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Research article

Effects of landscape pattern and vegetation type on the fire regime of a mesic savanna in Mali

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ABSTRACT

Savanna fires are a critical earth-system process that alter vegetation regionally and contribute to changes in atmospheric composition globally. The fire regime in savannas has shifted over time resulting in a large reduction in burned area. Savanna fires, which are human caused and set for a plethora of reasons, produce complex mosaic burned area patterns that tend to result in lower overall burned area. Mosaic fire regimes are difficult to detect and map accurately using available satellite data. Imagery-induced low-resolution bias makes it difficult to link fires with relevant environmental and anthropogenic factors, while higher resolution imagery is temporally less frequent. We explore how landscape pattern affects the fire regime in a mesic savanna by quantifying relationships between the spatial patterns of vegetation, which are shaped by natural and human factors, widely used ecological indices, and the seasonality and frequency of fires. The study finds that landscape pattern influences the fire regime; fire seasonality and frequency varied by landscape index at both the vegetation class and landscape scales. Percent cover, shape index and largest patch landscape ecological indices demonstrated the most consistency in burn date trends across scales. The study finds that landscape fragmentation—specifically a reduction in the size of patches and an increase in their number–results in an earlier fire regime. We conclude that fire intensity and severity will continue to decline as agriculture expands and landscapes fragment from agriculture in savannas. Our methods also demonstrate the ability to integrate landscape indices with coarse-resolution fire data.

1. Introduction

There is a growing concern that climate change will cause larger and more catastrophic fires around the world. Indeed, several massive or so-called “mega-fire” events have already been attributed to a changing climate (Flannigan et al., 2009; Pyne, 2008; Williams et al., 2011). Wildfires produce carbon emissions equivalent to 26%–31% of those that stem from fossil fuel combustion and industrial activities (Schultz et al., 2008; van der Werf et al., 2006). It is thought that increased fire activity will be one of the major drivers of future vegetation change under a warming climate resulting in feedback loops that generate even more fire (Overpeck and Udall, 2010; Williams et al., 2010). However, while certain biomes have clearly experienced recent increases in fire size and intensity due to climate change, a recent study finds that globally, burned area declined by nearly one quarter between 1998 and 2015 (Andela et al., 2017).

How can fire events on the earth be simultaneously intensifying and decreasing? The answer is that the global decline in fire has been driven primarily by large decreases in burned area in the tropical savannas. The documented decline in savanna burning largely overrides the impacts of climate change globally. In large part this is because savanna fire regimes are not climate driven—they are a function of human land use and burning practices (Archibald, 2016; Archibald et al., 2013; Laris, 2013) especially in the mesic savannas of Africa which burn the most. In the African savannas, for example, the total area burned has declined by 1.27–1.7% per year over the last seventeen years resulting in a total decline in area burned between 22.9% and 30.6% (Andela et al., 2017). The decline in fire has resulted in both fewer and smaller fires, bucking the trend of increasing mega-fires in the more temperate biomes.

That a change in savanna burning could have global impacts is not surprising given that savannas are the most frequently burned biomes on Earth averaging 2.8 million sq-km per year (Giglio et al., 2006; Tansey et al., 2008). This burning potentially impacts ecosystem processes, biogeography (Laris, 2011; Staver et al., 2011), the global carbon cycle (Bond et al., 2005) and human livelihoods (Mistry, 2000).

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Understanding factors that produce changes in savanna fire regimes are critical for scientists seeking to predict changes in savanna tree and grass cover, improve land and fire management, as well as evaluate greenhouse gas emissions from fires. Yet, as the work by Andela et al. (2017) clearly points out, all of the commonly used fire models failed to reproduce the pattern and magnitude of observed declines in savanna fires. In summary, we know very little about how fire regimes change in savannas.

Fire is a landscape-scale phenomenon and, as such, landscape pattern plays a critical role in determining whether and how a fire burns through a landscape, a classic case of pattern influencing ecological process (McKenzie et al., 2011; Turner, 1989). Savannas, by definition, are composed of scattered trees and a near-contiguous herbaceous layer that desiccates during a prolonged annual dry season (Scholes and Archer, 1997). Savanna fires are surface fires that burn low-lying fuels (predominantly grasses but also shrubs, small trees and leaf litter) and require a continuous and flammable fuel bed to propagate across a landscape. However, despite the near-contiguous fuel-bed, most savannas burn in highly fragmented patterns (Laris, 2011; Mistry and Berardi, 2005; Randerson et al., 2012; Russell-Smith et al., 1997).

It is well established that the fire regime—defined as the frequency, intensity, type and regular spatiotemporal pattern of fires in a particular place—is a key determinant of woody vegetation cover and growth rates in a savanna (Higgins et al., 2000). In savannas, fire intensity is thought to increase during a long dry season as vegetation cures (Govender et al., 2006). In the savannas of Africa, where fires burn more widely and frequently than any other region, there is a need to develop a better understanding of how fire regimes, vegetation patterns and the broader environmental and human factors that create them, are interrelated.

The majority of savanna fires are set by people and burn in highly fragmented and patchy patterns. The common practice of setting fires to vegetation as it gradually cures, referred to as patch- or seasonal-mosaic burning, creates a burned mosaic landscape that is heterogeneous (Laris, 2011; Parr and Brockett, 1999; Russell-Smith et al., 1997). While natural features such as riparian woodlands, wetlands, streams, or rocky outcrops play a critical role in governing fire propagation, especially in highly humanized landscapes, their role is secondary to more subtle variations in vegetation cover for much of the savanna. For example—different patches of savanna dry at different rates. The majority of savanna fires are set so as to extinguish at the boundaries of herbaceous vegetation that are either too moist to burn or have already burned at the time of the passage of a fire creating patchy burn patterns (Archibald et al., 2009; Laris, 2011). The pattern of burning and the landscape mosaics it creates have important implications for ecological processes, biodiversity, carbon sequestration and human land uses (Bird et al., 2012; Parr and Brockett, 1999; Russell-Smith et al., 1997).

Unlike in semi-arid landscapes which form the basis of the patch-mosaic theory, in mesic savannas (precipitation 750–1500-mm) there is sufficient rainfall for burned vegetation to recover following a fire over the course of a single wet season. As such, the fire regime in a mesic savanna is not driven by ecological succession, because sufficient fuel to carry a fire is generated on an annual basis. Additionally, burning in mesic savannas is *seasonal*-as opposed to *patch*-mosaic burning because the same patches tend to burn on a regular annual basis and at specific times during the fire season (Laris, 2011).

Three main characteristics of landscape patches—strength of patch formation (the degree to which patches are differentiated from the surrounding area by their distinct, within-patch homogeneity), patch size, and patch repeatability across a landscape—are commonly used to describe patch structure of vegetation (Koerner and Collins, 2013). These characteristics can be quantified using *landscape indices* (Turner, 1989; White and Pickett, 1985). A key principle of landscape ecology is that the relationship between pattern and process is scale dependent (Wu and David, 2002).

Why does research find that subtle natural landscape features—specifically vegetation types—correlate with fire regimes while anthropogenic landscape features do not? A major reason appears to be the scale of analysis. Most research studying relationships between anthropogenic variables and fires have used widely accessible imagery-derived fire products generated from coarse-resolution satellite data such as AVHRR (1-km) or MODIS (0.5-km). These products contain a well-known "low-resolution bias" which creates a *fire bias* in which larger fires are detected and mapped while smaller ones are missed (Boschetti et al., 2004; Laris, 2005). The error contributed by this bias can be substantial because algorithms are designed to "miss" small fires and fragmented burned area patterns that are common in many savannas (Caillault et al., 2015; Laris, 2005; Randerson et al., 2012). Bias also occurs in the form of the "mixed pixel" problem when mapping key anthropogenic features such as agricultural fields that are often only a few hectares in size (Laris, 2011).

The purpose of this study was to determine relationships between patterns of savanna vegetation types and key parameters of the fire regime—seasonality and frequency of fire—as well as their variability, for an area of West African mesic savanna in Mali. We explore the relationship between fire and landscape pattern at multiple scales, recognizing and addressing the aforementioned low-resolution and mixed-pixel biases. In this research we also explore whether landscape ecological indices can be used to scale-up data to develop better linkages between land cover patterns and fire regimes. The methods developed for this research enable statistical comparison between a variety of landscape ecological indices and spatial data to evaluate fire regimes at three different spatiotemporal scales. We address four key research questions:

1. How does landscape pattern affect the fire regime in a savanna?
2. Do spatial patterns of particular types of vegetation have unique effects on specific aspects of the fire regime?
3. Which landscape ecological indices at which scale have the most potential for linking vegetation cover and fire regime?
4. Can landscape indices be used to resolve the issue of low-resolution bias when using coarse-resolution fire and land-cover data?

2. Materials and methods

2.1. Study area

The study area is located in southern Mali and northern Guinea, entirely within the southern edge of the Sudanian savanna belt (Fig. 1). The spatial extent corresponds to the Landsat scene WRS-199/52 (Lon: −7° 17'- −9° 2′, Lat: 10° 41′-12° 28′). The study area (32,927 km^2) is contained within this scene boundary and is smaller than the boundary because of scene shifting over the 11-year study period.

There are three distinct seasons: 1) a hot and dry season from February to June; 2) a warm and rainy season from June to October; and 3) a relatively cooler dry season from October to February. Although the rainy season extends over a five-month period, precipitation events are sporadic, often intense and concentrated in a period of just 70–80 days. Annual precipitation varies from 900-mm in Bamako in the north to 1050-mm in Bougouni in the south (Henry, 2011). The fire season typically begins in October just after the rainy season and ends after the first rains fall in early June.

Vegetation is classified as southern Sudanian savanna (Nasi and Sabatier, 1988); however, there is a great variety of vegetation types within the savanna formation. Landscape heterogeneity is largely a function of underlying soil and hydrology as well as agricultural use, the combination of which produces patterns of vegetation cover (Duvall, 2011). Ferricrete outcrops on hard pan cover considerable areas creating xeric conditions. Unproductive soils such as these support sparse vegetation referred to here as *short grass savanna* which is dominated by short, annual grasses (principally *Loudetia togoensis* but