A spatio-temporal analysis of fire recurrence and extent for semi-arid savanna ecosystems in southern Africa using moderate-resolution satellite imagery

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Abstract

Savanna ecosystems are semi-arid and fire-prone. Increasing temperatures and decreasing precipitation in Southern Africa will probably have a series of strong impacts on the various components of fire regimes in these ecosystems that will, in turn, affect their ecology, structure, and function. This paper presents a geospatial analysis to quantify changes in fire frequency, seasonality and spatial distribution during the last decade and creates a fire return interval map for the core area of the Kavango-Zambezi Transfrontier Conservation Area, which spans five Southern African countries and is the largest cooperative multistate conservation region in the world. To disentangle the relative contribution of environmental variability from country-specific land management decisions in driving changes in fire regimes, we use two different products from the MODIS Terra platform (Active Fire and Burned Area products), TRMM precipitation data and the Multivariate ENSO Index data to analyze change in fire regimes among the five countries, differentiating between different land uses such as protected areas, forest reserves, and communal lands and accounting for specific changes in fire management policies. 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. 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 occurrences mainly during the dry season. The mean size of fires also increases significantly across all land uses despite increasing fire prevention efforts in most protected areas in the five countries. These findings can contribute to more effective trans-boundary natural resource and wildlife habitat management by providing a baseline assessment of fire return intervals across five countries with different fire management policies and have implications in the climate change arena.

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1. Introduction and background

Fires are an intrinsic component of many ecosystems throughout the world, and are one of the controlling factors in maintaining the balance between grassy and woody vegetation in the semi-arid savannas of Southern Africa (Bond and Keeley, 2005).

Understanding the role of fire in driving ecosystem dynamics and its influence on land-cover change, atmospheric composition, and the global carbon cycle is a key focus of the global change research community (Stocks et al., 1998; USCCSP, 2004). Several models project changes in fire regimes in some ecosystems, especially increases in fire frequency with climate warming and resulting alteration of plant communities to domination by grasses and fire-tolerant shrub invaders (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; Bergeron et al., 2004; Flannigan et al., 2005). The characteristics of the C₄ grasslands, shrubs and woodlands of the savannas of Southern Africa, which are among the most frequently burnt ecosystems in the world, are expressions of fire disturbances at various recurrence rates (Bond et al., 2004). Natural fires usually occur in southern African savannas at the end of the dry season and beginning of the wet season, are caused by lightning, and their intensity depends on the physical characteristics of the fuel load and regional vegetation type (Scholes and Archer, 1997). In semi-arid savannas, tree-covered areas contain 40% of total fires observed and shrub-covered areas account for an additional 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 land use, vegetation structure, and climate (Lavorel et al., 2007). Wet years increase fuel availability so that abundant dry fuel burns more strongly during ensuing dry years. Recurring droughts reduce fuel production and subsequent burning (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).

The effects of changing fire regime are not well understood. 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. Conversely, 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. Fire also reduces species diversity by differentially affecting younger tree species (Russell-Smith et al., 1998) and promotes landscape heterogeneity (Hudak et al., 2004). Serneels et al. (2007) find increasing fire frequencies over time in East Africa, concluding that, especially for rangelands, the impact of fires translates more in changes in vegetation phenology than in vegetation productivity. These different outcomes of fire regime alterations indicate how location-specific the effects of fires are.

There is increasing interest in management approaches that are based on an understanding of historical natural disturbance dynamics and how those dynamics might be changing through time. Bergeron et al. (2004) emphasize that, in fire-dominated landscapes, this approach is possible only if current and future fire frequencies are sufficiently low, compared to historical fire frequencies, that active management by cutting, thinning, and firebreaks can be substituted for fire. This management approach requires understanding the nature of the current and past fire regimes and the kinds of probable changes in different aspects of fires regimes, especially fire frequencies. The effects of different fire management approaches in a region can be best studied when a variety of practices occur within a short distance of one another. In our study area, the areas in and around Chobe District of Botswana and the Caprivi Strip of Namibia are organized into a mosaic of units of protected areas, forest reserves, and communal lands, and are managed very differently. If the fire regime trends are similar across regions with different management regimes, then the underlying variability is more likely to be driven by climatic factors. If they are different, then the different management approaches are more important in fire regime changes.

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 (2000–2010). We use two fire products derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data. Specifically, we ask whether fire management results in changes in the annual extent of burned area in protected areas (PA) managed differently in the five countries of KAZA. Second, 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). Third, we describe the general trends in fire frequency and seasonality among the two neighboring countries with different fire policies and management and test whether there is an increasing trend in fire occurrences irrespective of fire policies and management regimes. The primary method of the paper is to create a mean fire return interval (FRI) map for the central KAZA region for the last decade, and then to compare the FRI of PAs in the different countries forming the nucleus of KAZA.

1.1. Fire regimes and fire policies in the central Kavango-Zambezi Transfrontier Conservation Area

KAZA is a large, multi-nationally managed network of national parks, game management areas, community-based wildlife management areas, communal lands, urban settlements, private land holdings and other types of land ownership. It encompasses an area of approximately 300,000 km² of Botswana, Namibia, Zambia, Zimbabwe, and Angola. The expressed purposes for the creation of KAZA by the member countries are 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 PAs (Peace Parks Foundation, South Africa, 2010). The largest and most important PAs of central KAZA used in this analysis were Chobe National Park, the Okavango Delta RAMSAR site and Moremi and Linyanti Game Reserves in Botswana; Bwabwata, Mamili and Mudumu National Parks in Namibia; Victoria Falls, Hwange, and Kazuma Pan National Parks in Zimbabwe; Sioma-Ngwezi National Park in Zambia; and Luiana Partial Reserve in Angola (Fig. 1).

These PAs form the central nucleus of KAZA and are in located closely to each other. However, despite the proximity of the PAs and the expressed common management goals of KAZA, each country has a different fire management policy. To some degree, all member countries have fire suppression policies within their protected areas originally setup as ‘green conditionality’ for aid and loan disbursement (Eriksen, 2007). 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) demonstrated 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. Research in Angola found that there was an increase in the extent of uncontrolled burning for subsistence agriculture and hunting, as well as an increase in anthropogenic mid-dry season fires both within and outside the PAs of Angola (USDA, 2006). The USDA assessment also found that the mid-dry season repeated burns have adverse effects on vegetation composition and forest integrity and resulted in 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 more destructive fires later in the season are common practice in PAs, 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 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 Inter-tropical Convergence Zone (ITCZ), with the wet season occurring during the summer between November and April (Fig. 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 maximum temperature of 30 °C and a mean minimum monthly temperature of 4 °C (Barnes, 2001).

Fig. 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).

Fig. 2. a) Monthly average rainfall data from the Tropical Rainfall Measuring Mission (TRMM) for the period January 1998 to May 2009 for the central KAZA region and b) monthly rainfall averages for 2008 showing the intra-annual typical distribution of precipitation in mm.
For the second part of the paper, we studied changes in the fire frequency, extent and seasonality in northeastern Botswana and the Caprivi Region of Namibia. We chose to zoom in on this region 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 made for an interesting case study in disentangling changes in fire regimes induced by environmental variability from land management decisions. Earlier work in the general area showed that between 27 and 51% of the area in Northern Namibia burned annually between 1989 and 2001, while only 10% of the area did not burn during the same period (settlements and permanent wetlands) (Verlinden and Laamanen, 2006). 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 should be reduced by building firebreaks and holding awareness programs to remedy some of the perceived environmental and economic consequences induced by uncontrolled burning. Starting in 2006, combined NGO and government fire managers in the Caprivi Region of Namibia initiated a program of annual, early dry-season, patch-mosaic prescribed burning program to promote grass regeneration for cattle and wildlife grazing (WWF/IRDNC Project Technical Progress Report, 2006). Accounting for this change in policy is particularly important as the Verlinden and Laamanen (2006) work did not include fires detected between May and July that 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, one of Namibia’s most populated regions. 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).

Understanding changes in fire regimes, and particularly in the frequency and extent of burning, is ultimately important for determining the ecological impacts of fires on vegetation communities. Fires of lower intensities and frequencies than currently taking place in Namibia, for example, have positive effects on woodland regeneration once species pass the sapling stage (Stahl et al., 1999), but the annual burning of woodlands, even at low intensities, can damage certain species regeneration and growth processes (Smit et al., 1999). Vegetation composition and structure in semi-arid savannas can therefore be affected by fires, land management policy 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 objectives 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 calculate a fire return interval for the region and 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). First, 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; 500 m spatial resolution, daily temporal resolution) for the larger area of central KAZA to assess annual fire patterns in protected areas. We expected to see highest fire recurrence rates occur 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 informant 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 land. We tested this hypothesis using, apart from the Burned Area product, the MODIS active fire data — MOD14CD (2000–2010; 1 km spatial resolution, 1–2 day temporal resolution) 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 an increase in fire frequency in Botswana 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 small number of low-areal extent fires that could start and stop over the year that might not usually be captured by orbiting satellites, leading to slight underestimations in fire detections. 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 320 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 pass over when burning occurs or because clouds may obscure active fire detection (Justice et al., 2002).
Previous to the creation of the MODIS Burned Area product, Pereira (1999) used the near-infrared (0.725–1.10 μm) and mid-infrared (3.55–3.93 μm) channels on the AVHRR instrument for burned vs. non-burned area discrimination. Roy et al. (1999) similarly used 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 found that by using the VI3 index instead of NDVI more strongly discriminated between 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). Alleaume et al. (2005) created an index called the Normalized Burn 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. 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, 2002, 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, summarized in Table 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 beginning in February 2000. For this study we acquired two separate products, both available through the University of Maryland Global Land Cover Facility (UMGLCF). 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 are available from November 2000 to April 2010 for our study region. The active fire data were acquired from the University of Maryland MODIS ILLUCI Fire Dataset for 2000–2010 (NASA/University of Maryland, 2002). It consists of spatially-explicit and georeferenced (WGS 1984, UTM 34 South) point layers for every year with the attributes of mid-infrared brightness value, acquisition date, time of day of fire detected, and confidence level for every active fire detected (Giglio et al., 2003). There are data missing from the end of June to the beginning of July in 2001, 2002 is missing some data throughout the dataset, 2007 has some missing data from mid-August and data are 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 UMGLCF and pre-processed according to the accompanying user manual. The data for June 2001 are 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 Quicklook-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 (MEI) for the period 1950 to 2010 (Fig. 3), (data available at: http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/). MEI is calculated from 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). Standardized positive departures higher than 1 are indicative of prevailing drought conditions and are usually associated with ENSO dry events (El Niño), while negative departures indicate wet conditions mostly associated with La Niña events.

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. Monthly spatial averages 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 (Fig. 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).

Table 1

<table>
<thead>
<tr>
<th>Data categories</th>
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<th>Data source</th>
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<td>area data</td>
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<td>MODIS ILLUCI Fire Dataset (U of Maryland)</td>
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land use and management regimes in the time series from 2000 to 2010. Then, to determine the burned area for each protected area for each year, we added the across all site in Botswana); and 5. Wildlife management areas (several Partial reserves (Luiana in Angola and the Okavango Delta RAMSAR the state and community forest reserves in the Caprivi, Namibia); 4. reserves (Chobe, Kasane, Maikaelo, and Sybuyu in Botswana and Zambia); 2. Game reserves (Moremi in Botswana); 3. Forest Mamili in Namibia, Hwange in Zimbabwe, and Sioma-Ngwezi in National parks (Chobe in Botswana, Bwabwata, Mudumu and Caprivi Region of Namibia. The data were then exported into a statistical package (SPSS, 19.x) where we analyzed them first at a regional level (Namibia vs. Botswana) to determine trends in fire occurrences and seasonality for the last decade. The data were 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) and between the two countries to determine whether the increasing trends in fire occurrences are constant throughout the differently-managed land-use categories and throughout the year. We conducted paired means T-tests 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.

We used meteorological data (station rainfall data and TRMM rainfall, as well as the MEI data) to check our burned area analysis following McCoy and Burn (2005). TRMM data have been used successfully in previous studies and have been shown to be accurate for these latitudes, comparing well with measured rainfall stations throughout the region (Huffman et al., 1997; Kummerow et al., 2000; Nicholson et al., 2003).
Archibald et al. (2009) and is beyond the scope of this paper. The year 2006 experienced the highest degree of burning throughout all included protected areas, probably as a result of the preceding three years being unusually dry and experiencing below average precipitation (see also Fig. 3). This hypothesis is supported 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 examines 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 (Fig. 5). Mudumu National Park in Namibia, a relatively small (727 km²) park created after the Namibian independence in the 1990s and located in an area surrounded by communal lands on all sides, experiences the highest proportion of area burned every year of all seven protected areas. In some years, e.g. 2006, 98% of the total park area burned (Fig. 5). Second and third after Mudumu NP by proportion of total area burned are Luiana Partial Reserve in Angola and Sioma-Ngwezi National Park in Zambia, both experiencing fires on more than 40% of their area annually. This pattern is, most likely, a result of the lack of 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 Hwange National Park, Zimbabwe, despite the history of active and effective fire prevention and management programs in the last few decades prior to 2000, the proportion of the park's area (14,651 km²) burned annually has been increasing for the last decade ($R^2 = 0.40$) for the linear trend for the last decade, making that the largest and most significant increasing trend in burned area across the central KAZA region. 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 km²) after the 1990s, in which annual burned area is decreasing ($R^2 = 0.37$; $p = 0.01$) in annual burned area, most likely as a result of increasing extent of annual flooding by the Kwando River (key informant interviews, Caprivi Strip, Namibia).

Fig. 5a through d thus 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, Fig. 5a shows a comparison between Luiana in Angola and Sioma-Ngwezi in Zambia; Luiana (8400 km²) burns on average between 40 and 84% of the area and shows a slight decrease in area burned through time, while Sioma-Ngwezi (5276 km²) 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 km², 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 highest elephant density in the world (Department of...
Wildlife and National Parks, personal communication; Chase and Griffin, 2011). 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. Farther away from the river, woodlands dominated by the economically-important *Baikiaea plurijuga* (Zambeszi Teak) species occur (Hytteborn et al., 2004). The park is actively managed to prevent fire spread from neighboring countries and adjacent communal lands, 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 experienced increasing annual fire extent 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; $p = 0.01$).

Hwange NP, 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 ($R^2 = 0.40$; $p = 0.01$) (Fig. 5b).

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 to suppress fires starting in 1996 but have been undergoing prescribed early-dry season burning programs since 2006 for grass regeneration for wildlife and, secondarily, prevention of more extensive late-dry season wildfires that could endanger the ever increasing human population living in the region. The largest of the three parks is Bwabwata (6334 km²), home to several extensive villages and divided by a major paved road. Between 15 and 50% of its area burns every year (Fig. 5c). This result is similar to findings by Verlinden and Laamanen (2006) who used fire scar mapping and Landsat Quicklook imagery. From the analysis of the MODIS burned area product, a slight decrease in fire extents through time is recorded in all three parks. That may be an indirect result of increasing human populations living in the Caprivi and therefore increasing numbers of cattle that 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 (Fig. 5d). While 15–59% of Bwabwata burns 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 consequence, 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 (C.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 vulnerable from fires originating in the communal lands to the west (Fig. 6). Also, there has been an intensification in the extent of area burned in Chobe in the second half of this decade, despite increasing fire prevention efforts. This may be an indirect result of overall increasing temperatures and decreasing precipitation in the region (Wessels et al., 2004) or an increase in fuel loads as a result of suppression efforts.

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 (Fig. 6). We chose to show only four years from the time series, namely 2001 and 2009 which were both unusually wet years preceded by two years of wet conditions (Fig. 3), 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 (Fig. 4). Fig. 3 shows that 2005 was preceded by two very dry years and 2006 was preceded by three anomalously dry years, also illustrated in the precipitation record from both station and TRMM precipitation data (Fig. 2). Parts of the Caprivi region in Namibia (especially Mudumu National Park), Angola and Zambia burn repeatedly, while rarer 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 Botswana’s 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 (Fig. 6).

An important objective for using the MODIS burned area product (MOD45A1) was to be able to create a spatial fire return interval map (FRI) for the central region of KAZA for the period 2000 to 2010 (Fig. 7). All land-use categories in Namibia and Botswana that are part of the central region of KAZA are included in this analysis. We study only the protected areas for the other three countries because we were unable to obtain adequate spatial data for other land-use categories. The FRI map shows that parts of the two protected areas in Angola and Zambia experienced high rates of fire return for the last decade ranging from 6 to 10 years out of 10 years in approximately 30–40% of their total area. Mudumu National Park in Namibia also experienced very high rates of fire recurrence (many of the same areas burning every year) for more than 50% of its total area, followed by some communal areas in the Caprivi (Fig. 7). The Caprivi region of Namibia for instance, with the exception of areas along the main roads 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 occurs 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). We have not differentiated between early and dry season burning as we were primarily interested in creating a fire return interval map 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 to the north of Chobe and adjacent to the communal areas of Caprivi, FRI is generally less than 3 years. In Botswana, the wildlife management areas to the south of Chobe National Park also have lower fire recurrence rates than Nxai-Pan and Magkadikgadi National Parks, the two national parks at the southernmost tip of central KAZA. Although an increase in fire extents has occurred in Zimbabwe’s Hwange National Park in the last decade, only a small proportion of its area experiences fire recurrences higher than 3 years, and most of those fires originate in the communal or wildlife management areas to the east and north of the park (Dr. Brian Child, personal communication, 2009).
Fig. 6. 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.

Fig. 7. Map of central Kavango-Zambezi Transfrontier Conservation Area (KAZA) showing the spatial extent of a mean fire return interval (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.
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)

We used the MOD14GD (active fires) product 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. Fig. 8 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 km² 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 \( (R^2 = 0.71, p = 0.001) \) whereas the same analysis for northern Botswana reveals an 88% increase in total fire detections \( (R^2 = 0.30, p = 0.01) \). 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% \( (R^2 = 0.65, p = 0.001) \).

To determine whether the trends observed in the total fires detected were consistent and could show 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 (Fig. 9). The intra-annual distribution of fires in the Caprivi indicates 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 for an indirect measure of the relative size of a fire based on the number of fires detected in one km² pixel.

In northeastern Botswana, on the other hand, while the fire season of 2006 clearly stands out, 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 (Fig. 10). However, there is an overall increase in fires during the later part of the dry season, especially during the months of September and October, 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 2001 and 2009 are the first and last of our series with complete fire records and also 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 (Fig. 11a). In northern Botswana there seems to be a difference in the standard deviation range between 2001 and 2009 from August to November and a 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 burning for more than one day). In the Caprivi, there is a statistically significant increase \( (t = -2.637, p = 0.001) \) 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 (Fig. 11a).

Finally, we performed a change analysis of the mean monthly number of active fires detected in both regions between different years relative to 2001. Our data show a 53% increase in active fire detections in northern Botswana during September between 2001 and 2009 and a consistent increase (50%) in fire detections from July to September between 2001 and 2008 (Fig. 11b). In the Caprivi, where fire suppression is not practiced throughout all land-use categories as it is in Botswana, there is an above 100% increase in active fire detections beginning with May and an almost a 400% increase in the month of June. Because 2008 was preceded by a two dry years 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 (Fig. 11b), due in part to a later onset of the rainy season during 2008.

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, shows consistently increasing trends in active fire detections in both regions and a shift in fire seasonality in the Caprivi consistent with a transition to active fire management based on early-dry season burns.
3.3. 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

The analysis of active fires in the previous section indicated a significant increase in fire frequencies in both regions that is consistent with current fire management practices in both Namibia and Botswana and also 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 intra-annual distribution of active fires for selected land uses in the Caprivi Strip and the Chobe District. The two regions are organized into a mosaic of units of protected areas, forest reserves, and communal lands, and are managed very differently. If the fire regime trends are similar across regions with different management regimes, then the underlying variability is more likely to be driven by climatic factors. If they are different, then the different management approaches are more important in fire regime changes.

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 (Fig. 12). Even though September has the highest overall 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 hypothesized that 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 in Section 3.2 revealed such a change. When analyzed at the land-use category level, the active fire data show a series of significantly increasing trends in fire occurrences for the month of June only in the land uses in Caprivi Strip, Namibia (Fig. 12). Specifically, in Bwabwata National Park for the period 2001 to 2009, an increase in fires of 29% ($R^2 = 0.76, p = 0.001$) 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% ($R^2 = 0.56, p = 0.04$). 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 ($R^2 = 0.80, p = 0.001$) and of only 4.6% ($R^2 = 0.17$) during June (Fig. 12). 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% ($R^2 = 0.71, p = 0.007$).

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% ($R^2 = 0.62; p = 0.02$) 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
suggests that the underlying cause for the changes documented can be attributed to climatic changes and variability.

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 (IPCC, 2007), 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., 2004; 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).

Fig. 12. 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.
4. Conclusions

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 from MODIS instrument data in conjunction with climatological data. We hypothesized that 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. 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 enforcement regulations, for example, averages between 58 and 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. This result indicates that fire management plays a key role but, given increases in the area burned yearly across all PAs, we might surmise underlying climate-driven influences related to an intensification of dry ENSO phases, reductions in precipitation and increases in temperature to southwestern Africa (Nelsonson et al., 2000; Wessels et al., 2004; Gaughan and Waylen, in press). The end objective of using the MODIS burned area product was to create a fire return interval (FRI) map for the central KAZA region for the last decade, showing the areas that burn most frequently. This represents a first attempt of the literature to map the spatial and temporal distribution of fires in the form of a spatio-temporal index and in particular for this transfrontier conservation region in Southern Africa which is becoming increasingly important, ecologically and economically for all the five member countries.

Secondly, we studied 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 suggests that the underlying cause for the changes documented in fire frequencies in this region can be attributed to climatic changes and variability, particularly an increase in dry years and warm ENSO phases in the region (Gaughan and Waylen, in press).

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). This is particularly important in this region of southern Africa that is increasing striving to adopt transboundary management approaches to both natural resources and wildlife habitat management because these findings provide a good baseline for fire frequency and extent changes during the last decade.

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