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Utilization of the SAVANNA model to analyze future patterns of vegetation cover in Kruger National Park under changing climate

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ABSTRACT

Within southern Africa's savanna ecosystems, woody and herbaceous species have differing growth characteristics that allow a tenuous co-existance. The high dependence of humans on the landscape, through agricultural production, tourism, and natural resource extraction makes understanding savanna vegetation dynamics essential. Studies analyzing resilience of savannas suggest potential state changes in vegetation structure from continuous grasslands with sporadic woody cover to less biologically productive landscapes. One of the biggest questions in this landscape is the impact of climate change. The spatially explicit SAVANNA model is used to analyze the impact of climate change on vegetation cover across Kruger National Park's (KNP) main land system classifications (Satara, Skukuza, Letaba, and Phalaborwa). Manipulating climate inputs and management regimes allowed us to analyze the resilience of savanna vegetation under multiple Intergovernmental Panel on Climate Change (IPCC) scenarios. Trends in future climate indicate an increase in temperatures greater than 1.0 °Celsius and a slight decrease in precipitation by 2080. Model results indicate a long-term decrease in multiple size classes of vegetation across all the four land systems. However, the model runs show differing response to climate change between the woody and herbaceous cover types. Spatial trends across the park follow closely with the north-south climate gradient. The most spatially distinct land system was Skukuza, which exhibited some of the highest initial net primary production (NPP) values and also the greatest decreases in NPP into the future. While this region is projected to lose large proportions of its herbaceous and shrub vegetation it is projected to increase in tree green leaf, mostly related to increasing fine leaf vegetation (*Acacia* sp.*)*. The northern land systems were already dominated by mopane, but under all model scenarios mopane will increase in Letaba and Phalaborwa. This mopane increase will offset the loss of herbaceous and shrub vegetation, resulting in little to no decrease in NPP across time for these land systems. This work illustrates that landscape resilience is not only impacted by the severity of changing climate but the degree to which we manage such systems.

1. Introduction

Researchers, conservationists, and most policymakers widely agree that the Earth's climate is changing (Peters and Lovejoy, 1992; Hughes, 2000; McCarthy, 2001). What is open to debate, however, is the degree to which terrestrial landscapes will change under future climate conditions. It has been a common theme in the climate change literature that countries, regions, economic sectors, and even social groups will differ in their degree of vulnerability to climate change (Watson et al., 1996). If we focus solely on the environmental impact of climate change, studies have shown that changes in biodiversity, home ranges, species distribution, and population shifts can occur under changing regimes of precipitation, temperature and carbon dioxide (Dale, 1997; Cowling et al., 1994; Myers et al., 2000; Midgley et al., 2010). In order to mitigate the effects of climate change, for example via management or shifts in landscape utilization, it is important to understand the potential climate change induced landscape alterations.

In the broad spectrum of terrestrial vegetation, we have witnessed compositional shifts within ecoregions as a result of global environmental change, specifically climate change. Within grassland ecosystems there are numerous studies that document increased woody vegetation cover (Higgins and Scheiter, 2012) as a result of multiple variables including precipitation change (eg. Huxman et al., 2005), increased CO2 levels (eg. Archer et al.,

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1994), and human alteration of the landscape. On the other end of the spectrum, forest cover has also seen a broad scale pattern of fragmentation and change resulting from intensive agricultural utilization, altered climate regimes, and livestock cultivation (eg.Tscharntke et al., 2005; Laurance and Williamson, 2001). In the middle of these two extremes lie savannas, ecosystems defined by their distinct seasonally-based continuous herbaceous layer of C4 grasses (.5–2 m tall) and discontinuous C3 woody cover of shrubs and/or trees (2–10 m tall; Huntley and Walker, 1982; Midgley et al., 2010). Such ecosystems have been the focus of much research as there is debate about the extent and driving force behind climate change induced landscape alteration. Savanna function and composition is greatly dictated by the precipitation regime but recent research has shown that temperature and rising CO_2 levels can cause either a restraint on greening or fertilization (Campo-Bescos et al., 2013; Parry et al., 2007; Higgins and Scheiter, 2012).

Savanna landscapes occupy a fifth of the Earth's surface including more than 60% of Africa (Huntley and Walker, 1982). These regions are considered stable in the long term, but whose inherent properties consist of fluctuating landscape composition around one or more steady states (Noy-Meir, 1975; Walker and Noy-Meir, 1982; Lamprey, 1983; Dublin et al., 1990). Such fluctuations in state can result in compositional changes from open savannas to woody savannas or shrublands. The driving force behind such ecosystem fluctuation is water, specifically mean annual precipitation (MAP) and resulting soil available moisture (Sankaran et al., 2005). As the mean annual precipitation increases across a region, the maximum potential vegetation cover also increases. When precipitation and associated soil moisture are sufficient then disturbances drive the vegetation fractional cover. In the absence of disturbances, such as repeated fires, clearing by humans, or large herbivores the tree cover increases at the expense of grass production until it is limited by events like species competition (Scholes and Archer, 1997). The amount of grasses remaining in the system at that point depends on the woody vegetation growth and the growth opportunities offered by the environment (Scholes and Archer, 1997).

Under climate change such systems could shift dramatically. Given that landscape pattern is dictated by unique interactions between climate and disturbance regimes it is essential to quantify the impact of climate change on the landscape. Projecting the impact of future climate change on savanna regions requires an understanding of the climate-disturbance interactions and the implications of changing interactions on the terrestrial environment.

More woody vegetation will suppress herbaceous production through both light competition and decreased fire sensitivity (Higgins and Scheiter, 2012). As Higgins and Scheiter (2012) pointed out, even minor increases in woody vegetation cover further increase the likelihood of a system tipping from a C4-dominated state to a C3-dominated state, essentially changing to a woody savanna or woodland. Under climate change, overarching global projections indicate an increase in woody vegetation, and the potential for grassland ecosystems to become more savanna/woodland systems (Higgins and Scheiter (2012)).

Vulnerability to climate change is an urgent issue among developing countries because the poor are the hardest hit and least able to adapt (Watson et al., 1996; Handmer et al., 1999). Currently, there are two main approaches to assessing the impact of future climate change on terrestrial landscapes: (1) modeling the response of vegetation and species to changes in climate, and (2) analyzing historic data to examine past response to climate change. This paper looks to the first approach to analyze future vegetation dynamics within Kruger National Park (KNP) using the spatially explicit SAVANNA model (Coughenour, 1993). SAVANNA is process-oriented rather than empirical or rule-based; it aims towards realistic, general and explanatory representations of ecological change as opposed to descriptions of ecological states. The model was first developed to study semi-arid pastoral regions of Kenya (Coughenour, 1992), but has been extensively modified and applied to countless places since its inception. Examples of its application include Yellowstone National Park (Coughenour and Singer, 1996), Elk Island National Park (Buckley et al., 1995) and the Kruger National Park (Hilbers, 2012). We utilized the SAVANNA model to analyze potential changes in net primary productivity (NPP) and the components that make up NPP, herbaceous and woody vegetation, under climate change via the Hadley General Circulation Model (GCM) and three IPCC emissions scenarios. By assessing the potential vegetation change that results under climate change scenarios we can begin to gauge the vulnerability of this savanna landscape. This research specifically asks to what extent can shifting climatic regimes impact the vegetated landscape, as a whole and by differing vegetation structural types, across Kruger National Park, South Africa?

2. Data & methods

2.1. Study area

Kruger National Park (KNP), located in the eastern portion of South Africa, is one of the most prominent conservation areas in all of Africa (Fig. 1). The park was established in 1926 and is approximately 20,000 km^2 in size. The elongated north to south shape of the park results in a precipitation gradient with mean annual precipitation (MAP) ranging from 750 mm in the south to around 440 mm in the north (Fig. 2; Eckhardt et al., 2000; Zambatis and Biggs, 1995; Tyson and Dyer, 1978). The majority of the precipitation falls between November and March, with a peak in January or February, from June to August the dry season commences. The driving force of this unimodal precipitation regime can be attributed to seasonal low-pressure systems and the occasional tropical cyclone, while precipitation variability has been linked to major ocean oscillations such as the El Nino Southern Oscillation (ENSO). Surface hydrology is driven by the six perennial rivers (Crocodile, Sabie, Olifants, Letaba, Luvuvhu, and Limpopo) as well as an additional 14 ephemeral rivers that only contain water during the wet season (Fig. 1; Venter et al., 2003). Geology also plays a large part in the landscape dynamics of KNP. Geologically there are two distinct regions, the western and eastern parts. In the western part, granites dominate the landscape (Fig. 1). In the eastern part basalts dominate. These two portions are separated by the Lebombo Hills, a rhyolite formation (Fig. 1).

The vegetation composition within the park is unique with 1900 differing species of herbaceous and woody vegetation (Eckhardt et al., 2000). Overall the park is classified as a deciduous savanna, but 11 land system classifications occur within the park, each based on differing vegetation dynamics, geologic patterns, and soil composition (Venter et al., 2003). The four largest, Skukuza, Satara, Phalaborwa, and Letaba, were the focus of much of our post modeling analysis (Fig. 1). The Skukuza land system is a granitic region in the southwestern portion of KNP. This land system has the highest elevations across the park, and receives the most precipitation with mean annual precipitation ranging from 500 to 775 mm/yr. The vegetation of the region is generally classified as mixed woodland with large portions of thorn thicket. To the east of Skukuza is the Satara land system type. The north-south divide in geological formations results in basaltic rock formations underlying Satara. For the region, Satara exhibits relatively high mean annual precipitation, ranging from 475 to 725 mm/yr. Within Satara, Acacia (Senegalia) species dominate, especially *Acacia (Senegalia) nigrescens*. The two prominent northern land systems, Letaba and Phalaborwa, exhibit the driest conditions with