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Impacts of precipitation variability on the dynamics of a dry tropical montane forest

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ABSTRACT

Ecosystem structures of tropical mountain forests are under threat due to changes in climate and land-use. The dry tropical montane forest of Munessa-Shashemene in south-east Ethiopia is a prominent example of degradation and deforestation in the sub-humid tropics. In recent years an increasing number of precipitation events has been observed, mainly during the short rainy season. Moreover, the recent IPCC Report envisages an increase in total annual precipitation, accompanied by more frequent extreme weather events (drought, torrential rains) for the Horn of Africa until the end of the 21st century.

To evaluate possible consequences for local forest ecosystems, we applied the process-based, individual-oriented forest simulation model Formix3 to identify the influence of precipitation variability on the forest growth dynamics. We parameterised the model using field observation data including, for the first time, a tree-ring chronology of *Croton macrostachyus*. By using different levels of annual precipitation and intra-annual precipitation patterns, we analysed explicit simulation scenarios focussing on both overall and species-specific aboveground biomass dynamics and tree species composition.

We found that the model reproduces aboveground biomass productivity precisely under current precipitation conditions. Variations in precipitation cause ecological shifts in the conditions for tree growth. Biomass and species richness both increase with mean annual precipitation, with the effects stabilising over time. Our results emphasise the impact of the duration and frequency of periods of water limitation on forest structure and growth.

Our model has a variety of potential applications including investigation of the impacts of precipitation variability on forest structure and tree species diversity. It is thus a useful tool for extrapolating local growth measurements and succession, and analysing the impact of different management strategies on dry tropical montane forests.

1. Introduction

Changes in climate are predicted to influence future forest conditions such as forest habitat, composition and productivity (Aber et al., 2001; Shugart et al., 2001; IPCC, 2014). For all practical purposes climate change is confident to drive the migration of tree species that result in changes in the geographic distribution of forest types and new mixtures of species within forests. Mainly, tree species are awaited to move northwards or to higher altitudes (Shugart et al., 2001; Dullinger et al., 2012). Moreover, climate change is probably to influence forest productivity, such as photosynthesis, respiration, litter fall, and biomass allocation, depending on location, tree species, water availability and carbon dioxide enrichment (Huth et al., 1998; Shugart et al., 2001). Slightly higher temperatures, a greater accumulation of CO_2 in the atmosphere, and more soil moisture due to higher precipitation levels accelerate growth rates of species in forest ecosystems (Kirilenko and Sedjo, 2007; Achard, 2009). Vice versa, climate variability may also cause

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plant productivity to drop. In terms of the stabilisation of the global climate as well as the protection of the biodiversity, especially tropical forests play an important role (Myers et al., 2000; Bonan, 2008). They cover approximately 15% of the Earth's land surface, though, containing up to 40% of the terrestrial carbon and net primary production, and probably more than 40,000 tree species are estimated to grow in them (Page et al., 2009; FAO and JRC, 2012; Silk et al., 2015). Intact forest ecosystems are able to bind huge amounts of carbon in their living biomass as well as to regulate the water cycle through processes of evapotranspiration. As a result they stabilise the global climate (Reifsnyder, 1982; Pan et al., 2011). How tropical forests respond to climate change may strongly affect the rate of accumulation of atmospheric CO_2.

Among tropical forest types there is a high risk potential of losing montane forests of the dry tropics, such as semi-humid regions, under observed and predicted climate changes (Colwell and Rangel, 2010; Dullinger et al., 2012). Tropical dry forests account for the largest proportion, more than 40%, of all tropical forests (Murphy and Lugo, 1986). Varying precipitation distributions in regions with dry periods on the one hand and temperature-dependant shifts in the altitudinal zoning of different mountain forest types on the other hand may endanger in particular these forest types and tree species growing in them. Tree species that have to deal with seasonal droughts are using adaption strategies, such as stomata closure or leaf shedding, leading to plant productivity drops in case of water scarcity (Krepkowski et al., 2011b). It is therefore of a high priority to quantify the effects of current and future shifts in precipitation distributions on forest growth and composition in dry tropical montane forests. Since the main carbon pools are typically the living aboveground biomass and the dead mass of litter, woody debris and soil organic matter (Gibbs et al., 2007), a precise estimation of aboveground forest biomass is very important.

One prominent example in the sub-humid tropics, where climate changes have been observed (Strobl et al., 2011) and are predicted for the future (IPCC, 2014; Niang et al., 2014) is the dry tropical montane forest of Munessa-Shashemene in south-east Ethiopia. Like many other regions in Ethiopia this forest was concerned by deforestation and degradation for a long period of time, whereas the percentage of natural high forest cover decreased from 16% to only 3% during 1972–2000 (Zeleke and Hurni, 2001; Nyssen et al., 2004; Dessie and Kleman, 2007; Garedew et al., 2009). The current forested area covers approximately 23,000 ha, consisting of a mixture of plantations and highly disturbed remnant natural forest patches (Fritzsche et al., 2007). The vegetation of this remnant natural forest is dominated mostly by the indigenous canopy species *Croton macrostachyus* and *Podocarpus falcatus* with existence of other indigenous tree species (Tesfaye et al., 2010). These two dominant tree species are from different functional types and have an ecological and economic importance for the local people (Bekele-Tesemma, 2007; Tesfaye et al., 2010). To ensure that the Munessa-Shashemene Forest and other natural forest remnants are protected and managed sustainably, we need to broaden our knowledge of dry tropical forest ecosystems and the mechanisms that determine natural forest dynamics, which are currently poorly understood. This applies in particular to possible response patterns related to regional climate change scenarios. In this context we are seeking to answer the following questions:

1. How resilient is the forest stand structure and species composition to variations in annual precipitation?
2. What is the influence of intra-annual precipitation variability on the aboveground biomass production?

To assess the possible ecological effects of changes in precipitation patterns on the succession of the investigated forest stand structure of Munessa-Shashamene, we used the process-based, individual-oriented forest simulation model Formix3 including dynamic soil water and precipitation modules (Huth, 1999; Fischer et al., 2014). We developed appropriate climate change scenarios and simulated long-term and large-scale spatiotemporal dynamics of the forest productivity (aboveground biomass). Since our forest model is sensitive to parameter settings for the individual stem diameter increment, these parameters have to be derived precisely for each tree species by means of multi-year tree-ring dating and dendrometer data. We demonstrate the first tree-ring chronology of *C. macrostachyus* and this chronology was used as one part of the parameterisation to adjust parameter values of the model's stem diameter increment curve. Supplementing this investigation of tree-ring dating, additional multi-year dendrometer data for five indigenous tree species of the Munessa-Shashemene forest (Krepkowski et al., 2011a; Krepkowski et al., 2011b) were used to parameterise their diameter increment curves as well. Concerning the methodology of combining forest modelling and tree-ring dating in the Formix3 model for the first time, this paper addresses another question on how useful dendrochronological measurements for the parameterisation of the forest model's stem diameter increment curves are.

In the following, the model's simulation outcomes of the two experiments with changing annual levels and intra-annual patterns of precipitation will be presented and discussed in relation to changes in aboveground biomass and stem numbers. Then we test the influence of precipitation variability on the growth dynamics of the dry tropical montane forest in Ethiopia. We simulate several annual precipitation patterns, where a single precipitation scenario is defined by the change in precipitation amount and the change in precipitation frequency. Furthermore, we assess the value of dendrochronological data for the parameterisation of stem diameter increment curves.

2. Materials and methods

2.1. Study area and forest inventory

The study site is located in the dry tropical mountain forest of Munessa-Shashemene in south-east Ethiopia at an altitude of 2300 m a.s.l. (7°26′N, 38°52′E; Fig. 1 left). The photograph (Fig. 1 right) shows the structure of the natural forest consisting of indigenous tree species of different life-forms like evergreen conifers (*P. falcatus*), evergreen broad-leafed trees (*Syzygium gineese, Prunus africana, Aningeria adolfi-friedericii, Allophylus abyssinicus, Polyscias fulva, Olea capensis*), and deciduous broadleaved trees (*C. macrostachyus, Celtis africana*) (Bekele-Tesemma, 2007; Krepkowski et al., 2011a; Krepkowski et al., 2011b).

The annual course of precipitation shows strong seasonal variations, with a long dry season from November to March, a long rainy season from July to October, and a very variable short rainy season from April to June (Fig. 1 left). Climate data registered very close to the study site from 2001 to 2011 revealed a mean annual precipitation of 1245 mm and a mean annual temperature of 14.9 °C. Otherwise, Strobl et al. (2011) suggested that the gap between the short and the long rainy seasons has disappeared (March–May) and the climate has generally become more humid since 2001. This is in line with the recent IPCC Report (2014) and Niang et al. (2014), both of which predict and increase in annual precipitation of 20–30%, accompanied by more frequent extreme weather events, such as drought, heat, and torrential rains, for the Horn of Africa until the end of the 21st century.

The soils at the study site are classified as mollic Nitisols (Fritzsche et al., 2007).

We recorded inventory data from five randomly selected square plots in the natural forest with sides measuring 31.5 m in length