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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 transboundary 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.

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,

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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 C_4 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 Image 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 km^2 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