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Ecosystem management can mitigate vegetation shifts induced by climate change in West Africa

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ABSTRACT

The welfare of people in the tropics and sub-tropics strongly depends on goods and services that savanna ecosystems supply, such as food and livestock production, fuel wood, and climate regulation. Flows of these services are strongly influenced by climate, land use and their interactions. Savannas cover c. 20% of the Earth's land surface and changes in the structure and dynamics of savanna vegetation may strongly influence local people's living conditions, as well as the climate system and global biogeochemical cycles. In this study, we use a dynamic vegetation model, the aDGVM, to explore interactive effects of climate and land use on the vegetation structure and distribution of West African savannas under current and anticipated future environmental conditions. We parameterized the model for West African savannas and extended it by including sub-models to simulate fire management, grazing, and wood cutting. The model projects that under future climate without human land use impacts, large savanna areas would shift toward more wood dominated vegetation due to CO_2 fertilization effects, increased water use efficiency and decreased fire activity. However, land use activities could maintain desired vegetation states that ensure fluxes of important ecosystem services, even under anticipated future conditions. Ecosystem management can mitigate climate change impacts on vegetation and delay or avoid undesired vegetation shifts. The results highlight the effects of land use on the future distribution and dynamics of savannas. The identification of management strategies is essential to maintain important ecosystem services under future conditions in savannas worldwide.

1. Introduction

Tropical savannas provide ecosystem goods and ecosystem services (ESS), such as food production, livestock grazing, fuel wood production, climate stabilization and biodiversity (Costanza et al., 1997). Many ESS have a high socio-economic value (Costanza et al., 1997) and their sustained flow is essential for the survival and welfare of many people living in savanna regions. Savannas cover c. 20% of the Earth's land surface and contribute approximately 30% of global net primary productivity (Grace et al., 2006). Hence, changes in climatic conditions and land use in savannas may have significant impacts at both local and continental scales. At a local scale, climate and land use change modify vegetation dynamics and thereby the flow of ESS, which may directly affect the people who depend on savanna ecosystems. At the continental or global scale, climate change induced biome shifts may have strong feedback effects on the climate system via changes in biogeochemical fluxes and albedo (Bonan, 2008), thereby influencing the Earth system (Lenton et al., 2008).

In recent decades, an increasing human population density lead to the transformation of large savanna areas for livestock and crop production, thereby influencing ESS (Ramankutty et al., 2008). The Millennium Ecosystem Assessment (2005) reported that, of the 24 ecosystem services examined, only four have improved in the last 50 years while the others have remained unchanged or declined markedly. For example, food production has increased, however, the general picture includes significant declines in biodiversity, depletion of natural resources and ecosystem degradation (Sala et al., 2000; Hooper et al., 2012). In this context, West African savannas are one of the hotspots (Brito et al., 2014). Land use in these

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regions is intense and an assessment of land use impacts on vegetation and ESS is needed to develop management strategies that ensure the continuation of subsistence farming, timber production, livestock grazing, extraction of fuel wood and conservation of biodiversity (Bellefontaine et al., 2000; Savadogo et al., 2009; Bodart et al., 2013). Current management practices in West Africa often focus on woody vegetation and typically include fire, selective tree cutting and prohibition of grazing (Bellefontaine et al., 2000; Savadogo et al., 2009). Thus, Eva and Lambin (1998) estimated that 1% of the Sahel, 28.2% of the Sudan zone and 57.7% of the Guinea zone in West Africa burn annually. Most of these fires are anthropogenic dry season fires (Menaut et al., 1991; Savadogo et al., 2007a) to promote pasture growth and species richness (Savadogo et al., 2007b). However, the management strategies adopted in many savanna zones are not based on sound scientific evidence (Savadogo et al., 2007a) and underlying studies have focused on impacts of single management activities rather than on their interactive effects (Savadogo et al., 2007a, 2008). Thus, the suitability of current management strategies for savanna ecosystems is uncertain from both ecological and economic perspectives.

Management of savanna ecosystems is also complicated by the complexity of grass-tree dynamics (Higgins et al., 2000) and the interactions between vegetation and climate change. Savannas are typically characterized by a homogeneous layer of C_4 grasses and scattered trees (Ratnam et al., 2011). It has been argued that many savannas are bi-stable, that is, the environmental conditions are suitable to support forests, however, fire, herbivory and anthropogenic impacts maintain an open savanna state (Hirota et al., 2011; Staver et al., 2011; Higgins and Scheiter, 2012). Many savanna systems across Africa experience woody encroachment, suggesting that vegetation shifts from an open savanna state toward a tree dominated woodland or forest state are ongoing (Kgope et al., 2010; Buitenwerf et al., 2012; Donohue et al., 2013). In these studies, vegetation shifts have been attributed to factors associated with climatic and atmospheric changes, particularly CO_2 fertilization and the advantage of C_3 vegetation over C_4 vegetation at elevated CO_2 concentrations (Ehleringer et al., 1997), rather than changes in land use.

Field studies have explored the responses of the vegetation to variations in land-use at the site-scale. In West Africa, results from long-term field experiments in Burkina Faso highlight the importance of management impacts on vegetation dynamics, vegetation structure and biodiversity (Savadogo et al., 2008, 2009; Dayamba et al., 2011), suggesting that landscape-scale approaches are required to understand impacts of disturbances on savanna ecosystem dynamics. Models can serve as a tool to address questions related to complex interactions in savannas as they allow integration of knowledge about processes and parameters drawn from multi-disciplinary studies and the projection of results from short-term and small-scale studies to larger spatial and temporal scales (Lohmann, 2012). Sophisticated vegetation models are required in order to model interactions between vegetation, climate and anthropogenic impacts in complex ecosystems and to establish robust knowledge. Dynamic global vegetation models (DGVMs, Prentice et al., 2007) are appropriate tools; these models simulate vegetation dynamics based on ecophysiological processes at the leaf, plant and population level and they allow simulation of the impacts of climate change and land use at large temporal and spatial scales. Previous DGVM studies projected vegetation shifts in Africa under future climate conditions (e.g. Higgins and Scheiter, 2012; Sato and Ise, 2012). However, many DGVMs do not represent complex grass-tree dynamics in savannas adequately (Scheiter and Higgins, 2009) and model projections often focus on potential vegetation, while ignoring land use and management.

In this study we used the aDGVM (adaptive dynamic global vegetation model), an individual-based dynamic vegetation model developed and parameterized for African savannas (Scheiter and Higgins, 2009), to investigate the long-term impacts of fire, wood cutting and grazing on the future vegetation of West African savannas. We test the hypothesis that management can contribute to maintain vegetation in a desired ecosystem state, prevent woody encroachment and shifts toward tree-dominated biomes under anticipated future climate scenarios.

2. Methods

2.1. The aDGVM

We used the adaptive Dynamic Global Vegetation Model (aDGVM, Scheiter and Higgins, 2009), a dynamic vegetation model for tropical grass-tree systems. A detailed model description is provided by Scheiter and Higgins (2009), here we summarize important model features. The aDGVM integrates plant physiological processes generally used in dynamic global vegetation models (DGVMs, Prentice et al., 2007) and processes that allow plants to dynamically adjust leaf phenology and carbon allocation to environmental conditions. The aDGVM is individual-based, i.e., it simulates state variables such as biomass, height and photosynthetic rates of individual plants. This approach is necessary to adequately model the impacts of herbivores (Scheiter and Higgins, 2012) and fire (Scheiter and Higgins, 2009) on vegetation structure and demography because these impacts are influenced by the height of individual plants. Grasses are simulated by two super-individuals, representing grasses beneath and between tree canopies. The aDGVM only requires generally available environmental input data and typically simulates vegetation in 1 ha stands. The original version of the aDGVM as described by Scheiter and Higgins (2009) only simulates fire-resistant savanna trees and C_4 grasses. Here, we used an updated model version, with details provided in Scheiter et al. (2012). The updated version simulates both C_3 and C_4 grasses as well as fire-resistant savanna trees and fire-sensitive forest trees. The grass types mainly differ in leaf level physiology (C_3 or C_4 photosynthesis). Differences between tree types are mainly related to re-sprouting behavior after fire and to carbon allocation patterns (Bond, 2008; Ratnam et al., 2011).

Fire is an important driver of savanna vegetation dynamics and is simulated in the aDGVM. In the model, a fire starts when an ignition event occurs. The number of ignitions per year is linked to tree cover because grass biomass is the main fuel type and the tree cover influences how quickly the grass layer desiccates in the dry season. In the model, we assume that the ignition probability is low in vegetation stands with high tree cover and high in open vegetation stands. Days when ignition events occur are randomly generated. An ignition event does not necessarily imply fire spread; fire only spreads with a certain probability (p_{fire}) and when the fire intensity exceeds a threshold value of 300 kJ/m/s (Van Wilgen and Scholes, 1997). Fire intensity is a function of fuel loads, fuel moisture and wind speed (Higgins et al., 2008). This fire sub-model ensures that fire regimes are influenced by fuel biomass and climate. Fires are more likely in the dry season because grass biomass, the main fuel, cures rapidly in the dry season and high fire intensities are possible. Fire removes aboveground grass biomass while the response of trees to fire is a function of tree height and fire intensity (“topkill” effect, Higgins et al., 2000). Seedlings and juveniles in the flame zone are damaged by each fire while adult trees are more fire-resistant and are only damaged by intense fires. In the aDGVM, savanna trees have lower topkill probabilities than forest trees. Grasses and topkilled savanna trees can regrow from root reserves after fire (Bond and Midgley, 2001). After fire and the removal of leaf biomass, the carbon balance of a tree may be negative, which increases the probability of mortality in the aDGVM. By this process, fire influences tree mortality indirectly but does not directly kill trees.