observed multi-date changes in vegetation productivity in CRB, assessing these patterns is important and will hopefully lead to more detailed ecological studies in this region.

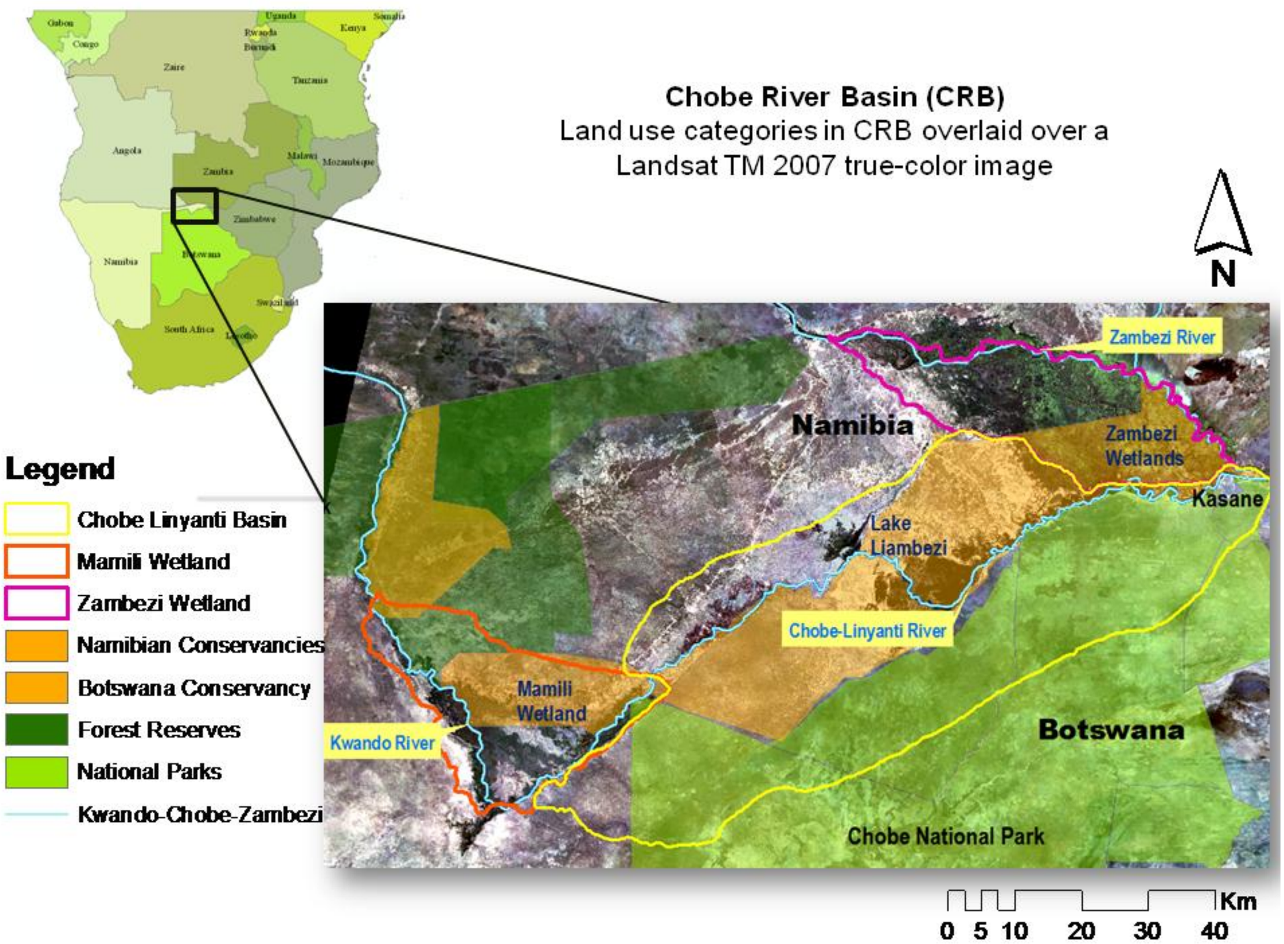


Figure 4-1. Study area in Southern Africa: Chobe River Basin (made up of the Chobe-Linyanti River basin, Mamili Wetland and Zambezi Wetlands) and land use categories in the basin.

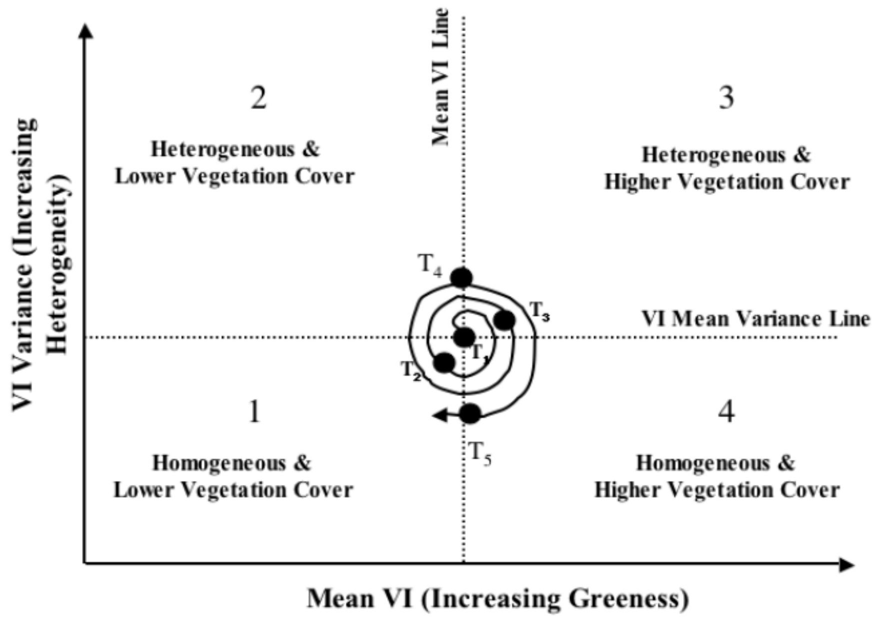
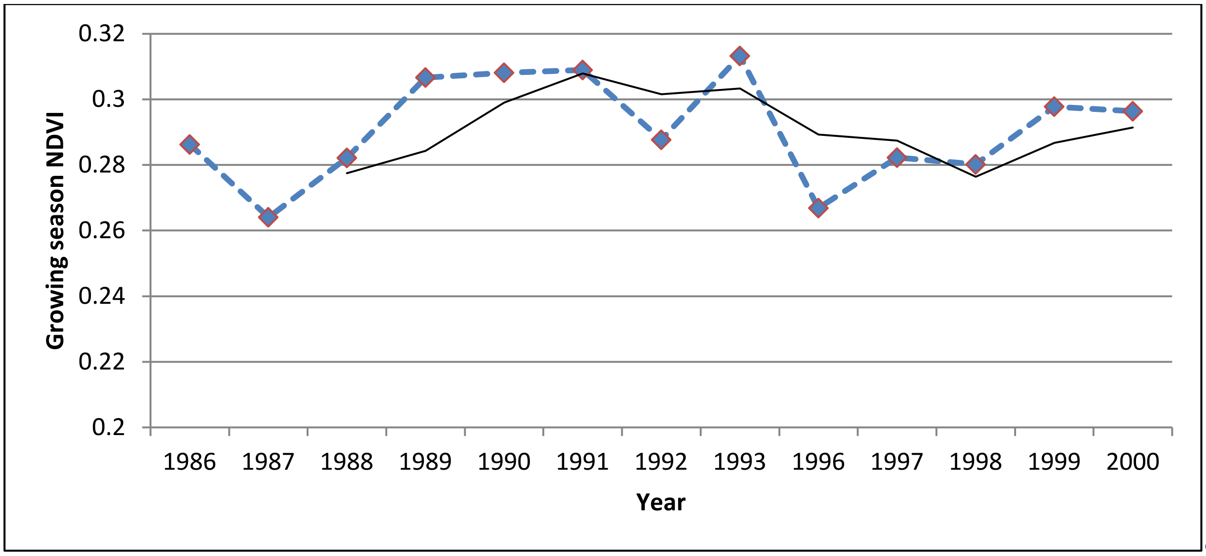
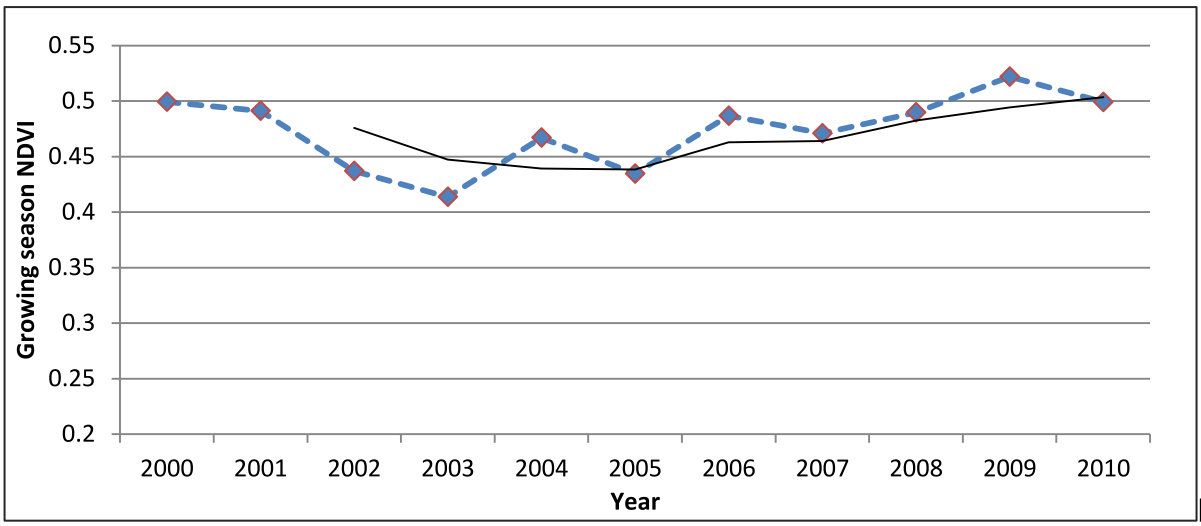


Figure 4-2. Mean-variance analysis portrait of a landscape's vegetation trajectory through time (T_1 through T_5 in the figure) showing four hypothesized vegetation states (Source: Washington-Allen et al., 2008).



a)



b)

Figure 4-3. a) AVHRR growing season NDVI (October to September) from 1986 to 2000 and b) MODIS growing season NDVI (October to September) from 2000 to 2010. Both graphs display a three-year moving average of growing season NDVI in black.

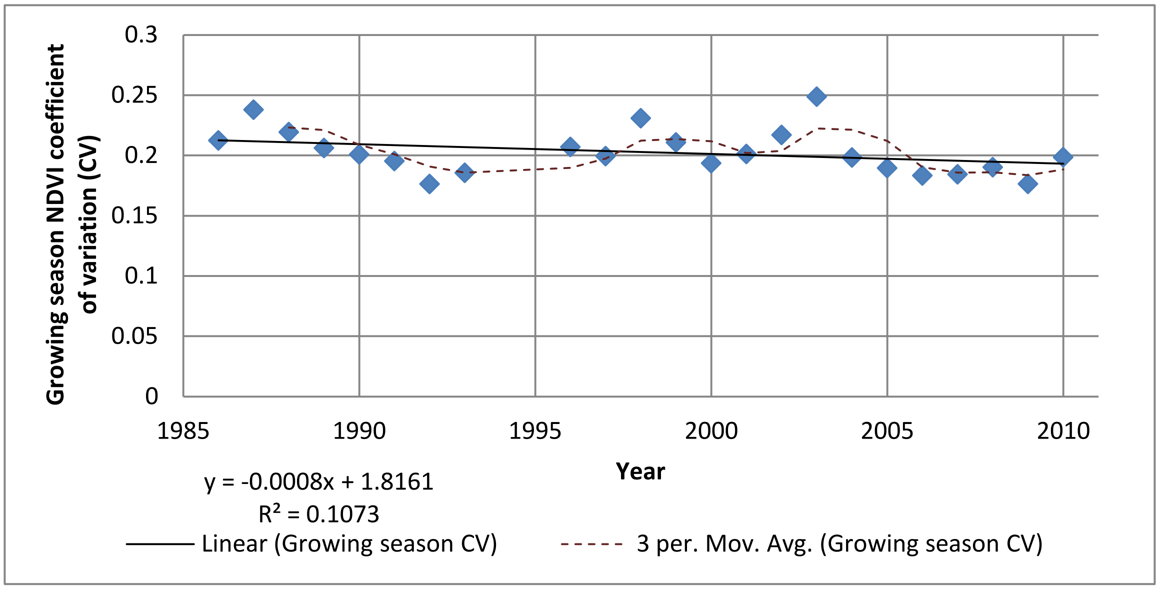


Figure 4-4. Growing season NDVI coefficient of variation measured from 1985 to 2010 showing both a linear trend (not statistically significant, R^2 = 0.10) and a three-year moving average and varying degrees of variability through time. Note that 2003 displays the most variability in NDVI, while 2009 and 1992 the least.

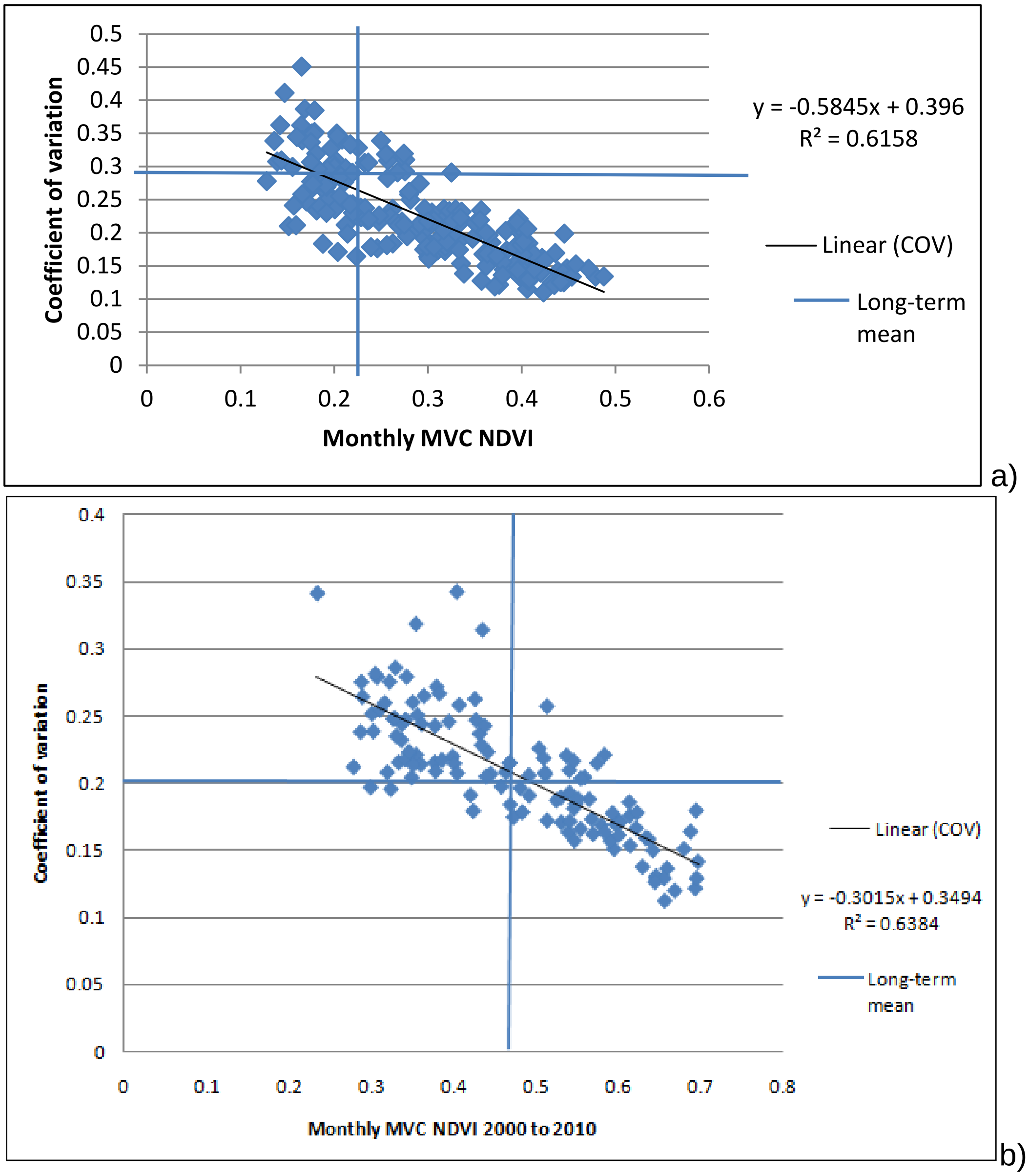


Figure 4-5. a) Mean-variance plot for monthly AVHRR MVC NDVI from September 1985 to August 2004 and b) mean-variance plot for monthly MVC NDVI data from MODIS between 2000 and 2010; blue lines indicate the long-term mean of the variance (CV) and monthly MVC NDVI. The graph shows decreasing CV with increasing monthly MVC NDVI value for the period 2000 to 2010. The blue lines in both graphs indicates the long-term mean MVC NDVI value and mean CV respectively and are used to create the four vegetation dynamics sectors proposed by Washington-Allen et al. (2003).

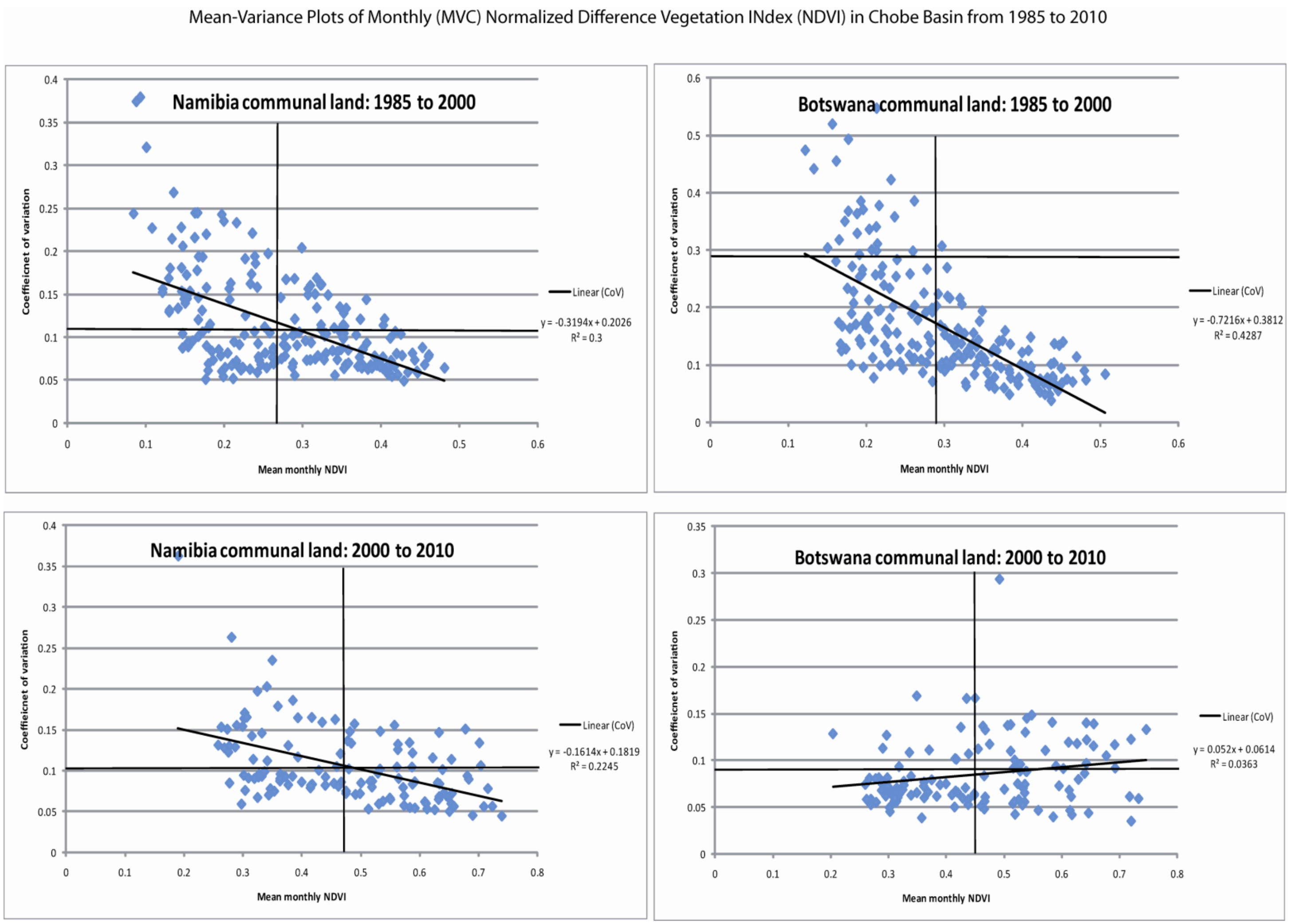


Figure 4-6. Mean-variance plots of monthly MVC DVI data for subsets of the communal lands in Botswana and Namibia both for the 1985 to 2000 and the 2000 to 2010 time-period. The black lines in the graphs indicates the long-term mean MVC NDVI value and mean CV respectively and are used to create the four vegetation dynamics sectors proposed by Washington-Allen et al. (2003).

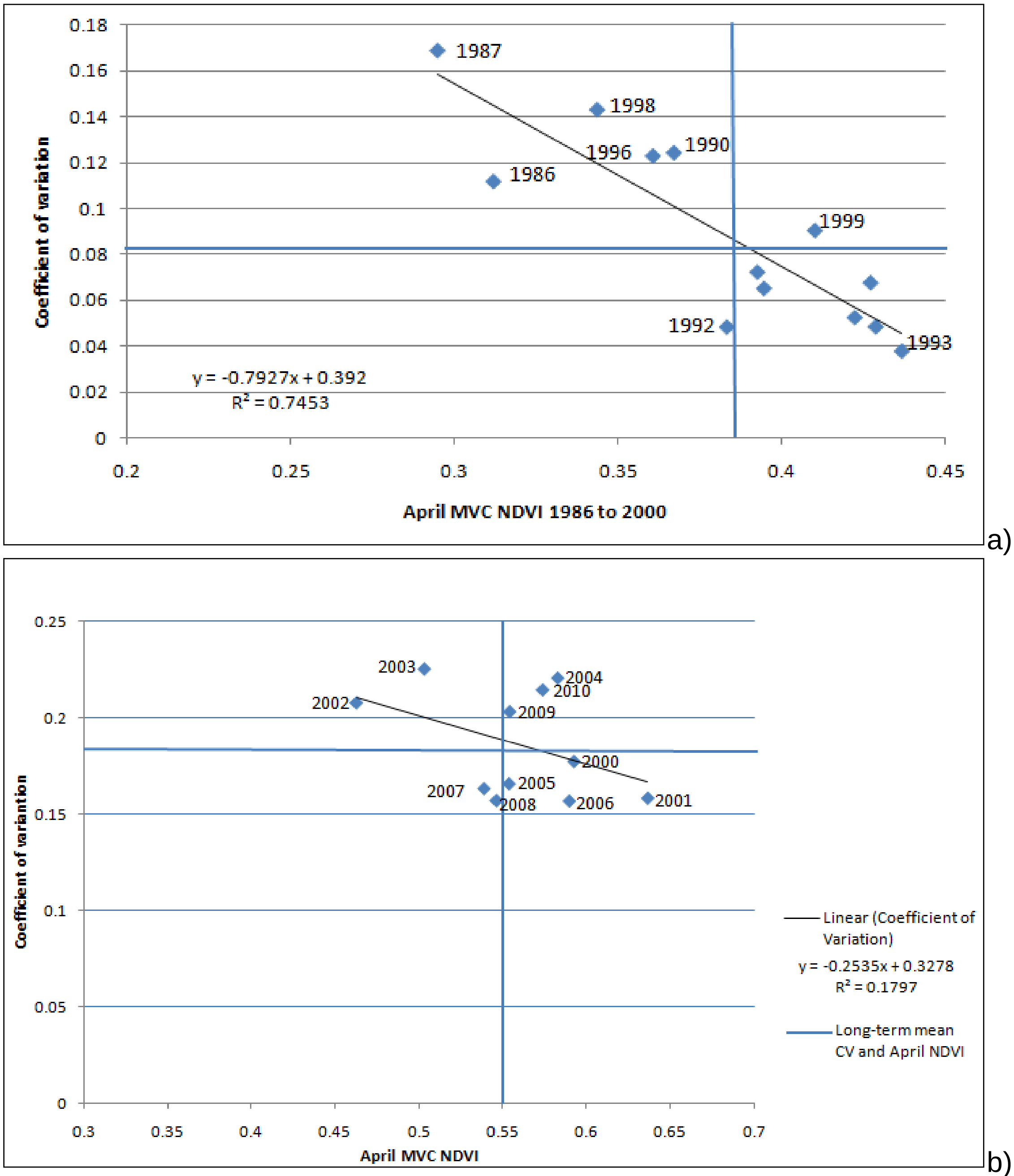


Figure 4-7. a) Mean-variance plot of AVHRR April MVC NDVI data from 1985 to 2000 and b) Mean- variance plot of MODIS April MVC NDVI data from 2000 through 2010 for Chobe River Basin. The blue lines in both graphs indicates the long-term mean MVC NDVI value and mean CV respectively and are used to create the four vegetation dynamics sectors proposed by Washington-Allen et al. (2003).

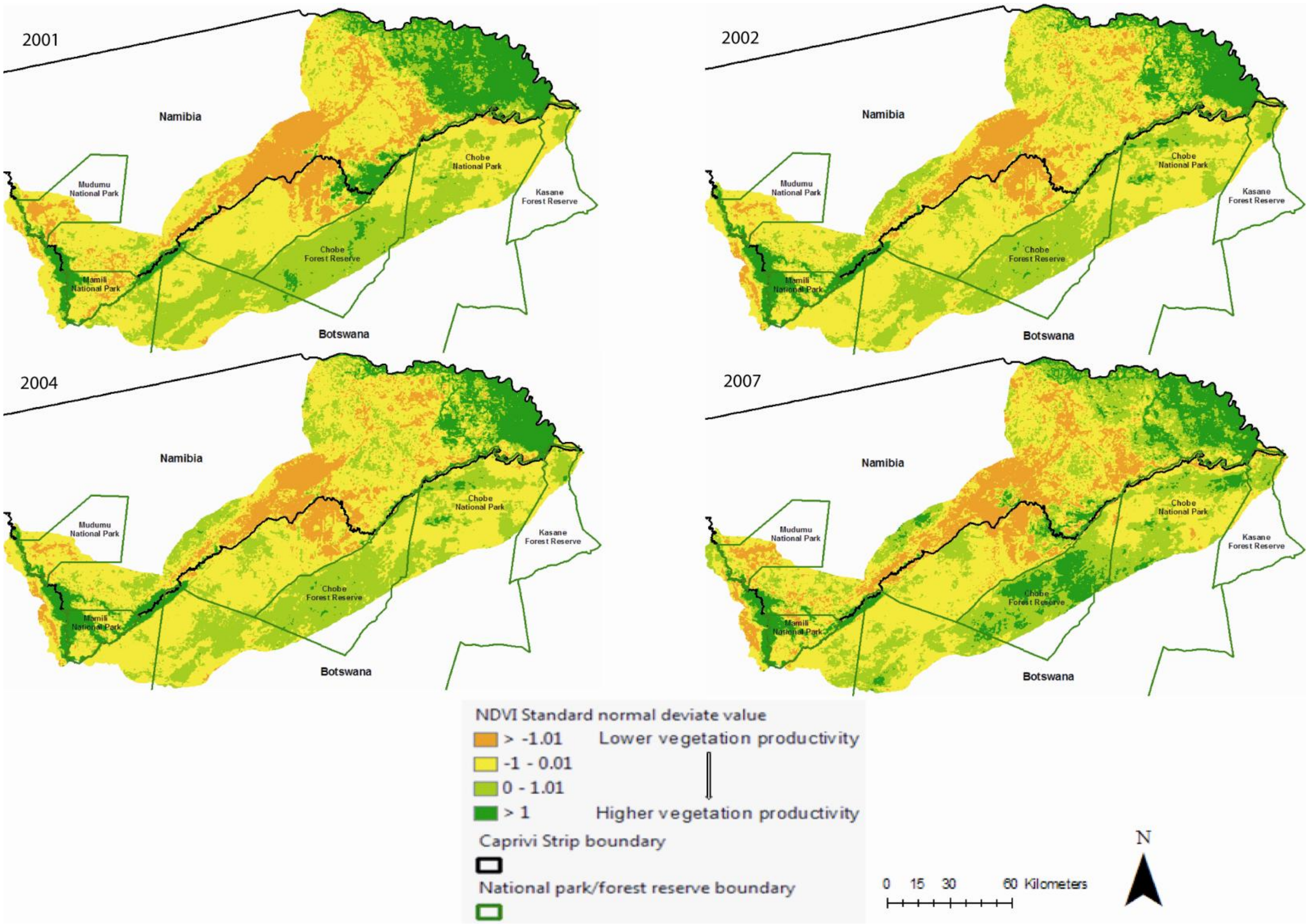


Figure 4-8. Spatial patterns of growing season standardized NDVI values for CRB for four years of highest vegetation variability (in terms of mean and CV) representative of each of the four mean-variance plot sectors identified in Figure 10 b, as such: sector 1: 2007, sector 2: 2002, sector 3: 2004, and sector 4: 2001.

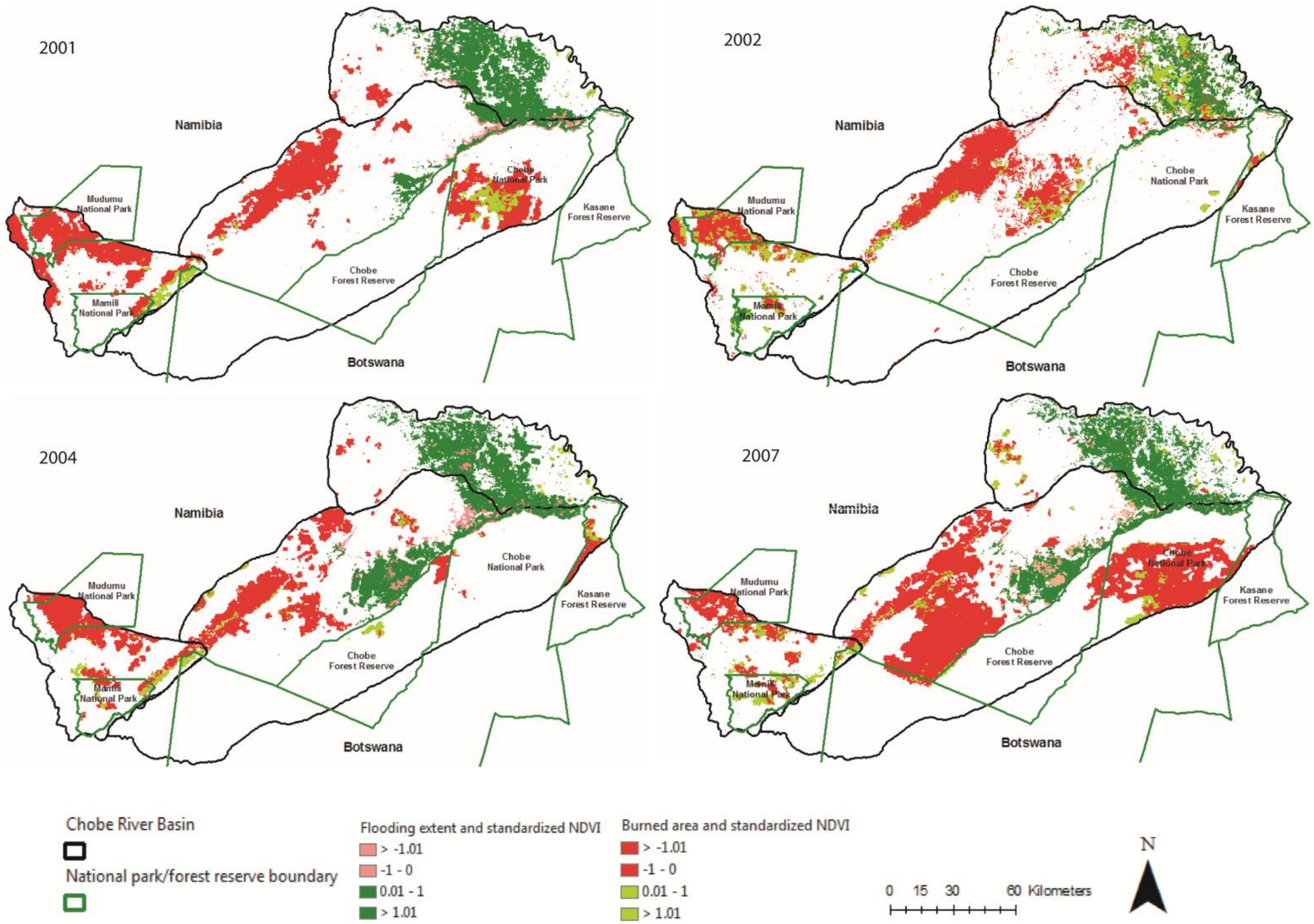


Figure 4-9. Spatial patterns of growing season standardized NDVI values for CRB for four years of highest vegetation variability (in terms of mean and CV) representative of each of the four mean-variance plot sectors identified in Figure 10 b and their spatial correlation with the flooding and fire extents for each individual year.

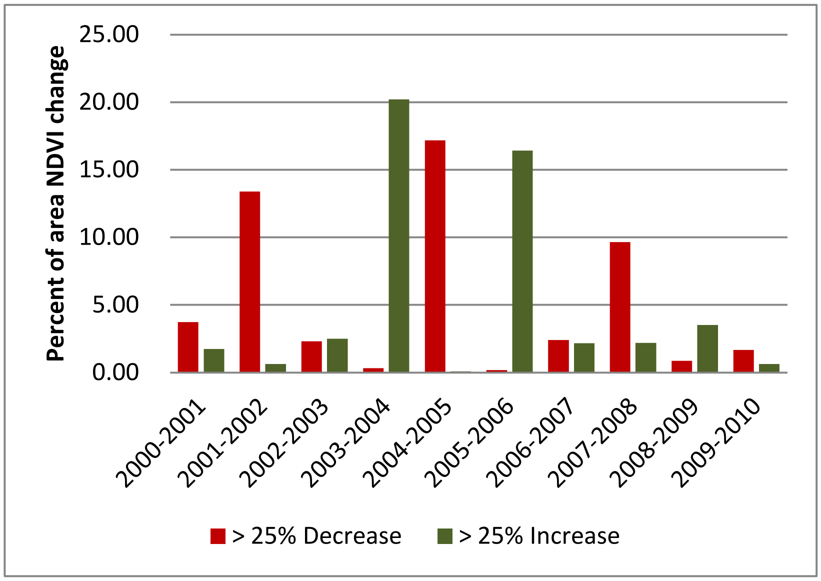


Figure 4-10. Two-date standardized NDVI change detection expressed in percent of total Chobe Basin area from 2000 to 2010 based on MODIS growing season NDVI data. Two-date change detection performed at a 25% change threshold.

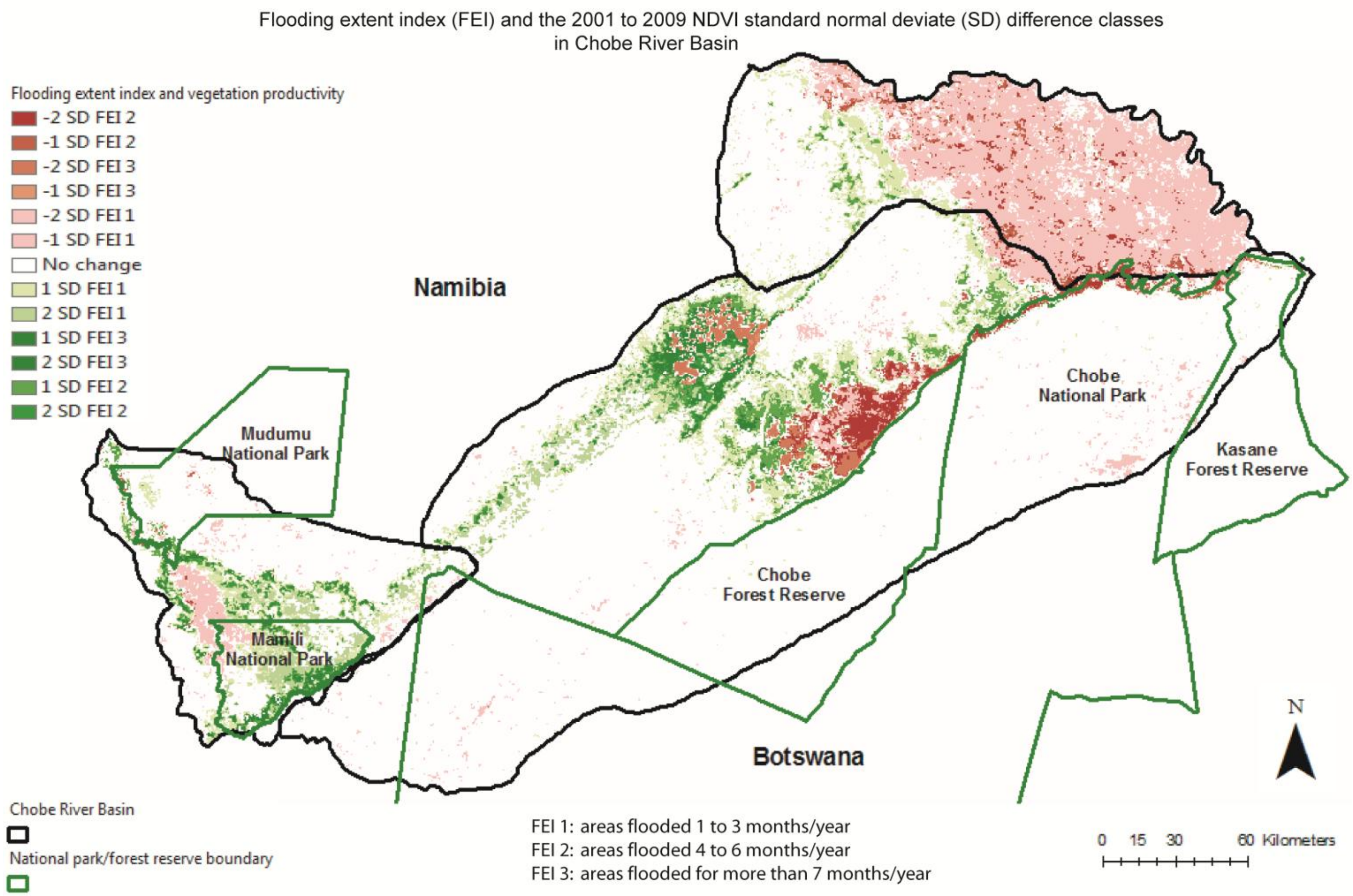


Figure 4-11. Spatial patterns of the correlation between the 2001 to 2009 FEI (defined as the number of months an area was under inundation per year during the 2000 to 2009 interval) and the standardized 2001 to 2009 growing season NDVI image difference. Areas in green indicate increases in vegetation productivity in 2009 versus 2001, while areas in shades of red indicate lower vegetation productivities in 2009 as compared to 2001.

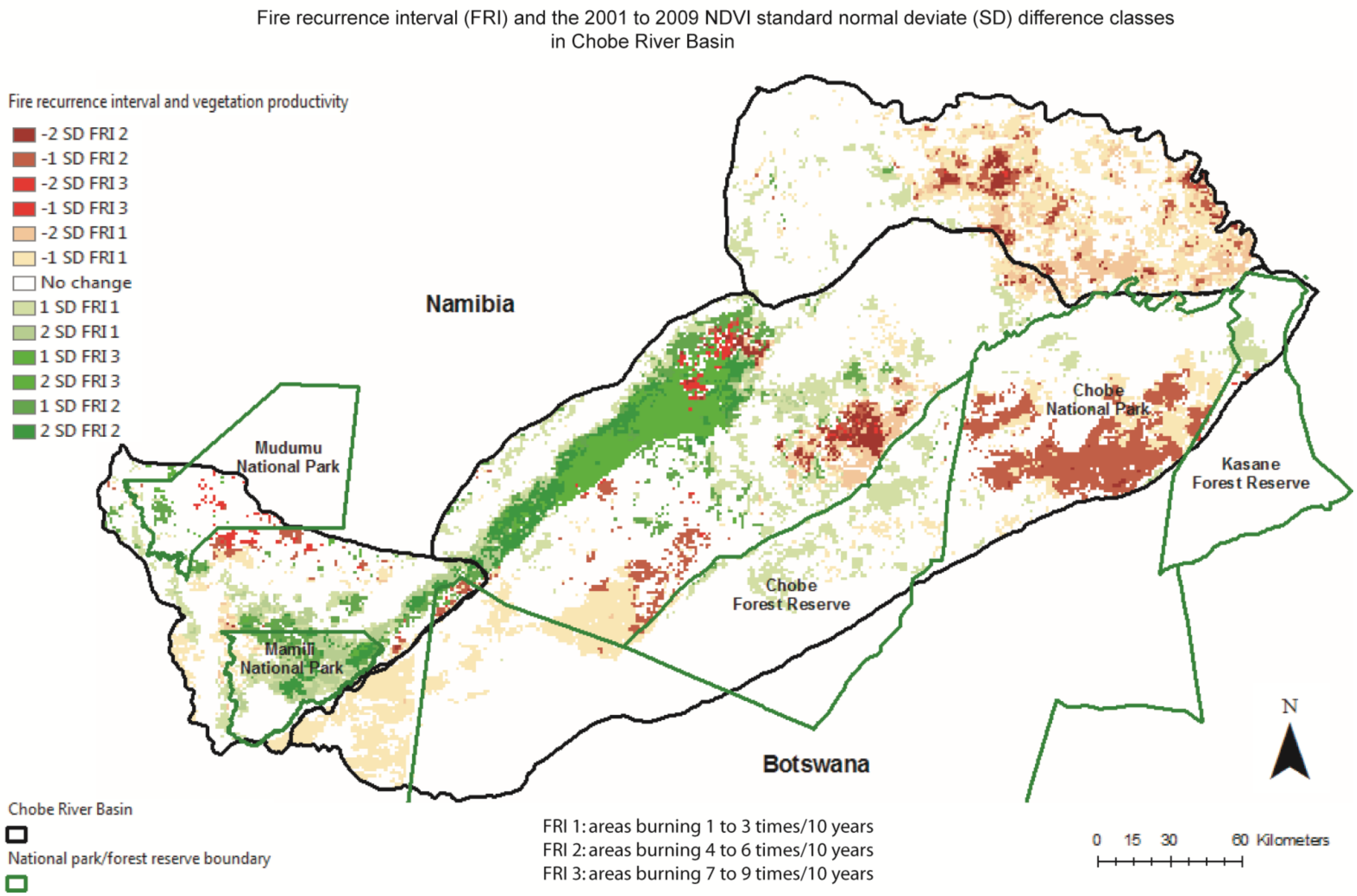


Figure 4-12. Spatial patterns of the correlation between the 2001 to 2009 FRI (defined as the number of times an area burned during the 2000 to 2009 interval) and the standardized 2001 to 2009 growing season NDVI image difference. Areas in green indicate increases in vegetation productivity, while areas in shades of red indicate lower vegetation productivities in 2009 as compared to 2001.

Table 4-1. Correlations between higher and lower vegetation productivity (represented in the table as +NDVI and –NDVI respectively) expressed as a standardized NDVI score and individual year flooding extent and current and previous year area burned (expressed as percent of the total area in CRB).

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
flood (+ NDVI)	11.11	4.59	7.73	10.65	0.60	6.19	9.86	6.85	5.69
flood (- NDVI)	1.23	3.09	3.20	5.86	7.84	3.77	1.64	2.58	9.95
fire (- NDVI)	11.26	7.95	5.37	9.28	7.43	19.56	16.62	18.14	13.32
fire (+NDVI)	1.71	1.77	1.33	1.68	1.27	2.31	2.91	4.94	1.22
	25.31	**17.39**	**17.62**	**27.47**	**17.14**	**31.83**	**31.03**	**32.51**	**30.18**
fire (-) prev. year	20.96	11.54	7.53	4.37	9.27	5.95	19.07	16.58	17.47
fire (+) prev. year	3.51	1.43	2.18	1.33	1.69	3.64	2.80	2.96	2.45
	24.47	12.97	9.71	5.70	10.96	9.59	21.87	19.53	22.92
Total	**49.78**	**30.37**	**24.34**	**33.17**	**28.10**	**41.42**	**52.90**	**52.04**	**50.10**

Table 4-2. Two-date standardized growing season NDVI change detection in percent of total Chobe Basin area from 2000 to 2010 based on MODIS growing season NDVI data (in red, statistically significant decreases; in green, statistically significant NDVI increases).

	2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	***2001-2009***
> 25% Decrease	3.73	13.38	2.32	0.31	17.18	0.17	2.40	9.65	0.86	1.68	***1.72***
> 25% Increase	1.73	0.64	2.51	20.20	0.09	16.43	2.17	2.20	3.51	0.63	***6.63***
Total NDVI Change	**5.46**	**14.02**	**4.83**	**20.51**	**17.27**	**16.60**	**4.57**	**11.85**	**4.37**	**2.31**	***8.35***

CHAPTER 5
CONCLUSIONS

This dissertation addressed changes in the spatial and temporal patterns of inundation, fire distribution, and vegetation productivity in a semi-arid savanna watershed located in the center of southern Africa's Kavango Zambezi Area (KAZA) region. The first paper concludes that the extent of flooding decreased about 6% from 1985 to 2009, and there was a two-week to one-month lag between the highest discharges in Zambezi River and highest extent of flooding in Chobe Basin, thus quantifying for the first time for this system the interconnections between the Chobe and Zambezi systems. I also showed how dependent the entire Chobe system is on the magnitude of the flood pulse from the Zambezi. This finding implies that this entire system would change if diversions or other water abstraction schemes were to happen upstream along the Zambezi River as currently planned by water recources officials in Botswana.

In the second paper, I showed that there are significant differences in fire frequencies between countries with more effective fire management (Botswana and Zimbabwe) and countries where anthropogenic, mainly early-dry season, burning is largely uncontrolled (Namibia, Angola, and Zambia), both within and outside protected areas, while all countries and land-use units show an overall increasing trend in fire occurrences. For instance, protected areas in Angola and Zambia have highest rates of fire recurrence (most frequent burning), with anywhere between 30 and 84% of their total area burned every year, followed by Namibia. Mudumu National Park in Namibia, a small park with lax fire management regulations, for example, averages between 58-99% of its area burned annually. The two national parks we analyzed in Botswana and

Zimbabwe, on the other hand, are characterized by fairly low rates of fire recurrence and low, between 0 and 15%, proportions of their total area burned in any given year.

Large fire occurrences increased up to 200% in the period before the beginning of the natural fire season in Namibia, where a new prescribed burn policy was introduced in 2006, while the other countries show a slightly different shift in seasonality of increasing fire frequencies during the dry season predominantly. The mean size of fires also increased significantly across all land uses, despite increasing fire prevention efforts in most protected areas in this central transfrontier conservation area of southern Africa. More specifically, I determined that approximately 29-55% of area in Caprivi burns every year, with only approximately 1-10% of the area in Northern Botswana experiencing the same fire frequencies. Finally, we showed that fire frequencies have increased across all land use categories of Eastern Caprivi and northeastern Botswana during the last decade, with the most significant increases occurring in September irrespective of the fire management policy of each country. This may indicate that the underlying cause for the changes documented in fire frequencies in this region can be attributed to climatic changes and variability.

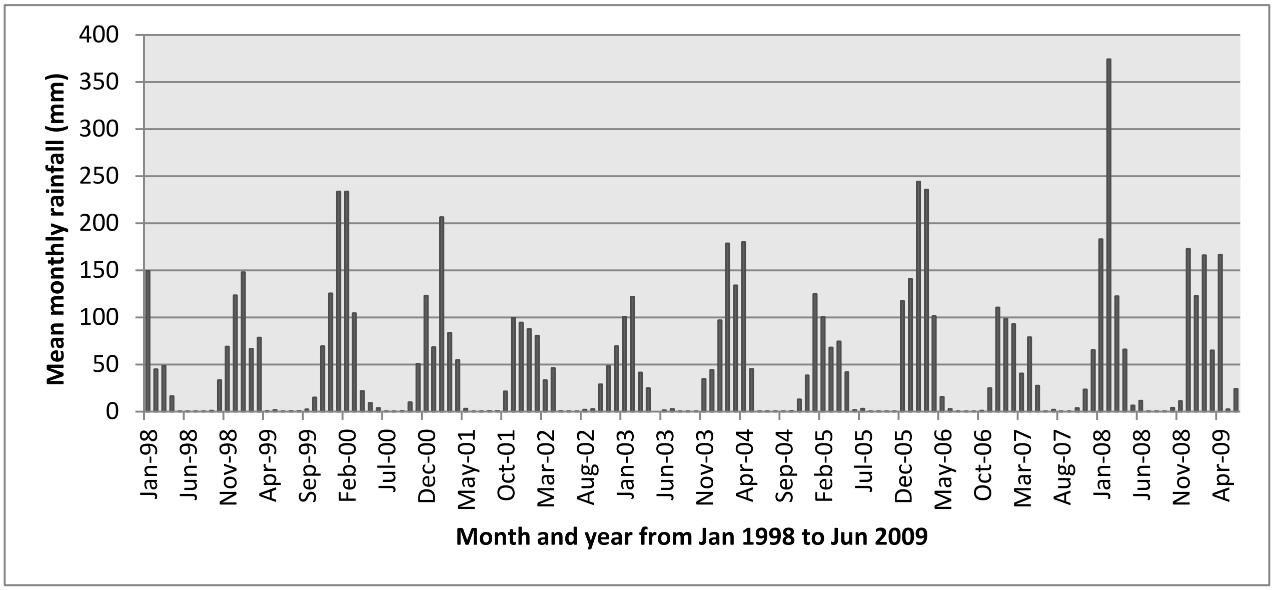
As long as population pressure in this region continues to intensify land use, anthropogenic fire ignitions are unlikely to limit fire frequencies, permitting fire frequency to respond to future climates (Hoffman et al., 2002). This in turn might translate in further increases in vegetation cover and especially heterogeneity that could have serious implications for vegetation structure and functionality in the future (Bond et al., 2005; van Leeuwen et al., 2010). As expected, I found that vegetation is highly responsive to climatic fluctuations and that the long-term trend is one of increased vegetation cover and increasing variance of the vegetation cover that could be related to more frequent and intense burning and spatial variations in water availability from both precipitation and regional inundation patterns. We specifically demonstrate the usefulness of mean-variance analyses in describing the overall dynamics of vegetation through time and how they can potentially inform analyses of spatial patterns of vegetation productivity.

Given the fact that 94% of Botswana's water resources have their headwaters in other southern African countries (Turton, 1999), and that the flow of Chobe River itself is largely regulated by back-flooding from the Zambezi River, the findings of this dissertation can be of significance to water-resources and land-resources managers, especially given new developments in irrigated agriculture and the crucial importance of this water source to both wildlife and human populations in both riverine countries.

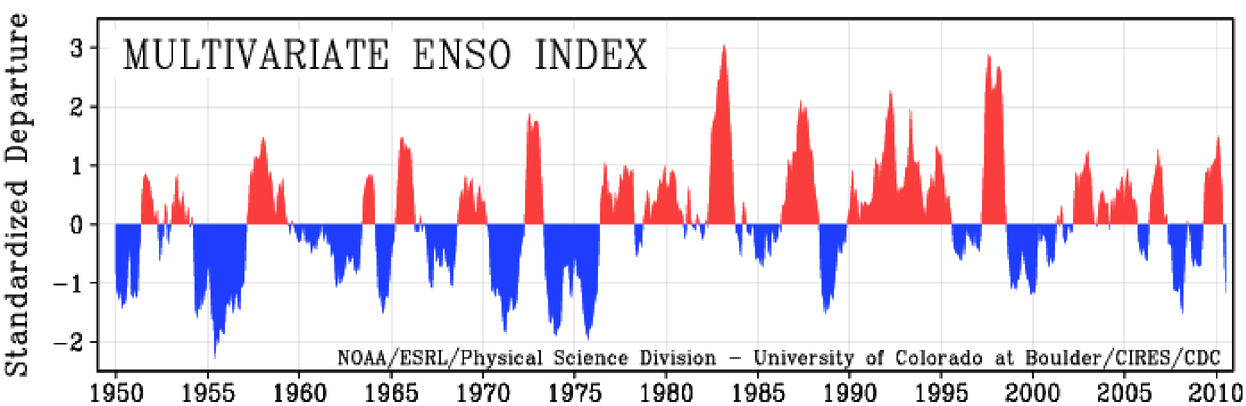
The findings of this project contribute towards filling a gap in the land-change science literature as few studies have considered the effects of flooding, the world's most widespread and damaging natural disaster, on vegetation dynamics in semi-arid ecosystems. They also represent a useful addition to the wildfire management field by demonstrating a simple and reproducible method that uses two separate satellite-derived fire products to examine changes in different components of fire regimes in fire-prone ecosystems. Finally, this dissertation contributes to the field of land use and land change science by proposing a novel spatial coincidence analysis framework for analyzing how the inter- and intra-annual extents of inundation and fire are correlated with both annual patterns of vegetation productivity and multi-date changes in vegetation productivity.

APPENDIX

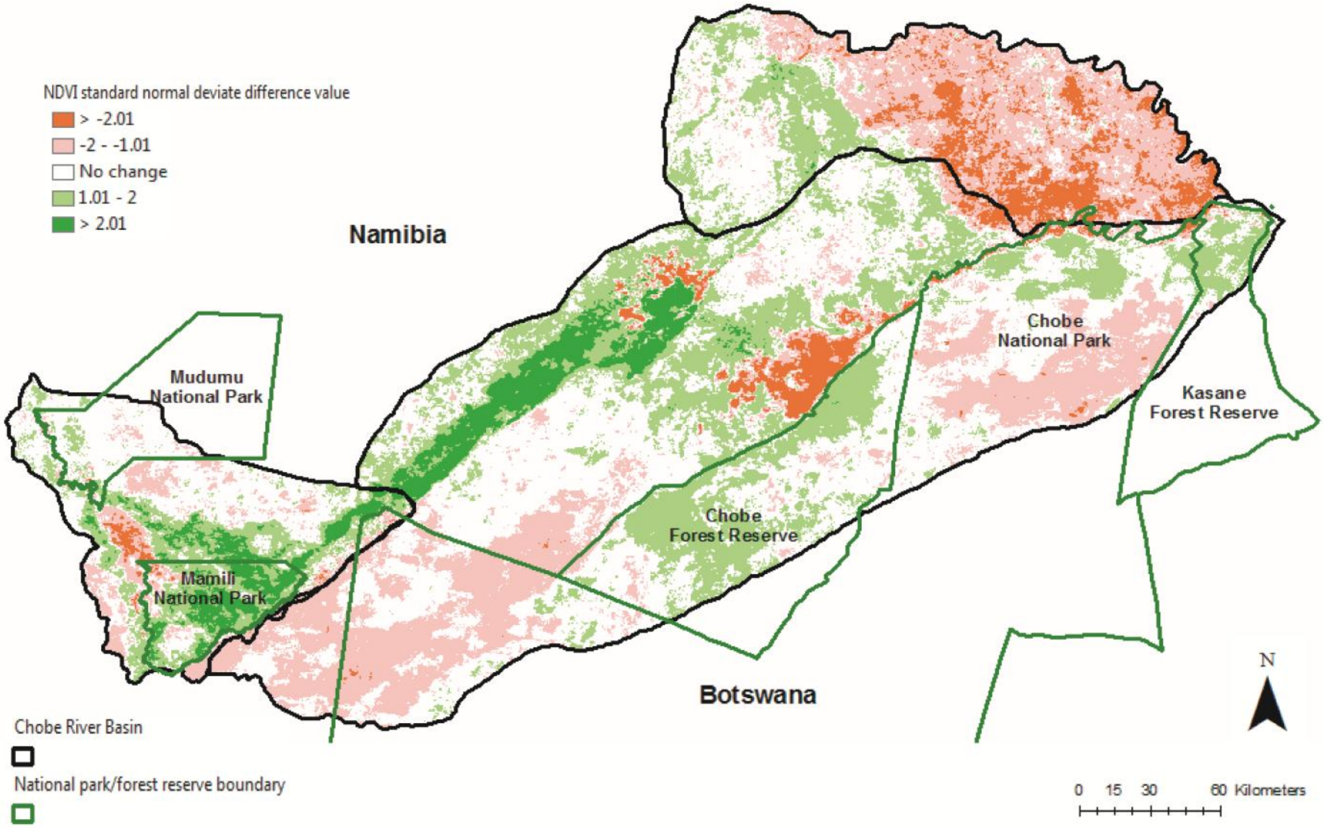
Additional Figures for Chapter 4



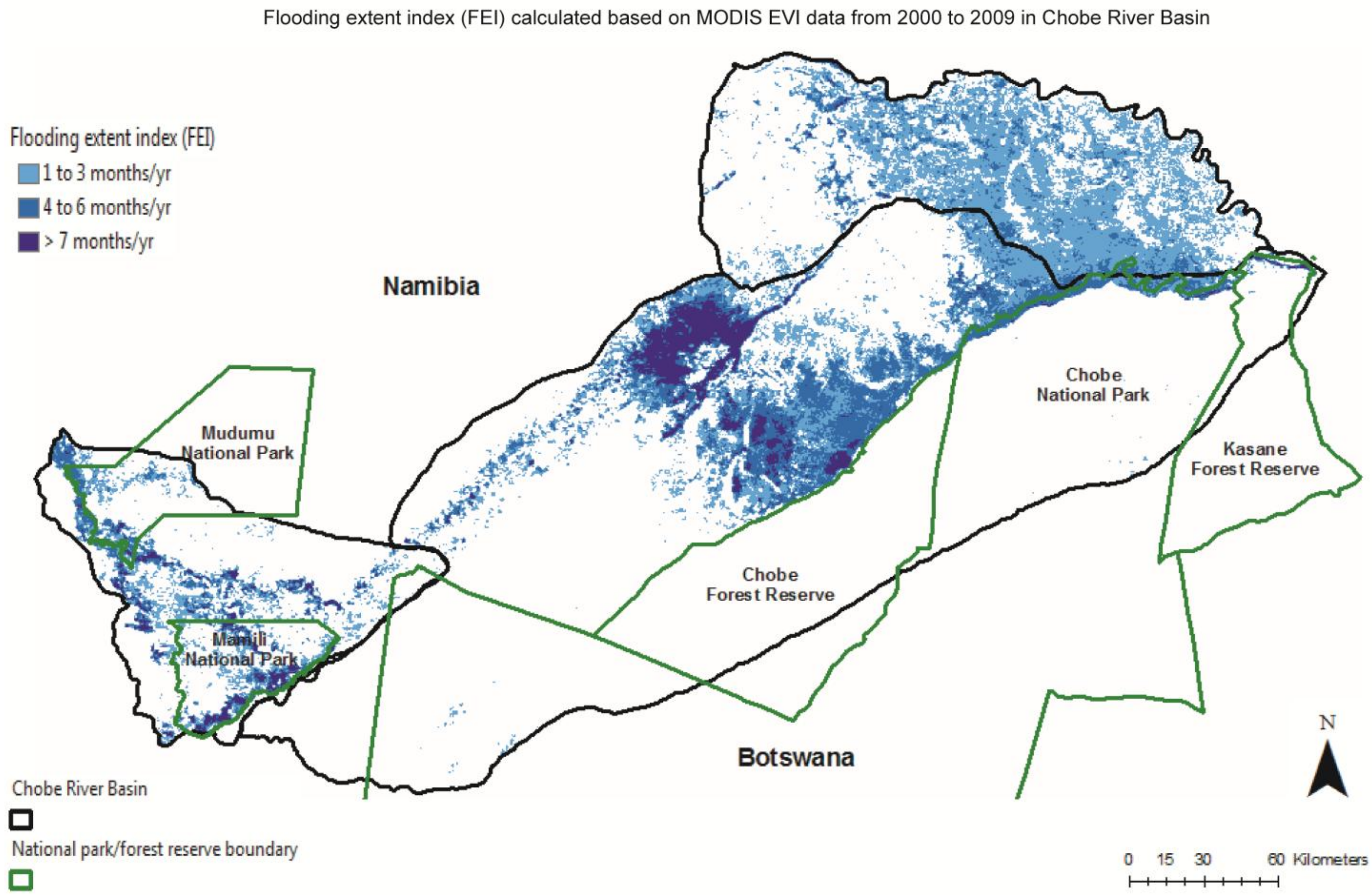
A - 1. Mean monthly rainfall data from the Tropical Rainfall Measuring Mission (TRMM 3B43) for the period January 1998 to May 2009 extracted for the Chobe River Basin.



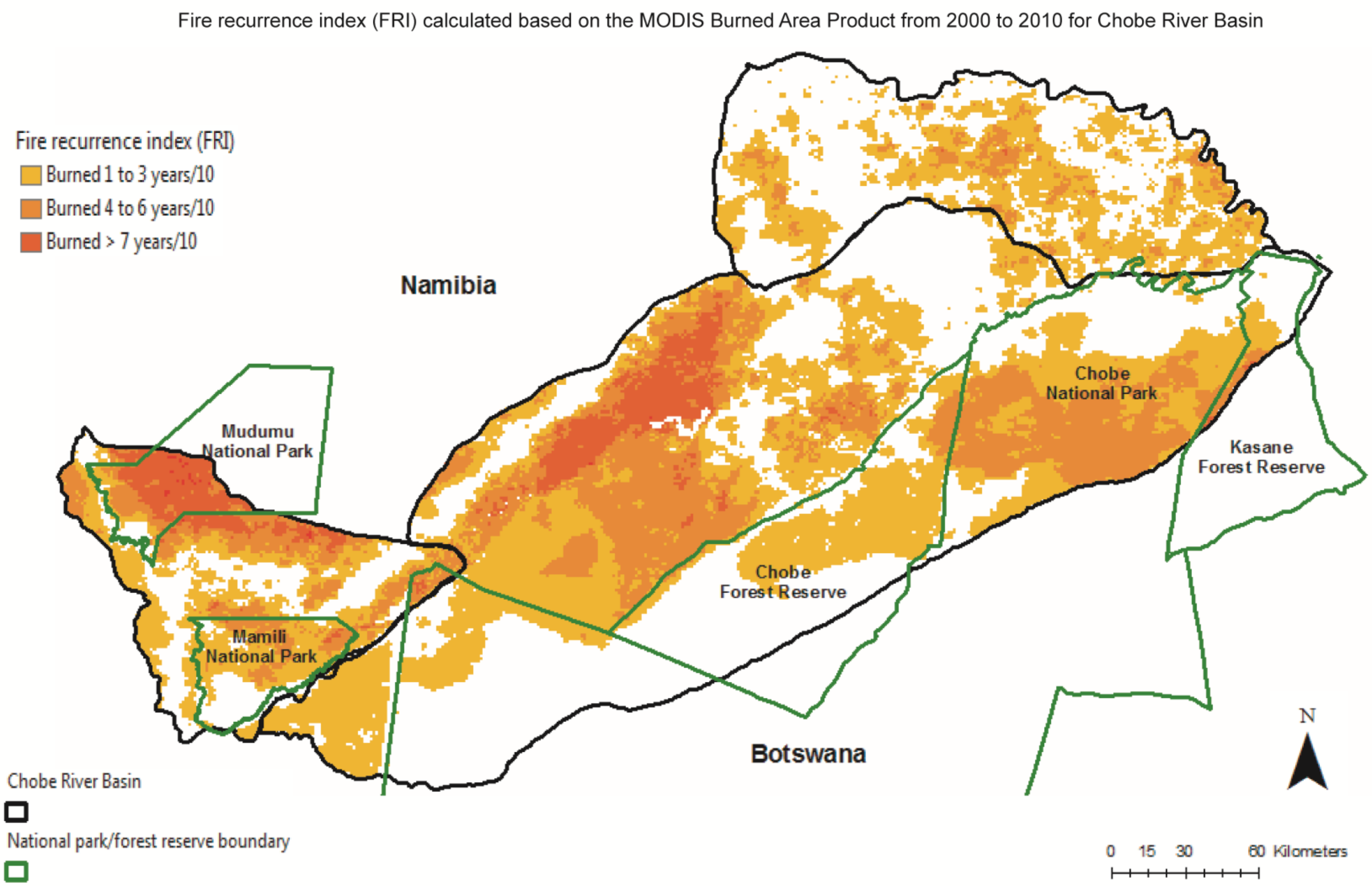
A - 2. Multivariate ENSO Index (Source: Wolter and Timlin, 1998).



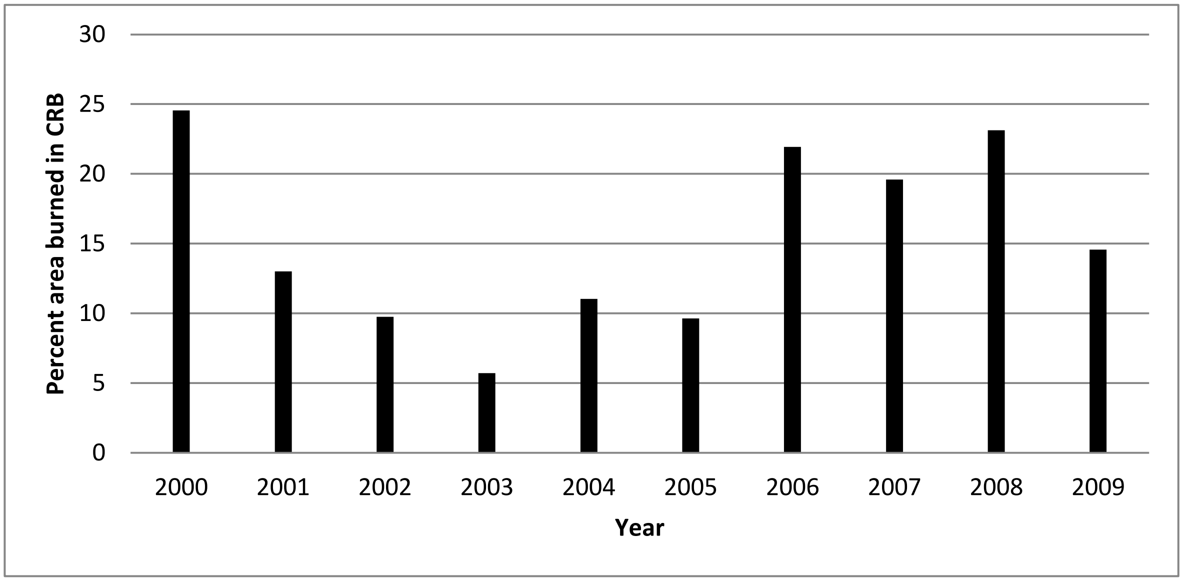
A - 3. Growing season NDVI standard normal deviate two-date image difference value between 2001 and 2009 for CRB.



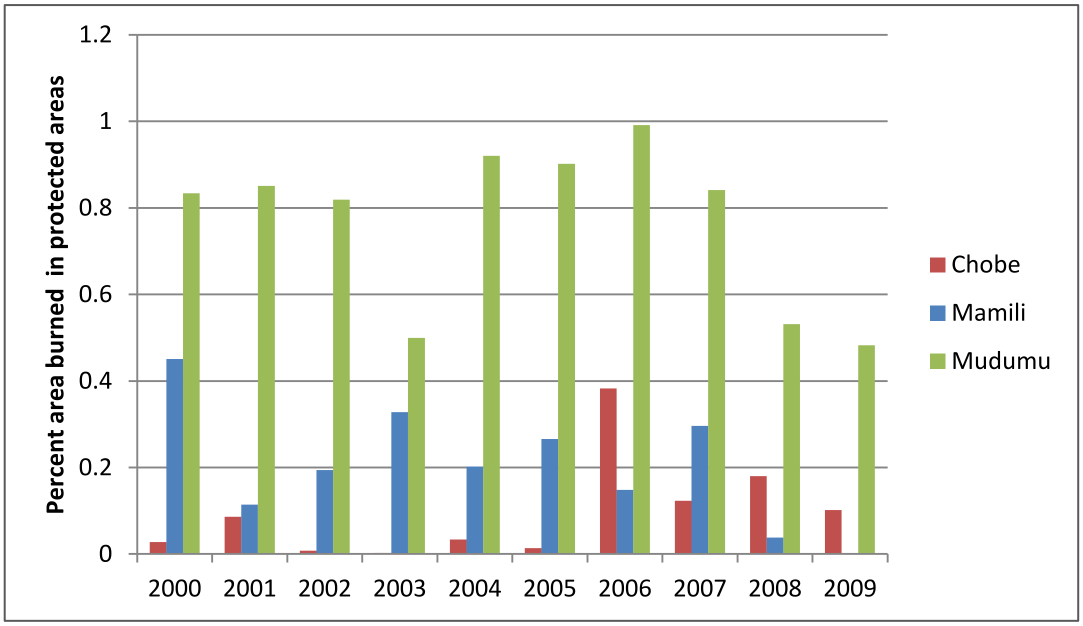
A - 4. Flooding Extent Index (FEI) in CRB



A - 5. Fire Recurrence Index (FRI) in CRB.



A - 6. Percent area burned in CRB for all land management categories from 2000 to 2009 based on MODIS Burned Area Product.



A - 7. Percent area burned inside protected areas in the CRB from 2000 to 2009 based on MODIS Burned Area product data.

LIST OF REFERENCES

Abel, N., Cumming, D., and Anderies, J. 2006. Collapse and reorganization in social-ecological systems: questions, some ideas, and policy implications. Ecology and Society 11: 1-17.

Adger, W. N., Kelly, P.M., Winkels, A., Huy, L.Q. and Locke, C. 2002. Migration, remittances, livelihood trajectories, and social resilience. Ambio 31 (4): 358: 366.

Adger, W.N. 2000. Social and ecological resilience: are they related? Progress in Human Geography 24 (3): 347-364.

Adger, W.N., Hughes, T.P., Folke, C., Carpenter, R., and Rockstrom, J. 2005. Social-ecological resilience of coastal environments. Science 309: 1036:1039.

All, J. D. and S. Yool. 2004. Indexing Endangered Species Risk in the Colorado River Delta, Mexico using AVHRR NDVI Time Series Data. Geocarto International, 19(4): 5-13.

All, J.D. 2006. Colorado River floods, droughts and shrimp fishing in the Upper Gulf of California, Mexico. Environmental Management 37: 111-125.

All, J.D. 2006. Colorado River floods, droughts and shrimp fishing in the Upper Gulf of California, Mexico. Environmental Management 37: 111-125.

Alleaume, S., C. Hély, J. Le Roux, S. Korontzi, R.J. Swap, H.H. Shugart, and C.O. Justice, 2005. Using MODIS to evaluate heterogeneity of biomass burning in southern African savannahs: A case study in Etosha. International Journal of Remote Sensing. 26(19), 4219-4237.

Alsdorf, D.E. and Lettenmeier, D.P. 2003.Tracking fresh water from space. Science 301: 1491-1494.

Alsdorf, D.E. and Lettenmeier, D.P. 2003.Tracking fresh water from space. Science 301: 1491-1494.

Amaraoui, M., DaCamara, C.C., and Pereira, J.M.C. 2010. Detection and monitoring of African vegetation fires using MSG-SEVIRI imagery. Remote Sensing of Environment 114 (5), 1038-1052.

Anderies, J.M., Walker, B.H., Kinzig, A.P. 2006. Fifteen weddings and a funeral: case studies and resilience-based management. Ecology and Society 11 (1): 1-21.

Anon. 1996. Climate Change 1995 Impacts. Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.

Anyamba, A., Tucker, C., and Mahoney, R. 2002. From El Niño to La Niña: vegetation response patterns over East and Southern Africa during the 1997-2000 period. Journal of Climate 15: 3096-3103.

Appleton, C.C., Ellery, W.N., Byskov, J., and Mogkweetsinyana, S.S. 2008. Epidemic transmission of intestinal schistosomiasis in the seasonal part of the Okavango Delta, Botswana. Annals of Tropical Medicine and Parasitology. 102 (7): 611-623.

Archibald, S., Roy, D.P., Van Wilgen, B.W., Scholes, R.J., 2009. What Limits Fire?: An examination of drivers of burnt area in sub-equatorial Africa, Global Change Biology special issue on Fire Ecology and Climate Change, 15, 613-630.

Arntzen, J. 2006. Case studies on successful Southern African NRM initiatives and their impacts on poverty and governance. The World Conservation Union and Transboundary Protected Areas Research Initiative.

Bandyopadhyay, S., Humavindu, M., Shyamsundar, P. and Want, L. 2004. Do households gain from community-based natural resource management? An evaluation of community conservancies in Namibia. World Bank Policy Research Working Paper 3337.

Barbosa, P.M., Stroppiana, D., Gregoire, J.M., and Pereira, J.M.C. 1999. An assessment of vegetation fire in Africa (1981–1991): Burned areas, burned biomass, and atmospheric emissions. Global Biogeochemical Cycles. 13 (4), 933-950.

Barnes, M. 2001. Effects of large herbivores and fire on the regeneration of Acacia erioloba woodlands in Chobe National Park, Botswana. African Journal of Ecology 39: 340-350.

Barnes, M. 2001. Effects of large herbivores and fire on the regeneration of Acacia erioloba woodlands in Chobe National Park, Botswana. African Journal of Ecology. 39, 340-350.

Basist, A., Williams Jr., C., Grody, N., Ross, T., Shen, S., Chang, A., et al. (2001). Using the Special Sensor Microwave Imager to Monitor Surface Wetness. Journal of Hydrometeorology, 2(3), 297-324.

Bastawesy, M. A., Khalaf, F.I., and Arafat, S.M. 2008. The use of remote sensing and GIS for estimation of water loss from Tushka lakes, southwestern desert, Egypt. Journal of African Earth Sciences. 52:73-80.

Bergeron, Y., Flanigan, M., Gauthier, S., Leduc, A., and Lefort, P. 2004. Past, current and future fire frequency in the Canadian Boreal Forest: implications for sustainable forest management. Ambio 33 (6), 356-360.

Berkes, F. 2007. Understanding Uncertainty and Reducing Vulnerability: Lessons from Resilience Thinking. Natural Hazards 41: 283-295.

Berkes, F., Colding, J., Folke, C. (2003). Navigating socio-ecological systems. Cambridge, UK: Cambridge University Press.

Birkett, C.M. 2000. Synergistic remote sensing of Lake Chad: variability of basin inundation. Remote Sensing of Environment 72: 218-236.

Birth, G.S. and McVey, G. 1968. Measuring the color of growing turf with a reflectance spectroradiometer. Agronomy Journal 60: 640-643.

Bishop, K., Phillips, A., and Warren, L. 1995. Protected forever? Factors shaping the future of protected areas policy. Land Use Policy 12: 291-305.

Bond, W.J. and Keeley, J.E. 2005. Fire as a global ‘herbivore’: the ecology and evolution of flammable ecosystems. Trends in Ecology and Evolution 20 (7), 387-394.

Bond, W.J. and Keeley, J.E. 2005. Fire as a global ‘herbivore’: the ecology and evolution of flammable ecosystems. Trends in Ecology and Evolution 20 (7): 387-394.

Bond, W.J., Woodward, F.I., and Midgley, G.F. 2004. The global distribution of ecosystems in a world without fire. New Phytologist 165 (2), 525-538.

Boulain, N., Cappelaere, B., Seguis, L., Gignous, J., and Peugeout, C. 2006. Hydrologic and land use impacts on vegetation growth at the watershed scale in a semi-arid environment. Regional Environmental Change 6: 147-156.
Boulain, N., Cappelaere, B., Seguis, L., Gignous, J., and Peugeout, C. 2006. Hydrologic and land use impacts on vegetation growth at the watershed scale in a semi-arid environment. Regional Environmental Change 6: 147-156.
Brand, F.S. and K.Jax. 2007. Focusing the meaning(s) of resilience: resilience as a descriptive concept and a boundary object. Ecology and Society 12(1): 23-33.

Brown, M.E., Pinzon, J.E., Didan, K., Morisette, J.T. and Tucker, C.J. 2006. Evaluation of the consistency of long-term NDVI time series derived from AVHHR, SPOT Vegetation, SeaWiFS, MODIS and LandSat ETM+ Sensors. IEEE Transactions on Geoscience and Remote Sensing 44: 1787-1793.
Brown, M.E., Pinzon, J.E., Didan, K., Morisette, J.T. and Tucker, C.J. 2006. Evaluation of the consistency of long-term NDVI time series derived from AVHHR, SPOT Vegetation, SeaWiFS, MODIS and LandSat ETM+ Sensors. IEEE Transactions on Geoscience and Remote Sensing 44: 1787-1793.

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

Bryant, R.G. 1999. Application of AVHRR to monitor a climatically sensitive playa: Case study, Chott el Djerid, southern Tunisia. Earth Surface Processes and Landforms 24: 283-302.

Bryant, R.G. 1999. Application of AVHRR to monitor a climatically sensitive playa: Case study, Chott el Djerid, southern Tunisia. Earth Surface Processes and Landforms 24: 283-302.

Bryant, R.G. 2003. Monitoring hydrological controls on dust emissions: preliminary observations from Etosha Pan, Namibia. The Geographical Journal. 169 (2): 131-141.

Bucini, G. and Lambin, E. 2002. Fire impacts on vegetation in Central Africa: a remote-sensing-based statistical analysis. Applied Geography 22: 27-48.

Bucini, G. and Lambin, E. 2002. Fire impacts on vegetation in Central Africa: a remote-sensing-based statistical analysis. Applied Geography. 22, 27-48.

Burgess, R.L. and Sharpe, D.M. (Eds). 1981. Forest island dynamics in man-dominated landscapes. Springer, New York.

Carpenter, S. R., B. Walker, J. M. Anderies, and N. Abel. 2001. From metaphor to measurement: resilience of what to what? Ecosystems 4:765-781.

Carpenter, S.R. and Brock, W.A. 2006. Rising variance: a leading indicator of ecological transition. Ecology Letters: 9, 311-318.

Carreiras, J. M.B., Pereira, J.M.C., and Pereira, J.S. 2006. Estimation of tree canopy cover in evergreen oak woodlands using remote sensing. Forest Ecology and Management 223: 45-53.

Central Statistics Office (CSO). 2004. Wildlife Statistics 2004. Department of Printing and Publishing Services, Gaborone.

Chan, NH. And Wong, H.Y. 2007. Data mining of resilience indicators. IIE Transactions 39: 617-627.

Child, G. 1965. An ecological Survey of Northern Botswana. FAO. #TA2563. Rome, Italy.

Chipman, J. W. and Lillesand, T.M. 2007. Satellite-based assessment of the dynamics of new lakes in southern Egypt. International Journal of Remote Sensing. 28 (19): 4365-4379.

CIPEC.2002 (Center for the Study of Institutions, Population, and Environmental Change) (2002). International Forestry Resources and Institutions (IFRI) field manual, ver. 10.5. Bloomington: Indiana University.

Cohen, W.A., T. K. Maiersperger, Z. Yang, S. T. Gower, D. P. Turner, W. D. Ritts, M. Berterretche, S. W. Running. 2003. Comparisons of land cover and LAI estimates derived from ETM+ and MODIS for four sites in North America: a quality assessment of 2000/2001 provisional MODIS products. Remote Sensing of Environment 88: 233-255.

Conca, K. 2006. Governing Water – contentious transnational politics and global institutions building. The MIT Press, Cambridge, Massachusetts.

Cumming, D. H. M. 1982. The influence of large herbivores on savanna structure in Africa. In B. J. Huntley and B. H. Walker (Eds) Ecology of tropical savannas. W. Junk, The Hague (Ecological studies number 42): 217-245.

Cumming, G. S., G. Barnes, S. Perz, M. Schmink, K. E. Sieving, J. Southworth, M. Binford, R. D. Holt, C. Stickler and T. Van Holt. 2005. An exploratory framework for the empirical measurement of resilience. Ecosystems 8:975-987.

D.J., Hytteborn H., Makhabu S., Mari M., Marokane W., Masunga G., Modise D.(†), Moe S.R., Mojaphoko R., Mosugelo D., Motsumi S., Neo-Mahupeleng G., Ramotadima M., Rutina L., Sechele L., Sejoe T.B., Stokke S., Swenson J.E., Taolo C., Vandewalle M. and Wegge P. 2004. The return of the giants; Ecological effects of an increasing elephant population. Ambio 33: 276-282.

Dahlberg, A. 2000. Vegetation diversity and change in relation to land use, soil and rainfall – a case study from North-East District, Botswana. Journal of Arid Environments 44: 19-40.

Davies, D.K., Ilavajhala, S., Wong, M.M., and Justice, C.O. (2009). “Fire Information for Resource Management System: Archiving and Distributing MODIS Active Fire Data”. IEEE Transactions on Geoscience and Remote Sensing 47 (1), 72-79.

De Luis, M., Garcia-Cano, M. F., Cortina, J., Raventos, J., Gonzalez-Hidalgo, J. C. and Sanchez, J.

De Luis, M., Garcia-Cano, M. F., Cortina, J., Raventos, J., Gonzalez-Hidalgo, J. C. and Sanchez, J.R.: 2001, ‘Climatic trends, disturbances and short term vegetation dynamics in a Mediterranean shrubland’, Forest Ecol. Manage. 147, 25–37.

Deering, D.W. 1978. Rangeland Reflectance Characteristics Measured by Aircraft and Spacecraft Sensors. College Station, TX: Texas A&M Univ. Press, p. 338.

Directorate of Environmental Affairs, Ministry of Environment and Tourism, Government of Namibia.

Domenikiotis, C., Loukas, A., and Dalezios, N.R. 2003. The use of NOAA/AVHRR satellite data for monitoring and assessment of forest fires and floods. Natural hazards and Earth System Sciences 3: 115-128.

Domenikiotis, C., Loukas, A., and Dalezios, N.R. 2003. The use of NOAA/AVHRR satellite data for monitoring and assessment of forest fires and floods. Natural hazards and Earth System Sciences 3: 115-128.

Dozier, J., 1981: A method for satellite identification of surface temperature fields of subpixel resolution. Remote Sens. Environ., 11, 221–229.

Dozier, J., 1981: A method for satellite identification of surface temperature fields of subpixel resolution. Remote Sensing of Environment. 11, 221–229.

du Toit J.T. and Cumming D.H.M. 1999. Functional significance of ungulate diversity in African savannas and the ecological implications of the spread of pastoralism. Biodiversity and Conservation 8: 1643–1661.

Dunteman, G. H. 2006. An introduction to generalized linear models. Thousand Oaks, Calif.: Sage Publications.

Eakin, H. 2003. “The Social Vulnerability of Irrigated Vegetable Farming Households in Central Puebla. Journal of Environment and Development 12(4): 414–429.

Eakin, H. 2005. Institutional change, climate risk, and rural vulnerability: cases from Central Mexico. World Development 33, 1923–1938.

Ellis, J.E. and Swift, D.M. 1988. Stability of African pastoral ecosystems: Alternate paradigms and implications for development. Journal of Range Management 41: 450-459.

Emore, A., Asner, G. and Hughes, F. 2005. Satellite monitoring of vegetation phenology and fire fuel conditions in Hawaiian Drylands. Earth Interactions 9, Paper No. 21.

Eriksen, C. 2007. Why do they burn the “bush”? Fire, rural livelihoods and conservation in Zambia. The Geographical Journal 173(3): 242-256.

Fensham, R.J., Fairfax, R.J., and Archer, S.R. 2005. Rainfall, land use and woody vegetation cover change in a semi-arid Australian savanna. Journal of Ecology 93: 596-606.

Fensholt, R., & Sandholt, I. 2005. Evaluation of MODIS and NOAA AVHRR vegetation indices with in situ measurements in a semi-arid environment. International Journal of Remote Sensing, 26(12), 2561-2594.

Flannigan, M.D., Bergeron, Y., Engelmark, O. and Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9, 469-476.

Flannigan, M.D., Stocks, B.J. and Wotton, B.M. 2000. Climate change and forest fires. The Science of the Total Environment 262, 221-229.

Flannigan, M.D., B. D. Amiro, K. A. Logan, B. J. Stocks and B. M. Wotton. 2005. Forest fires and climate change in the 21st century. Mitigation and adaptation strategies for Global Change 11 (4), 847-859.

Folke, C. 2006. Resilience: the emergence of a perspective for socio-ecological systems analyses. Global Environmental Change 16, 253-267.

Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S., and Walker, B. (2002). Resilience and sustainable development: building adaptive capacity in a world of transformations. Ambio 31(5), 437-440.

for retrospective remote sensing-based ecological monitoring of rangelands. Rangeland Ecology and Management 59(1):19-29.

Foster, R. 2006. Methods for assessing land degradation in Botswana. Earth & E-nvironment 1: 238-276.

Frost, P.1996. The Ecology of Miombo Forests, in B. Campbell, (ed), The Miombo in Transition:Woodlands and Welfare in Africa, Centre for International Forestry Research, Bogor, Indonesia, pp. 26–45.

Frost, P.1996. The Ecology of Miombo Forests, in: B. Campbell, (ed), The Miombo in Transition:

Galwey, N. 2006. Introduction to mixed modeling: beyond regression and analysis of variance. Chichester, England; Hoboken, NJ: Wiley.

Giglio, L., J. Descloitres, C. O. Justice, and Y. Kaufman, 2003: An enhanced contextual fire detection algorithm for MODIS. Remote Sens. Environ., 87, 273–282.

Giglio, L., J. Descloitres, et al. (2003). "An Enhanced Contextual Fire Detection Algorithm for MODIS." Remote Sensing of Environment 87 (2-3), 273-282.

Gill, A.M. 1975. Fire and the Australian flora: a review. Australian Forestry 38, 4-25.

Goldammer, J.G. and Price, C. 1998. Potential impacts of climate change on fire regimes in the tropics based on MAGICC and a GISS GCM-derived lightning model. Climatic Change 39, 273-296.

Gumbricht, T., McCarthy, T.S., and Merry, C.L. 2001. The topography of the Okavango Delta, Botswana, and its tectonic and sedimentological implications. South African Journal of Geology 104: 243-264.

Gunderson, L.H. and C.S Holling, editors. 2002. Panarchy: understanding transformations in human and natural systems. Washington D.C.: Island Press.

Gunderson, L.H., Carpenter, S.R., Folke, C., Olsson, P. and Peterson, G. 2006. Water RATs (Resilience, Adaptability, and Transformability) in Lake and Wetland Socio-ecological Systems. Ecology and Society: 11 (1): 16.

HadCM3 IS92a Climate change model 2007. Hadley Center for Climate Prediction and Research. The Meteorological Office.

Harrington, G.N. 1991. Effects of soil moisture on shrub seedling survival in semi-arid grasslands. Ecology: 72: 1138-1149.

Harris, A.R. and Mason, I.M. 1989. Lake area measurement using AVHRR: a case study. International Journal of Remote Sensing 10: 885-895.

Hawbaker, T.J., Radeloff, V., Siphard, A., Zhu, Z., and Stewart, S. 2008. Detection rates of MODIS Active Fires in the United States. Remote Sensing of Environment 112, 2656-2664.

Holling, C.S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4: 1-23.

Holling, C.S. 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. Ecological Monographs 62(4), 447-502.

Holling, C.S. 1996. Engineering resilience versus ecological resilience. In P.C. Schulze, Ed. Engineering within ecological constraints. Washington D.C.: National Academy Press.

Holm, A. M., Cridland, S. W., & Roderick, M. L. 2003. The use of time-integrated NOAA NDVI data and rainfall to assess landscape degradation in the arid shrubland of Western Australia. Remote Sensing of Environment, 85(2), 145-158.

Hough, J.L. 1993. Why burn the bush? Social approaches to bush fire management in West African National parks. Biological Conservation. 65, 23-28.

Hudak, A.T., Fairbanks, D.H.K., and Brockett, B.H. 2004. Trends in fire patterns in a southern African savanna under alternative land use practices. Agriculture, Ecosystems and Environment 101: 307-325.

Hudak, A.T., Fairbanks, D.H.K., and Brockett, B.H. 2004. Trends in fire patterns in a southern African savanna under alternative land use practices. Agriculture, Ecosystems and Environment. 101, 307-325.

Huete, A.R., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., and Ferreira, G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment 83: 195-213.

Huete, A.R., H.Q. Liu, K. Batchily and W.J.D. van Leeuwen. 1999. A comparison of vegetation indices over a global set of TM images for EOS-MODIS. Remote Sensing of Environment 59: 440–451.

Huffman, G. J., R. F. Adler, et al. (1997). "The Global Precipitation Climatology Project (GPCP) Combined Precipitation Dataset." Bulletin of the American Meteorological Society 78(1): 5-20.

Huffman, G. J., R. F. Adler, et al. 1997. "The Global Precipitation Climatology Project (GPCP) Combined Precipitation Dataset." Bulletin of the American Meteorological Society 78(1), 5-20.

IUCN Parks for Life: Report of the Fourth World Congress on National Parks and Protected Areas, Caracas, Venezuela, February 1992 World Conservation Union, Cambridge, UK (1993).

Jain, S.K., Saraf, A.K., Goswami, A., and Ahmad, T. 2006. Flood inundation mapping using NOAA AVHHR data. Water Resources Management. 20: 949-959.

Jansen, R. and H. T. Riezebos. 1988. The Chobe Enclave: Soils, Hydrology and Farming Systems Inventories for Land Use Planning. Technical Report 1. Report prepared for the Community First Development Area Programme. University of Utrecht, Geographical Institute. Utrecht.

Jeltsch, F., Weber, G.E., and Grimm, V. 2000. Ecological buffering mechanisms in savannas: a unifying theory of long-term tree-grass coexistence. Plant Ecology 161: 161-171.

Jensen, John R., 2005, Introductory Digital Image Processing, 3rd Ed., Upper Saddle River, NJ: Prentice Hall, 526 pages.

Jia, Z. and Luo, W. 2009. A modified climate diagram displaying net water requirements of wetlands in arid and semi-arid regions. Agricultural Water Management. 96: 1339-1343.

Johnson RW, Tothill JC. 1985. Definition and broad geographic outline of savanna lands. In Ecology and Management of the World's Savannus, ed. JC Tothill, JJ Mott,pp. 1-13. Canberra, ACT: Aust. Acad. Sci.

Jones, B.T. 2002. Chobe Enclave, Botswana: Lessons learnt from a CBNRM project 1992-2002. CBNRM Support Programme Occasional Paper No. 7. IUCN/SNV CBNRM Support Programme.

Justice, C.O., E. Vermote, J.R.G. Townshend, R. Defries, et al. 1998. The Moderate Resolution Imaging Spectroradiometer (MODIS): land remote sensing for global change research. IEEE Transactions on Geoscience and Remote Sensing 36 (4): 1228–1249.

Justice, C.O., L. Giglio, S. Korontzi, J. Owens, J.T. Morisette and D. Roy et al. 2002. The MODIS fire products. Remote Sensing of Environment 83, 244–262.

Kates, R., Clark, W., Corell, R., Hall, J., Jaeger, C., Lowe, I., McCarthy, J., Schellnhuber, H., Bolin, B., Dickson, N., Faucheux, S., Gallopin, G., Grubler, A., Huntley, B., Jager, J., Jodha, N., Kasperson, R., Mabogunje, A., Matson, P., & Mooney, H. 2001. Sustainability science. Science 292 (5517):641-642.

Kaufman, Y.J. and Remer, L.A. 1994. Detection of forests using mid-IR reflectance: an application for aerosol studies. IEEE Transactions on Geoscience and Remote Sensing 32 (3): 672-683.

Kaufman, Y.J. and Remer, L.A. 1994. Detection of forests using mid-IR reflectance: an application for aerosol studies. IEEE Transactions on Geoscience and Remote Sensing. 32 (3), 672-683.

Kgathi, D.L., Sekhwela, M.B., and Hamandawana, H. 2003. Sustainability of Commercial Agriculture in Chobe District, Botswana. South African Geographical Journal 85 (1), 18-25.

Kinuya, P.I., van Kooten, G.C., and Bulte, E.H. 2000. African wildlife policy: protecting wildlife herbivores on private game ranches. European Review of Agricultural Economics 27:227-244.

Klein, R.J.T., R.J. Nicholls, and F. Thomalla. 2003. Resilience to natural hazards: how useful is this concept? Environmental Hazards 5, 35-45.

Krug, W. 2001. Private supply of protected land in Southern Africa: a review of markets, approaches, barriers and issues, Workshop Paper: World Bank / OECD International Workshop on Market Creation for Biodiversity Products and Services Paris, 25 and 26 January 2001.

Krugman H. 2001. Toward Improved Indicators to Measure Desertification and Monitor the Implementation of the Desertification Convention, IDRC p1-13

Krummel, J.R., Gardner, R.H., Sugihara, G., O'Neill, R.V., and Coleman, P.R. 1987. Landscape patterns in a disturbed environment. Oikos 48: 321-324.

Kummerow C, Simpson J, Thiele O et al. (2000) The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. Journal of Applied Meteorology, 39, 1965-1982.

Kummerow C, Simpson J, Thiele O. et al. 2000. The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. Journal of Applied Meteorology. 39, 1965-1982.

Kutt, A.S. and Woinarski, J.C.Z. 2007. The effects of grazing and fire on vegetation and the vertebrate assemblage in a tropical savanna woodland in north-eastern Australia. Journal of Tropical Ecology 23: 95-106.

Laliberte, A.S, Rango, A., Havstad, KM., Paris, J., Beck, R., McNeely, R., and Gonzales, A. 2004. Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico. Remote Sensing of Environment 93: 198-210.

Lambin, E. F., and Strahler, A. H., 1994, Indicators of land-cover change for change-vector analysis in multi-temporal space at coarse spatial scales. International Journal of Remote Sensing: 15, 2099-2119.

Lambin, E.F., 1999. Monitoring forest degradation in tropical regions by remote sensing: some methodological issues. Global Ecology and Biogeography 8: 191-198.

Lavorel, S., Flannigan, M.D., Lambin, E.F., and Scholes, M.C. 2007. Vulnerability of land systems to fire: inteercations among humans, climate, the atmosphere, and ecosystems. Mitigation and Adaptation Strategies for Global Change 12: 33-53.

Lavorel, S., Flannigan, M.D., Lambin, E.F., and Scholes, M.C. 2007. Vulnerability of land systems to fire: interactions among humans, climate, the atmosphere, and ecosystems. Mitigation and Adaptation Strategies for Global Change. 12, 33-53.

Levin, S., Barrett, S., Aniyar, S., and others. 1998. Resilience in natural and socio-economic systems. Environment and Development Economics 3: 221-262.

Levin, S.A. (1998). Ecosystems and the biosphere as complex adaptive systems. Ecosystems 1, 431-436.

Li R.R., Kaufman Y.J., Hao W.M., Salmon J.M., Gao B.C. 2004. A technique for detecting burn scars using MODIS data. IEEE Transactions of Geoscience and Remote Sensing 42 (6): 1300-1308.

Li, H and Reynolds, J.F. 1994. A simulation experiment to quantify spatial heterogeneity in categorical maps. Ecology 75: 2446-2455.

Liu, H.Q. and A.R. Huete. 1995. A feedback based modification of the NDVI to minimize canopy background and atmospheric noise.IEEE Trans. Geosci. Remote Sens. 33: 457–465.

MacGregor, S.D. and O'Connor, T.G. 2004. Response of Acacia tortilis to utilization by elephants in a semi-arid African savanna. South African Journal of Wildlife Research 34(1): 55-66.

Mbow, C., Goita, K., and Benie, G.b. 2006. Spectral indices and fire behavior simulation for fire risk assessment in savanna ecosystems. Remote Sensing of Environment 91: 1-13.

McCarthy, J., Gumbricht, T., and McCarthy T.S. 2005. Ecoregion classification in the Okavango Delta, Botswana from multitemporal remote sensing. International Journal of Remote Sensing. 26 (19): 4339-4357.

McCarthy, J.M., Gumbricht, T., McCarthy, T., Frost, P., Wessels, K. and Seidel, F. 2003. Flooding patterns of the Okavango Wetland in Botswana between 1972 and 2000. Ambio. 32(7): 453-457.

McCarthy, J.M., Gumbricht, T., McCarthy, T., Frost, P., Wessels, K., and Seidel, F. 2003. Flooding patterns of the Okavango Wetland in Botswana between 1972 and 2000. Ambio 32 (7): 453-457.

McCoy., V.M. and Burn, C.R. 2005. Potential alteration by climate change of the forest-fire regime in the Boreal Forest of Central Yukon Territory. Arctic 58(3), 276-285.

Mendelsohn, J. and C. Roberts. 1997. An Environmental Profile and Atlas of Caprivi. Directorate of Environmental Affairs, Gamsberg Macmillan Publishers, Winhoek, Namibia.

Mendelsohn, J. and C. Roberts. 1997. An Environmental Profile and Atlas of Caprivi. Directorate of Environmental Affairs, Gamsberg Macmillan Publishers, Winhoek, Namibia.

Meyer, KM., Wiegard, K., Ward, D. and Moustakas, A. 2007. The rhythm of savanna patch dynamics. Journal of Ecology 95: 1306-1315.

Mildrexler, D.J., Zhao, M., and Running, S.W. 2009.Testing a MODIS Global Disturbance Index across North America. Remote Sensing of Environment. 113: 2103:2117.

Milton, S.J., Powell, J. and Anderson, M.D. 2001. Incentives for Camelthorn (Acacia erioloba) clearing in the Kalahari. Arid Zone Ecology Forum, Calitzdor 4-7, Pretoria, p.54.

Moleele, N.M., Ringrose, S., Matheson, W. and Vanderpost, C. 2002. More woody plants? The status of bush encroachment in Botswana's grazing areas. Journal of Environmental Management 64: 3-11.

Morisette, J., Giglio, L., Csiszar, I., Setzer, A., Schroeder, W., Morton, D., and Justice, C. 2005. Validation of MODIS Active Fire detection products derived from two algorithms. Earth Interactions 9, Paper 9: 1-25.

Morisette, J., Giglio, L., Csiszar, I., Setzer, A., Schroeder, W., Morton, D., and Justice, C. 2005. Validation of MODIS Active Fire detection products derived from two algorithms. Earth Interactions 9, Paper 9: 1-25.

Mosugelo, D., Moe, S.R., Ringrose, S., and Nelleman, C. 2002. Vegetation changes during a 36-year period in northern Chobe National Park, Botswana. African Journal of Ecology 40 (3): 232-240.

Mosugelo, D., Moe, S.R., Ringrose, S., and Nelleman, C. 2002. Vegetation changes during a 36-year period in northern Chobe National Park, Botswana. African Journal of Ecology 40 (3): 232-240.

Nakamura, T. 2006. Development of decision-making indicators for ecosystem-based river management. Hydrological Processes 20: 1293-1308.

Namibia Association of CBNRM Support Organizations – NACSO. 2002. Accessed on November 22nd 2008 online at: http://www.nacso.org.na/index.php.

NASA/University of Maryland. 2002. MODIS Hotspot / Active Fire Detections. Data set. MODIS Rapid Response Project, NASA/GSFC [producer], University of Maryland, Fire Information for Resource Management System [distributors]. Available on-line [http://maps.geog.umd.edu]

Nellemann C, Moe SR, Rutina LP. 2002. Links between terrain characteristics and forage patterns of elephants (Loxodonta Africana) in Northern Botswana. Journal of Tropical Ecology 18:835-844.

Nicholson SE, Some B, McCollum J et al. (2003) Validation of TRMM and other rainfall estimates with a high-density gauge dataset for West Africa. Part I: Validation of GPCC rainfall product and pre-TRMM satellite and blended products. Journal of Applied Meteorology, 42, 1337-1354.

Nicholson SE, Some B, McCollum J et al. 2003. Validation of TRMM and other rainfall estimates with a high-density gauge dataset for West Africa. Part I: Validation of GPCC rainfall product and pre-TRMM satellite and blended products. Journal of Applied Meteorology. 42, 1337-1354.

Nicholson, S.E. 2001.Climatic and environmental change in Africa during the last two centuries. Climate Research 17: 123-144.

Nicholson, S.E., Some, B., and Kone, B. 2000. An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Nino and 1998 La Nina Years. Journal of Climate 13: 2628-2640.

O'Connor., T.G., Goodman, P.S., and Clegg, B. 2007. A functional hypothesis of the threat of local extirpation of woody plant species by elephant in Africa. Biological Conservation 136: 329-345.

O'Neill, R.V., Johnson, A.R., and King, A.W. 1989. A hierarchical framework for the analysis of scale. Landscape Ecology 3: 193-205.

Overpeck, J.T., Rind, D. & Goldberg, R. 1990. Climate-induced changes in forest disturbance and vegetation. Nature. 343, 51-53.

Painter, L., and Maotonyane, M. 1996. Chobe Enclave – Socio-economic study (Ecosurv), produced as part of the Natural Resource Management Project USAID Project 690-0251.33.

Patil, G.P. and Myerst, W.L. 1999. Environmental and ecological health assessment of landscapes and watersheds with remote sensing data. Ecosystem Health 5: 221-224.

Peace Parks Foundation, The Global Solution, South Africa, 2010. Accessed online August 5th, 2010 at: www.peaceparks.org.

Peters, DP.C., and Havstad, K.M. 2006. Nonlinear dynamics in arid and semi-arid systems: interactions among drivers and processes across scales. Journal of Arid Environments 65: 196-206.

Peters, DP.C., and Havstad, K.M. 2006. Nonlinear dynamics in arid and semi-arid systems: interactions among drivers and processes across scales. Journal of Arid Environments 65: 196-206.

Pricope, N.G. and Binford, M.W. 2011 (forthcoming). Variable-source flood pulsing in a semi-arid transboundary watershed: the Chobe River, Botswana and Namibia. Earth Interactions Journal.

Prigent, C., Papa, F., Aires, F., Rossow, W.B., and Matthews, E. 2007. Global inundation dynamics inferred from multiple satellite observations, 1993-2000. Journal of Geophysical Research: 112, D12107.

Qi, J., Cabot, F., Moran, M.S., and Dedieu, G. 1995. Biophysical parameter estimations using multidirectional spectral measurements. Remote Sensing of Environment 54: 71-83.

R.: 2001, ‘Climatic trends, disturbances and short term vegetation dynamics in a Mediterranean

Republic of Botswana Tourism Policy. 1990. Government Paper No. 2 of 1990. Government Printer Gaborone.

Riney, T. 1963. A rapid field technique and its application in describing conservation status and trends in semi-arid pastoral areas. African Soils 8: 159-257.

Ringrose, S., Chipanshi, A., Matheson, W., Chanda, R., Motoma, L, Magole, I., amd Jellema, A. 2002. Climate- and human-induced woody vegetation changes in Botswana and their implications for human adaptation. Journal of Environmental Management 30 (1): 98-109.

Ringrose, S., Matheson, W., Wolski, P., Huntsman-Mapila, P. 2003. Vegetation cover trends along the Botswana Kalahari transect. Journal of Arid Environments 54: 297-317.

Ringrose, S., Vanderpost, C., Matheson, W., Wolski, P., Huntsman-Mapila, P., Murray-Hudson, M., et al. 2007. Indicators of desiccation-driven change in the distal Okavango Delta, Botswana. Journal of Arid Environments, 68(1), 88-112.

Ringrose, S., Vanderpost, C., Matheson, W., Wolski, P., Huntsman-Mapila, P., Murray-Hudson, M., et al. 2007. Indicators of desiccation-driven change in the distal Okavango Delta, Botswana. Journal of Arid Environments, 68(1), 88-112.

Rogers, A. S., & Kearney, M. S. (2004). Reducing signature variability in unmixing coastal marsh Thematic Mapper scenes using spectral indices. International Journal of Remote Sensing, 20, 2317−2335.

Roques, K.G, O'Connor, T.G. and Watkinson, A.R. 2001. Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall, and density dependence. Journal of Applied Ecology 38: 268-280.

Roques, K.G, O'Connor, T.G. and Watkinson, A.R. 2001. Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall, and density dependence. Journal of Applied Ecology. 38, 268-280.

Rouse, J.W., Haas, R. H., Schell, J.A., and Deering, D.W. 1974. Monitoring vegetation systems in the Great Plains with ERTS. Proceedings, 3rd Earth Resource Technology Satellite (ERTS) Symposium 1: 48-62.

Roy D, Frost P, Justice C et al. 2005a. The Southern African Fire Network (SAFNet) regional burned area product validation protocol. International Journal of Remote Sensing, 26, 4265– 4292.

Roy, D.P. and Boschetti, L., 2009, Southern Africa Validation of the MODIS, L3JRC and GLOBCARBON Burned Area Products,IEEE Transactions on Geoscience and Remote Sensing. 47 (4), 1032 – 1044.

Roy, D.P., Boschetti, L., Justice, C.O., and Ju, J. 2008. The collection 5 MODIS burned area product – Global evaluation by comparison with the MODIS active fire product. Remote Sensing of Environment. 112, 3690-3707.

Roy, D.P., Giglio, L., Kendall, J.D., and Justice, C.O. 1999. Multi-temporal active-fire based burn scar detection algorithm. International Journal of Remote Sensing 20 (5), 1031-1038.

Roy, D.P., Giglio, L., Kendall, J.D., and Justice, C.O. 1999. Multi-temporal active-fire based burn scar detection algorithm. International Journal of Remote Sensing 20 (5): 1031-1038.

Roy, D.P., P.E. Lewis and C.O. Justice. 2002. Burned area mapping using multi-temporal moderate spatial resolution data – a bi-directional reflectance model-based expectation approach. Remote Sensing of Environment. 83, 263-286.

Roy, D.P., Y. Jin, P.E. Lewis and C.O. Justice. 2005b. Prototyping a global algorithm for systematic fire affected area mapping using MODIS time series data. Remote Sensing of Environment. 97, 137-162.

Russell-Smith, J., Ryan, P., KLessa, D., Waight, G. and Harwood, R. 1998. Fire regimes, fire-sensitive vegetation and fire management of the sandstone Arnhem Plateau, monsoonal northen Australia. Journal of Applied Ecology 35: 829-846.

Russel-Smith, J., Ryan, P.G., and Dureiu, R. 1997. A LANDSAT MSS-derived fire history of Kakadu National Park, Monsoonal Northern Australia. Journal of Applied Ecology 34 (3), 748-766.

Rutina, L.P., Moe, S.R. & Swenson, J.E. 2005: Elephant Loxodonta Africana driven woodland conversion to shrubland improves dry-season browse availability for impalas Aepyceros melampus. Wildlife Biology 11: 207-213.

Rutina, L.P., Moe, S.R. & Swenson, J.E. 2005: Elephant Loxodonta Africana driven woodland conversion to shrubland improves dry-season browse availability for impalas Aepyceros melampus. Wildlife Biology 11: 207-213.

Sakamoto, T., Van Nguyen, N., Kotera, A., Ohno, H., Ishitsuka, N., and Yokozawa, M. 2007. Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta from MODIS time-series imagery. Remote Sensing of Environment. 109: 295-313.

Sankaran, M., Hanna, N., Scholes, R.J. and others. 2005. Determinants of woody cover in African savanna. Nature 438 (8): 846-849.

Sankaran, M., Hanna, N., Scholes, R.J. and others. 2005. Determinants of woody cover in African savanna. Nature 438 (8): 846-849.

Scanlon, T.M., Albertson, J.D., Caylor, K.K. and Williams, C.A., 2002, Determining land surface fractional cover from NDVI and rainfall time series for a savanna ecosystem. Remote Sensing of Environment, 82, pp. 376–388.

Scholes, R.J. and Archer, S.R. 1997. Tree-grass interactions in savanna. Annual Review of Ecology and Systematics, 28: 517-544.

Scholes, R.J. and Archer, S.R. 1997. Tree-grass interactions in savanna. Annual Review of Ecology and Systematics. 28, 517-544.

Scholes, R.J. and Walker, B.H. 1993. An African Savanna: Synthesis of the Nylsvley Study. New York: Cambridge University Press.

Serneels, S., Linderman, M., and Lambin, E. F. 2007. A multilevel analysis of the impact of land use on interannual land-cover change in East Africa. Ecosystems. 10, 402–418.

SIAPAC. 1992. Baseline Survey of the Chobe Enclave Final Report. Natural Resources Management Project. Gaborone.

Skarpe C., Aarrestad P.A., Andreassen H.P., Dhillion S., Dimakatso T., Du Toit J.T., Halley

Skarpe C., Aarrestad P.A., Andreassen H.P., Dhillion S., et al. 2004. The return of the giants; Ecological effects of an increasing elephant population. Ambio 33: 276-282.

Smit, G. N., Richter, C. G. F. and Aucamp, A. J. 1999, ‘Bush Encroachment, an Approach to Understanding and Managing the Problem’, in: N. M. Tainton, (ed), Veld Management in South Africa, University of Natal Press, Pietermaritzburg, pp. 246–260.

Smit, G. N., Richter, C. G. F. and Aucamp, A. J.: 1999, ‘Bush Encroachment, an Approach to

Smith, L.P. 1997. Satellite remote sensing of river inundation area, stage, and discharge: a review. Hydrological Processes 11: 1427-1439.

Smith, L.P. 1997. Satellite remote sensing of river inundation area, stage, and discharge: a review. Hydrological Processes 11: 1427-1439.

Snyder, K.A. and Tartowski, S.L. 2006. Multi-scale temporal variation in water availability: implications for vegetation dynamics in arid and semi-arid ecosystems. Journal of Arid Environments 65: 219-234.

Snyder, K.A. and Tartowski, S.L. 2006. Multi-scale temporal variation in water availability: implications for vegetation dynamics in arid and semi-arid ecosystems. Journal of Arid Environments 65: 219-234.

Southworth, J., D. Munroe, and H. Nagendra. 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.

Stahl, D. W., Mushove, P. T., Cleaveland, W. K., Roig, F. and Haynes, G. A.: 1999, ‘Management implications of annual growth rings in Pterocarpus angolensis from Zimbabwe’, Forest Ecol. Manage. 124, 217–229.

Stahl, D. W., Mushove, P. T., Cleaveland, W. K., Roig, F. and Haynes, G. A.: 1999, ‘Management implications of annual growth rings in Pterocarpus angolensis from Zimbabwe’, Forest Ecol. Manage. 124, 217–229.

Stocks, B.J., M. A. Fosberg, T. J. Lynham, L. Mearns, B. M. Wotton, Q. Yang, J-Z. Jin, K. Lawrence, G. R. Hartley and J. A. Mason, et al. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. Climatic Change. 38, 1-13.

Swetnam, T.M., Betancourt, J.L. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate. 11, 3128-3147.

Taylor, R.D. and Walker, B.H. 1978. Comparisons of vegetation use and herbivore biomass on a Rhodesian game and cattle ranch, Journal of Applied Ecollogy: 15, 565-581.

Teillet, P.M., K. Staenz and D.J. William. 1997. Effects of spectral, spatial, and radiometric characteristics on remote sensing vegetation indices of forested regions, Remote Sensing of Environment 61 (1997) (1): 139–149.

Tews, J., Esther, A., Milton, S., and Jeltsch, F. 2006. Linking a population model with a ecosystem model: Assessing the impact of land use and climate change on savanna shrub cover dynamics. Ecological Modelling 195: 219-228.

Trigg, S.N. 1998. Fire scar mapping in northern Namibia. Report. Forest Fire Control Component, Namibia Finland Forestry Programme, Directorate of Forestry, Ministry of Environment and Tourism, Namibian Government, Windhoek, Namibia, 1-22.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment 8: 127–150.

Tucker, C. J., Vanpraet, C. L., Sharman, M. J. and van Ittersum, G. 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980–1984. Remote Sensing of Environment 17: 233–249.

Turner, MG., O'Neill, R.V., Gardner, R.H. and Milne, B.T. 1989. Effects of changing spatial scale on the analysis of landscape pattern. Landscape Ecology: 3: 153-162.

Turton, A.R. 1999. Water and state sovereignty: the hydropolitical challenge for states in arid regions. MEWREW Occasional Paper No. 5, Water Issues Study Group.

Turton, A.R. 1999. Water and state sovereignty: the hydropolitical challenge for states in arid regions. MEWREW Occasional Paper No. 5, Water Issues Study Group.

Understanding and Managing the Problem', in: N. M. Tainton, (ed), Veld Management in SouthAfrica, University of Natal Press, Pietermaritzburg, pp. 246–260.

UNEP, 2002, Africa Environment Outlook: Past Present and Future Perspectives (Stevenage, UK: United Nations Environment Programme (UNEP)/GRID-Arendal, EarthPrint).

Urban, D. L., O'Neill, R.V., and Shugart, H.H. Jr. 1987. Landscape ecology. BioScience 37: 119-127.

USCCSP, 2004: Our Changing Planet, The U.S. Climate Change Science Program for Fiscal Years 2004 and 2005. A Report by the Climate Change Science Program and Subcommittee on Global Change Research. A Supplement to the President's Fiscal Year 2004 and 2005 Budgets (online at: http://www.usgcrp.gov/usgcrp/Library/ocp2004-5/default/htm).

USCCSP, 2004: Our Changing Planet, The U.S. Climate Change Science Program for Fiscal Years 2004 and 2005. A Report by the Climate Change Science Program and Subcommittee on Global Change Research. A Supplement to the President's Fiscal Year 2004 and 2005 Budgets (see http://www.usgcrp.gov/usgcrp/Library/ocp2004-5/default/htm).

USDA Forest Service Forest Resource Assessment Trip Kuando Kubango Province, Angola. 2006. In support of the USAID Southern Africa's Okavango Integrated River Basin and the Angolan Ministry of Agriculture and Rural Development's National Institute for Forestry Development and Management Project - Trip and Assessment Report.

Van Wilgen B.W., Trollope, W.S.W., Biggs, H.C., Potgieter A.L.F. and Brockett B.H. 2003. Fire as a driver of ecosystem variability. In The Kruger Experience: Ecology and Management of Savanna Heterogeneity, eds J. du Toit, K.H. Rogers and H.C. Biggs, pp. 149–170. Island Press, New York.

Van Wilgen, B.W. and Scholes, R.J., 1997, The Vegetation and Fire Regimes of Southern Hemisphere Africa. In Fire in Southern African Savannas: Ecological and Atmospheric Perspectives, B.W. van Wilgen, M.O. Goldammer, J.G. Goldammer and J.A. Lindesay (Eds), pp. 27–46 (Johannesburg, South Africa: Witwatersrand University Press).

Verlinden, A. and Laamanen, R. 2006. Long-term fire scar monitoring with remote sensing in Northern Namibia: relations between fire frequency, rainfall, land cover, fire management and trees. Environmental Monitoring and Assessment 112: 231-253.

Verlinden, A. and Laamanen, R. 2006. Long-term fire scar monitoring with remote sensing in Northern Namibia: relations between fire frequency, rainfall, land cover, fire management and trees. Environmental Monitoring and Assessment. 112, 231-253.

Walker, B. H. 1993. Rangeland Ecology - Understanding and Managing Change. Ambio 22, No. 2-3: 80-87.

Walker, B., L. Gunderson, A. Kinzig, C. Folke, S. Carpenter, and L. Schultz. 2006. A handful of heuristics and some propositions for understanding resilience in social-ecological systems. Ecology and Society 11(1):13.

Walker, B.H. 1976. An approach to the monitoring of changes in the composition and utilization of woodland and savanna vegetation. South African Journal of Wildlife Research 6(1): 1-32.

Walker, B.H., Holling, C.S., Carpenter, S.R., and Kinzig, A. 2004. Resilience, transformability and adaptability in socio-ecological systems. Ecology and Society 9(2): 1-5.

Walz, Y., Maier, S.W., Dech, S.W., Conrad, C., and Colditz, R.R. 2007. Classification of burn severity using Moderate Resolution Imaging Spectroradiometer (MODIS): A case study in the jarrah-marri forest of southwest Western Australia. Journal of Geophysical Research – Biogeosciences 112 (G2): Art. No. G02002.

Wang, F. and D'Sa, E. 2010. Potential of MODIS EVI in identifying hurricane disturbance to coastal vegetation in the northern Gulf of Mexico. Remote Sensing 2:1-18.

Washington-Allen, R. A., N. E. West, R. D. Ramsey, and R. A. Efroymson. 2006. A protocol

Washington-Allen, R. A., R. D. Ramsey, and N. E. West. 2004. Spatiotemporal mapping of the dry season vegetation response of sagebrush steppe. Community Ecology 5(1):69-79.

Washington-Allen, R. A., T. G. Van Niel, R. D. Ramsey, and N. E. West. 2004. Remote sensing based piosphere analysis. GIScience and Remote Sensing 41(2):136-154.

Watkinson, A.R. and Powell, J.C. 1997. The life history and population structure of Cycas armstrongii in monsoonal northern Australia. Oecologia 111: 341-349.

Watkinson, A.R. and Powell, J.C. 1997. The life history and population structure of Cycas armstrongii in monsoonal northern Australia. Oecologia. 111, 341-349.

Wessels, K.J., Prince, S.D., Frost, P.E., and van Zyl, D. 2004. Assessing the effects of human-induced land degradation in the former homelands of northern South Africa with a 1 km AVHRR NDVI time-series. Remote Sensing of Environment 91: 47-67.

Wessels, K.J., Prince, S.D., Frost, P.E., and van Zyl, D. 2004. Assessing the effects of human-induced land degradation in the former homelands of northern South Africa with a 1 km AVHRR NDVI time-series. Remote Sensing of Environment 91: 47-67.

Westbrooke, M. E., & Florentine, S. K. 2005. Rainfall-driven Episodic Flood Events: are they a major factor in moulding New South Wales arid land vegetation patterns? Australian Geographer, 36(2), 171-181.

Westbrooke, M. E., & Florentine, S. K. 2005. Rainfall-driven Episodic Flood Events: are they a major factor in moulding New South Wales arid land vegetation patterns? Australian Geographer, 36(2), 171-181.

Westbrooke, M. E., Florentine, S. K., & Milberg, P. 2005. Arid land vegetation dynamics after a rare flooding event: influence of fire and grazing. Journal of Arid Environments, 61(2), 249-260.

Westbrooke, M. E., Florentine, S. K., & Milberg, P. 2005. Arid land vegetation dynamics after a rare flooding event: influence of fire and grazing. Journal of Arid Environments, 61(2), 249-260.

Whelan, R.J. 1995. The Ecology of Fire. Cambridge: Cambridge University Press, 1995: 346.

Whittaker, R. H. 1975. Communities and ecosystems. MacMillan, New York.

Wilcox, B.P. and Thurow, T.L. 2006. Emerging issues in rangeland hydroecology: vegetation change and the water cycle. Rangeland Ecology and Management 59: 220-224.

Wolski, P. and Murray-Hudson, M. 2006. Flooding dynamics in a large low-gradient alluvial fan, the Okavango Delta, Botswana, from analysis and interpretation of a 30-year hydrometric record. Hydrology and Earth Systems Sciences. 10: 127-137.

Wolter, K., 1987: The Southern Oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian Oceans as captured by cluster analysis. J. Climate Appl. Meteor., 26, 540-558.

Wolter, K., 1987: The Southern Oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian Oceans as captured by cluster analysis. J. Climate Appl. Meteor., 26, 540-558.

Wolter, K., and M. S. Timlin, 1998: Measuring the strength of ENSO events - how does 1997/98 rank? Weather, 53, 315-324.

Wolter, K., and M. S. Timlin, 1998: Measuring the strength of ENSO events - how does 1997/98 rank? Weather. 53, 315-324.

Woodlands and Welfare in Africa, Centre for International Forestry Research, Bogor, Indonesia, Wu, X.B. and Archer, S.R. 2005. Scale-Dependent Influence of Topography-Based Hydrologic Features on Patterns of Woody Plant Encroachment in Savanna Landscapes. Landscape ecology 20(6): 733-742.

Yan, Y.E., Ouyang, Z.T., Guo, H.Q., Jin, S.S. and Zhao, B. 2010. Detecting the spatio-temporal changes of tidal flood in estuarine wetlands by using MODIS time series data. Journal of Hydrology 384: 156-163.

Zimbabwe Environmental Law Association (ZELA) 2010. Environmental Management (Environmental Impact Assessments and Ecosystems Protection) Regulations, Statutory Instrument No. 7 of 2007; accessed online on August 5th 2010 at: http://www.zela.org/site/newsletter.asp.

BIOGRAPHICAL SKETCH

Narcisa Gabriela Pricope was born in Romania and attended university for her undergraduate degree at Babes-Bolyai University in Cluj-Napoca, Romania until 2004. She obtained a Bachelor of Arts Magna cum Laude in geography and English from Babes-Bolyai after also studying at Glasgow University in Scotland as an Erasmus/Socrates exchange student in 2003. She received a joined United States Geological Survey/United States Department of Agriculture research assistantship at Western Kentucky University (WKU) in 2004 when she started her Master of Science degree in Geoscience at WKU. Her master's thesis focused on modeling the risk of soil erosion and sediment mobilization in an agricultural watershed in Kentucky affected by water siltation problems.

In the summer of 2006, Narcisa received a National Science Foundation (NSF) Interdisciplinary Graduate Education and Research Traineeship (IGERT) fellowship at the University of Florida in the Adaptive Management: Water, Wetlands, and Watersheds under the guidance of Dr. Mark Brown, director of the Center for Wetlands at UF. She first traveled to southern Africa with the IGERT group for a seven-week field course and she decided to pursue her PhD dissertation research work in Namibia and Botswana. In 2008, Narcisa was awarded an NSF Dissertation Improvement Grant which allowed her to complete her field research in southern Africa in 2009. Narcisa is currently an assistant professor at Southern Oregon University and a visiting scholar for the 2011-2012 academic year at University of California Santa Barbara where she will continue working on natural resources management issues and land cover change in Africa.