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High-resolution modelling closes the gap between data and model simulations for Mid-Holocene and present-day biomes of East Africa

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ABSTRACT

East Africa hosts a striking diversity of terrestrial ecosystems, which vary both in space and time due to complex regional topography and a dynamic climate. The structure and functioning of these ecosystems under this environmental setting can be studied with dynamic vegetation models (DVMs) in a spatially explicit way. Yet, regional applications of DVMs to East Africa are rare and a comprehensive validation of such applications is missing. Here, we simulated the present-day and mid-Holocene vegetation of East Africa with the DVM, LPJ-GUESS and we conducted an exhaustive comparison of model outputs with maps of potential modern vegetation distribution, and with pollen records of local change through time. Overall, the model was able to reproduce the observed spatial patterns of East African vegetation. To see whether running the model at higher spatial resolutions ($10' \times 10'$) contribute to resolve the vegetation distribution better and have a better comparison scale with the observational data (i.e. pollen data), we run the model with coarser spatial resolution ($0.5° \times 0.5°$) for the present-day as well. Both the area- and point-wise comparison showed that a higher spatial resolution allows to better describe spatial vegetation changes induced by the complex topography of East Africa. Our analysis of the difference between modelled mid-Holocene and modern-day vegetation showed that whether a biome shifts to another is best explained by both the amount of change in precipitation it experiences and the amount of precipitation it received originally. We also confirmed that tropical forest biomes were more sensitive to a decrease in precipitation compared to woodland and savanna biomes and that Holocene vegetation changes in East Africa were driven not only by changes in annual precipitation but also by changes in its seasonality.

1. Introduction

East Africa hosts a striking diversity of terrestrial ecosystems, ranging from deserts to rainforests and mountainous forests (White, 1983) as a function of its geography and highly variable topography which consists of central and coastal lowlands, elevated plateaus and adjacent rift basins (Pik, 2011). Superimposed on this complex topography, a dynamic system of Atlantic- and Indian Ocean-related air movements (monsoon systems) determine the amount of precipitation and its timing in the region (Tierney et al., 2011). The varied and heterogeneous ecosystems of East Africa are sensitive to the temporal and spatial changes in this environmental setting in terms of structure and functioning, all of which can be studied by predictive tools such as dynamic vegetation models (DVMs) (Cramer et al., 2001). Yet, regional applications of DVMs to East Africa are rare and a comprehensive validation of such applications is missing.

The present-day vegetation of East Africa has been simulated by DVMs as a part of global (Hickler et al., 2006) and continental studies (Jolly et al., 1998a; Scheiter and Higgins, 2009), and even in regional studies (as control runs in Sepulchre et al., 2006; Doherty et al., 2010; Prömmel et al., 2013). However neither of these studies validated their findings specifically and extensively for East Africa, and it is therefore not clear, if they can adequately represent the abrupt changes in biomes induced by the complex topography of the area. In this study, we apply a process-based DVM, LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator) for East Africa at two different spatial resolutions and compare the resulting biome distributions with vegetation maps as well as with pollen data. LPJ-GUESS is suitable for regional scale studies with its detailed representation of vegetation dynamics (Smith et al., 2001) and has been applied and validated for West Africa before (Hély et al., 2006). However unlike East Africa, West Africa does not have a highly variable topography. Here, we aim to assess if East African biome distribution can be adequately described by low

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resolution models at it has been done until now, or if a higher resolution significantly improves the representation of vegetation patterns due to the requirement of a spatially detailed approach under the complex climatic and topographic conditions.

In addition, we apply LPJ-GUESS to simulate the mid-Holocene biomes of East Africa. During the early- to mid-Holocene, the higher summer insolation over the Northern Hemisphere due to changes in Earth's orbital parameters caused more heating of the continents and altered the land-sea pressure gradients (Bosmans et al., 2012). This resulted in both intensification and displacement of moisture related air circulations over East Africa, bringing more precipitation to the north-eastern parts of the region (Junginger and Trauth, 2013). Meanwhile the Southern Hemisphere was partly in antiphase, experiencing less insolation and weaker monsoons which decreased the rainfall in south-eastern parts of the region (Castañeda et al., 2007). Our motivations in simulating mid-Holocene biomes are twofold: First, it provides a realistic scenario to test the regional application of LPJ-GUESS under different climatic conditions and understand the vegetation distribution, composition and its response to changing climate in East Africa. Second, for this period, high resolution climate outputs of global climate models (GCMs) to drive DVMs have recently been available. Here, we use the outputs of such an atmosphere-ocean coupled climate model, EC-Earth, which has one of the most sophisticated model parameterizations and highest resolution amongst the GCMs that simulated mid-Holocene so far (Bosmans et al., 2012).

Our approach follows these steps: (i) simulating the potential modern East African vegetation with regional application of LPJ-GUESS, and area- and point-wise validation of the model outputs, (ii) assessing the level of agreement for model-data comparison with different spatial resolutions, (iii) reconstructing the mid-Holocene biomes with more detailed representation of the mid-Holocene climate and (iv) analysis of the vegetation changes between the two periods and the drivers of these changes.

2. Methods

Dynamic Vegetation Models (DVMs) are widely accepted model platforms that simulate vegetation response to changing climatic variables and atmospheric CO_2 concentrations for both future (Koca et al., 2006; Doherty et al., 2010; Hickler et al., 2012) and past studies (Jolly et al., 1998a; Hély et al., 2009; Allen et al., 2010; François et al., 2011). In this study we analyse modern and palaeo-vegetation dynamics of East Africa simulated by the DVM, Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS). In order to assess the performance of the model in simulating the complex East African vegetation distribution, we first evaluated modern vegetation under modern climate data and compared the outputs with observational data (e.g. vegetation maps, modern pollen data). Afterwards, we simulated the mid-Holocene biomes and compared the outputs with fossil pollen data. Finally, by comparing the vegetation composition and distribution of both periods, we assessed the drivers behind the simulated differences and sensitivity of biomes to changes in precipitation regimes.

2.1. LPJ-GUESS Model

LPJ-GUESS is a mechanistic dynamic vegetation model in which ecosystem processes are simulated via explicit equations (Smith et al., 2001; Sitch et al., 2003; Gerten et al., 2004). It has been successfully applied worldwide both regionally and locally (e.g. Koca et al., 2006; Tang and Beckage, 2010; Hickler et al., 2012) and recently to tropical regions (Hély et al., 2006, 2009; Doherty et al., 2010).

LPJ-GUESS consists of communicating submodules, each corresponding to different subsets of ecosystem processes, in order to provide a realistic representation of how the physiological and biophysical components and functions are linked in nature. In the model, the status of the processes is updated in either daily or annual time step. The physiological processes such as photosynthesis and plant respiration are simulated on a daily time step whereas establishment, growth, reproduction, mortality and disturbance are updated annually. Vegetation is represented as a mixture of plant functional types (PFTs), which are characterized by their life-form, phenology, physiology and other biological requirements and limits. Based on descriptions of these ecosystem processes and PFTs, LPJ-GUESS then provides gridded values of outputs of different PFTs (e.g. biomass, leaf area index (LAI) etc.), which can be used to assess the vegetation composition of an ecosystem. The spatial resolution of the outputs depends on the resolution of the inputs. In this study we simulated the vegetation at two different spatial resolutions: $10' \times 10'$ (higher) and $0.5° \times 0.5°$ (coarser). Model parameters are provided in the Supplementary Material, Appendix I (for more detailed descriptions of the model structure, its (biogeochemical) computational background and hydrological updates, see also Smith et al. (2001), Sitch et al. (2003) and Gerten et al. (2004), respectively).

2.2. PFT parameterizations and classification rules

LPJ-GUESS requires a list of PFT parameters to simulate the vegetation dynamics. A set of PFTs representing the vegetation of Africa has been parameterized and used in previous studies (Hély et al., 2006; Doherty et al., 2010). Following the previous PFT sets and parameterizations (Hély et al., 2006; Allen et al., 2010; Doherty et al., 2010), with a number of changes, we used twelve PFTs in this study. In order to better represent tropical African biomes, we not only used tropical broadleaved evergreen/raingreen types, but we also split them into shade-tolerant and shade-intolerant types. Together with shade tolerance–intolerance distinction, we assumed shade intolerant trees to be more fire and drought resistant too, in order to distinguish them as savanna-type trees from forest-type trees. (Further details of PFT parameterizations can be seen in the Supplementary Material, Appendix I, Tables A1.2 to A1.5)

Classification of the outputs in terms of biomes is necessary in order to be able to compare the simulated vegetation with observational data. Amongst the outputs of the model, LAI provides an important representation of canopy structure and vegetation composition (ranging from 0 in bare soil to 7 in dense evergreen forests). Therefore, the resulting composition of annual LAI (averaged over the entire 111 years of simulation) was used to classify the corresponding biome of each grid cell according to a set of assignment rules (Table 1). As a starting point for these rules we used comparable studies for West Africa (Hély et al., 2006, 2009) and East Africa (Doherty et al., 2010). Then, we determined the final set of assignment rules by calibrating them to five East African study sites, for which biome classification according to modern pollen

Table 1
Biome classification rules. Rules are based on total leaf area index (LAI) and proportions of LAIs of different plant functional types (PFT) and are applied in the given order to classify the model outputs into biomes. XERO = Afroalpine, AFRO = Afromontane, TEFO = Tropical Evergreen Forest, TSFO = Tropical Seasonal Forest, WOOD = Woodland, SAVA = Savanna, STEP = Steppe, MNE = Mountainous Needle-leaved Evergreen, MBS = Mountainous Broad-leaved Summergreen, C3CG = Cold C3 Grass, TeNE = Temperate Needle-leaved Evergreen, TeBE = Temperate Broad-leaved Evergreen, TrBE = Tropical (Shade-tolerant) Broad-leaved Evergreen.

Rules	Biome
(1): If (MNE LAI > 0.01 or MBS LAI > 0.01) and C3CG LAI > 2.0	XERO
(2): If TeNE LAI > 0.01 or TeBE LAI > 0.1 TeBS LAI > 0.1	AFRO
(3): If Tot. LAI ≥ 6.0 and woody LAI ≥ 5.0 and TrBE is the dominant PFT	TEFO
(5): If Tot. LAI > 5.0 and woody LAI ≥ 4.0	TSFO
(5): If Tot. LAI > 2.5 and woody LAI ≥ 1.5	WOOD
(6): If Tot. LAI > 0.5 and woody LAI > 0	SAVA
(7): If Tot. LAI ≥ 0.1	STEP
(8): If Tot. LAI < 0.1	Bare Soil