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How vulnerable are ecosystems in the Limpopo province to climate change?

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ABSTRACT

South Africa's biomes are characterized by their exceptional biodiversity and they provide important ecosystem services such as food, livestock production, medical plants or fuel wood to people. However, during recent decades, vegetation in South Africa experienced substantial changes and loss of biodiversity due to habitat loss, intensification of land use and climate change. The development of sustainable management policies requires an understanding of interactions between vegetation, climate change as well as land use and an identification of the areas most vulnerable to vegetation change. Here, we use the aDGVM, a dynamic vegetation model for tropical ecosystems, to investigate the risk of biome shifts in South Africa's Limpopo province under a set of IPCC climate change trajectories. The Limpopo province exemplifies an area highly susceptible to climate and land use change, where people in rural areas heavily rely on natural resources. We found a general trend towards more tree-dominated ecosystems and a particularly high risk of vegetation shift in more open grassland and savanna areas. The rate of biome shift is strongly linked to the IPCC scenario applied with the highest risk of biome shifts in the RCP 8.5 scenario. We conclude that, irrespective of future climate trajectories, management and conservation initiatives should particularly focus on these more open grassland and savanna ecosystems.

1. Introduction

During recent decades, South African ecosystems experienced shifts in vegetation and loss of biodiversity (Biggs et al., 2008; Chown, 2010). These transformations often have been attributed to climate change, elevated CO_2, land use change and habitat loss. Temperatures in South Africa have increased since the 1950s (Kruger and Shongwe, 2004; DEA, 2011; MacKellar et al., 2014) and climate model simulations conducted for IPCC assessment reports predict further changes in the climate system for the next decades (IPCC, 2013, 2014a,b). Projected increases in temperature and extreme events such as heat waves, droughts and El Niño events amplify stress on vegetation and may threaten biodiversity (Ogutu and Owen-Smith, 2003; Mooney et al., 2009; Archer et al., 2017). Elevated CO_2 can serve as fertilizer for vegetation growth (Wigley et al., 2010), and Buitenwerf et al. (2012) suggest that elevated CO_2 had a significant impact on savanna vegetation in South Africa, in particular as driver of woody encroachment. Land use impacts due to livestock grazing, fuel wood collection and conversion of (semi-) natural ecosystems into cropland are widespread in many regions of South Africa and entail changes in vegetation structure and functioning that may lead to loss of biodiversity and soil erosion (Matsika et al., 2013; Twine and Holdo, 2016). Land use may mediate the magnitude of the CO_2 fertilization effects on vegetation (Stevens et al., 2016).

Alterations in vegetation distribution and biodiversity induced by climate and land use change feed back on socio-ecological systems and thereby affect people's livelihoods. In South Africa, many people in rural areas, and in particular in poor households, directly rely on ecosystem services and goods provided by natural resources, such as livestock production, wild food, medical plants or wood as energy source for cooking and heating (Le Maitre et al., 2007). Yet, the Millennium Assessment Report (Millennium Ecosystem Assessment, 2005) highlights that intensification of land use already reduced flows of important ecosystem services in many regions globally, and it also manifests locally (Coetzer-Hanack et al., 2016). South Africa's exceptional biodiversity, comprising three of the global biodiversity hotspots and a high degree of endemism (Mittermeier et al., 2005), is target of many conservation efforts (e.g., Reyers et al., 2007). However, the development of management actions to preserve

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biodiversity and ecosystem services requires an understanding of vegetation dynamics and tools to project trajectories of potential future vegetation.

The Limpopo Province in the North-East of South Africa exemplifies anthropogenic threats to biodiversity and ecosystem services (Reyers, 2004). In particular, rural smallholder farmers in the region depend heavily on natural resources and are therefore prone to environmental, economic and social impacts caused by climate change and land use intensification (Twine et al., 2003; Gbetibouo, 2009). Large areas of the province are highly impacted by commercial farming as well as by smallholder and subsistence farming (Lehohla, 2012). Its abundant agricultural resources make the Limpopo province one of the country's prime agricultural regions with respect to production of livestock, fruits, vegetables, cereals and tea. The Limpopo province is characterized by large gradients in rainfall, temperature, soil quality and elevation, allowing for high biodiversity. It hosts conservation areas and national parks, e.g., part of the Kruger National Park. Conservation initiatives resulted in the designation of South Africa's largest biosphere reserve, the Vhembe Biosphere Reserve, in 2009 (Pool-Stanvliet, 2013). These parks and nature reserves are not only important from a conservation point of view, but also from an economic perspective, because tourism substantially contributes to South Africa's economy (Lehohla, 2015).

To understand the feed-backs between climate, vegetation and land use in complex socio-ecological systems and to identify sustainable land use opportunities, it is necessary to assess the vulnerability of vegetation to climate change and the risk of undesired biome shifts. Dynamic global vegetation models (DGVMs, Prentice et al., 2007) can help to analyze these interactions as they provide a process-based representation of ecosystem dynamics and therefore allow us to simulate how climate change may influence vegetation patterns on large spatio-temporal scales. Published DGVM studies for Africa typically simulated more tree biomass under future conditions (e.g., Scheiter and Higgins, 2009; Higgins and Scheiter, 2012; Sato and Ise, 2012). However, these studies focused on the continental scale, a single future scenario, and did not provide a likelihood assessment for projected biome shifts.

Here, we use the aDGVM (adaptive Dynamic Global Vegetation Model, Scheiter and Higgins, 2009) to investigate the likelihood of regional-scale biome shifts until 2030, 2050 and 2100 under different IPCC climate change projections (IPCC, 2013, 2014a,b) at a high spatial resolution. The aDGVM is a particularly well-suited tool to study biome shifts in the region of interest as it has been explicitly developed and tested for tropical ecosystems characterized by C_4 grasses and trees, such as grasslands or savannas. It integrates important features of savanna dynamics such as grass-tree competition and fire impacts on vegetation structure (Higgins et al., 2000; Baudena et al., 2015). Specifically, we ask (1) what are likely trajectories of future vegetation in the Limpopo Province? (2) How uncertain are these projections of potential future vegetation? (3) Which areas and biome types are at high risk of vegetation change?

2. Methods

2.1. The aDGVM

We used the aDGVM (adaptive Dynamic Global Vegetation Model), a dynamic vegetation model designed for tropical grass-tree ecosystems (for details see Scheiter and Higgins, 2009; Scheiter et al., 2012). The aDGVM integrates plant physiological processes commonly implemented in DGVMs (Prentice et al., 2007) with additional processes that allow plants to dynamically adjust leaf phenology and carbon allocation to environmental conditions. The aDGVM is individual-based and simulates state variables such as photosynthetic rates, biomass or height of individual plants. This approach represents impacts of herbivory (Scheiter and Higgins, 2012) and fire (Scheiter and Higgins, 2009) on vegetation as a function of individual plant height. Grasses are simulated as two types of super-individuals to distinguish grasses growing beneath or between tree canopies.

The aDGVM simulates four vegetation types: C_3 grasses, C_4 grasses, forest trees and savanna trees (Scheiter et al., 2012). Differences between C_3 and C_4 grasses are due to the distinctive physiological characteristics of C_3 and C_4 photosynthesis. Savanna and forest tree types are different with respect to fire tolerance and shade tolerance (Bond and Midgley, 2001; Ratnam et al., 2011). While the forest tree type is shade-tolerant but fire-sensitive, the savanna tree type is shade-intolerant but fire-resistant. Forest trees dominate in dense communities and in the absence of fire while savanna trees dominate in more open, fire-driven communities.

In the aDGVM, fire intensity is modeled as a function of fuel load, fuel moisture and wind speed (Higgins et al., 2008). Fire spreads when (1) an ignition occurs, (2) the fire intensity exceeds a threshold value of 300 kJ m^{-1} s^{-1}, and (3) the likelihood for a fire to spread, p_{fire}, is exceeded. We use a constant value of $p_{fire} = 1\%$ as previous simulations show that this value ensures good agreement between observed and simulated fire patterns (Scheiter and Higgins, 2009). Ignition sequences, which indicate days with fire ignitions, are randomly generated. This approach implies that fire ignitions and the ignition probability are not directly linked to factors such as region, climate seasonality, lightning strikes or other ignition sources. However, fire regimes in aDGMV's fire model are indirectly determined by climate, as climate influences biomass growth, fuel accumulation, and fuel moisture. These variables are used to calculate fire intensity (Higgins et al., 2008).

The proportion of aboveground grass biomass removed by fire is a function of burn patchiness, which is calculated using fire intensity (Williams et al., 1998). The response of trees to fire is a function of tree type, tree height and fire intensity (Higgins et al., 2000). Seedlings and juveniles of both savanna and forest trees are in the flame zone and are damaged by each fire. Adult savanna trees are largely fire resistant and get only damaged by intense fires. Adult forest trees are damaged by each fire. The critical height defining if a savanna tree is damaged by fire or if it is resistant is calculated from plant height and fire intensity (Higgins et al., 2000; Scheiter and Higgins, 2009). Grasses and damaged savanna trees can regrow from root reserves after fire (Bond and Midgley, 2001) while forest trees cannot regrow. In aDGVM, tree death following fire is indirect and occurs when the carbon balance becomes negative, a factor that increases a tree's probability of mortality.

The performance of the aDGVM was evaluated in previous studies. Scheiter and Higgins (2009) and Scheiter et al. (2012) show that the aDGVM can simulate the current distribution of vegetation in Africa better than alternative dynamic vegetation models. Scheiter and Higgins (2009) demonstrate that the aDGVM can replicate biomass observed in a long-term fire manipulation experiment in the Kruger National Park (Experimental Burn Plots, Higgins et al., 2007). Scheiter and Savadogo (2016) showed that a slightly adjusted version of the aDGVM can reproduce vegetation dynamics observed in a long-term experiment in Burkina Faso (Savadogo et al., 2008; Savadogo et al., 2009). In the current study, we did not perform a quantitative comparison between simulated and observed vegetation for several reasons: (1) the entire Limpopo province was classified as savanna in a recent biome map (except small grassland patches Rutherford et al., 2006). (2) The Limpopo province is strongly influenced by land use, which is reflected in remote sensing products but not considered in our simulations; this implies biases in data-model comparisons. (3) We conducted simulations at high spatial resolution. Accurate model testing at this resolution would require more detailed information on topography, soils and climate than data sources we used for this study.