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Reconstructing pre-agricultural expansion vegetation cover of Ethiopia

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ABSTRACT

Landscape reconstructions can be used to define a reference condition from which to assess the magnitude of land changes caused by human influence. Since the beginning of the last century, the population of Ethiopia has increased drastically with large effects on the natural vegetation and biodiversity. However, the original land cover patterns in Ethiopia have not been precisely mapped, which hinder the identification of the biophysical and socio-economic factors that contributed to the current landscape patterns. The objective of this study was to reconstruct the past century vegetation landscapes of Ethiopia (i.e. vegetation cover before agricultural expansion) and identify which ecosystems have been most affected by land changes. First, the net primary productivity (NPP) was modelled based on the climatic constraints of natural vegetation growth (water availability, solar radiation and minimum temperature) derived from remote sensing and climate data. This analysis showed that water availability is the most critical constraint for vegetation growth for all regions and land cover types in Ethiopia. Then, the past vegetation was mapped based on predicted NPP. Our results show that i) the extent of broadleaved evergreen or semi-deciduous forest, open broadleaved deciduous forest, closed to open shrubland, mosaic forest-shrubland/grassland, sparse vegetation and grassland was 18.8%, 12.4%, 20.6%, 31.5%, and 16.8%, respectively, and ii) current agricultural landscapes were previously covered mainly by broadleaved evergreen and deciduous forest, which encompassed 38.9%. The least affected by agricultural expansion were sparse vegetation and grassland. Our study provides novel insights on pre-agricultural expansion landscapes in Ethiopia with critical information for scientists and other stakeholders working on the restoration and rehabilitation of degraded areas.

1. Introduction

The rapid population growth observed in the East African highlands during the past century has had implications for land use requirements with subsequent impacts on natural vegetation cover, biodiversity, socio-economic stability and food security (Brink & Eva, 2009). Currently, due to overdependence on primary resources, Africa has the highest rate of deforestation in the world (Ademiluyi, Okude, & Adanni, 2008; Johnson and Chenje, 2008). Deforestation rate in East Africa, including Ethiopia, was the second highest in Africa with 0.94% for 1990–2000 and 0.97% for 2000–2005 (Garedew, Sandewall, Soderberg, & Campbell, 2009). Forest cover in the tropics continues to decrease, mainly because of forest conversion to agricultural land (Ahrends et al., 2010; DeFries, Rudel, Uriarte, & Hansen, 2010; Grecchi, Gwyn, Benie, Formaggio, & Fahl, 2014; Hundera et al., 2013; Sirén & Brondizio, 2009).

In Ethiopia, the natural forest cover has declined significantly with influences on biological richness and quality (Kuru, 1990). Woldu (2000) indicates that 34% of Ethiopia was covered by trees and 57% of the land above 1500 masl. was covered by dense forests and 20% by wooded savannah. Earlier studies indicated that 35–40% was covered by natural forest and 66% of the country was originally covered with forest or woodlands (Britenbach, 1961; Kuru, 1990; Wood, 1990; Yirdaw, 1996). According to FAO (2010), the annual rate of deforestation in Ethiopia was estimated to be 1% (0.14 million ha $year^{-1}$) from 1990 to 2010. Thirteen percent of the total area of the country (15.11 million ha) was covered by forests in 1990 and this was decreased to ca. 11% of the total area (12.29

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million ha) in 2010.

This rate of deforestation was mainly associated with the human population growth (Yirdaw, 1996). The population has increased from 22.2 million in 1960 to 94.1 million in 2013 (World Bank, 2013). According to Bishaw (2001), population pressures have decreased the size of holdings, including both arable and pasture lands as the production system is mainly rain fed, subsistence-based, and smallholder oriented (Rosell, 2011). This leads to conversion of forested and marginal areas into agricultural lands. From 1900 until 1989, about 4.7 million households required arable land for cultivation (Hurni, 2007). Since 1900 about 23 million hectare of forest land was cleared, mainly driven by a conversion to arable farmland (Assefa & Bork, 2014). Another study also revealed an increase of cultivated land from 27% to 63% in three different but adjacent sites in Ethiopia from 1957 until 1993 (Reid et al., 2000).

These changes in the natural landscape were established long before the advent of remote sensing technologies. As a consequence, the exact extent and spatial patterns of Ethiopia's vegetation cover before agricultural expansion is uncertain. Uncertainties on the original land cover patterns in Ethiopia hinder the identification of the biophysical and socio-economic factors that contributed for defining current landscape patterns. In the absence of a general knowledge on the historical landscape patterns, effective conservation actions are critically compromised, as the identification of areas at risk of land degradation becomes largely subjective. Furthermore, the exact biodiversity loss caused by the expansion of agricultural lands is unknown, causing difficulties in logistic and implementation of projects aiming to rehabilitate degraded natural vegetation areas.

In this research, we aimed to simulate past century natural vegetation cover of Ethiopia and to estimate the extent of natural vegetation cover affected by agricultural expansion. We expect that our results will provide new insights on pre-agricultural expansion landscapes and improve the understanding of how human activities contributed for defining current landscapes. Further, a better understanding of the spatial patterns of the original vegetation will allow the identification of socio-economic factors that contributed for delineating the current agricultural landscapes in Ethiopia.

1.1. Study area

Ethiopia is situated at 34°30′–45°30′ E and 3°30′–15° N covering an area of 110 million hectare in the northeastern part of Africa (Fig 1.). Ethiopia is characterized morphologically by three major regions; Main Ethiopian Rift (MER), Afar Triangle and Ethiopian Highlands (Skovitina et al., 2012). This morphology exhibits variation in altitude from about 110 m below sea level in the Afar depression to 4620 masl on Mt. Ras Dashen in the northern part of the Ethiopia highlands.

The climate of Ethiopia is governed by two main factors ((Friis, Demissew, & Van Breugel, 2010): the closeness of the Equator (the southern boundary of the country at approximately 3°30′ N) and the complexity of the relief. According to Seleshi and Zanke (2004), the altitudinal range greatly influences the Ethiopian climate, with the formation of microclimates ranging from cool highlands to hot desert climate. The traditional Ethiopian classification of climate (Conway, 2000) is based on altitude and identifies three zones: i) Kolla zone that is below 1800 m asl. with mean annual temperatures of 20–28 °C; ii) Woina Dega zone, 1800–2400 m asl with mean annual temperatures of 16–20 °C; iii) Dega zone above 2400 m asl with mean annual temperatures of 1–6 °C.

Ethiopia represents 50% of the land above 2000 m in Africa, which makes Ethiopia one of the largest highland areas in the tropics. Area that covers 73% of the region above 2000 m asl receives 1185 mm mean annual rainfall during the main rainy season, which is from June to September (Seleshi & Demaree, 1995). The mean monthly rainfall is between 9 mm in the Afar rift and 185 mm per month in the highlands. The mean annual temperature is between 3.9 °C in the highlands and 31.2 °C at the bottom of Afar Triangle.

2. Material and methods

In this research, vegetation net primary productivity (NPP) was modelled based on the climatic constraints of vegetation growth derived from remote sensing and climate data. This model was used to simulate productivity of agricultural area in order to identify the original extent of natural vegetation cover. A detailed description of the datasets and methodology used in this study is provided below.

The method was divided in four main stages. First, the natural vegetation was separated from agricultural areas and its NPP was characterized based on climatic productivity constraints. The constraints were minimum temperature, solar radiation based on cloudiness and water availability. Water availability was computed by the ratio of precipitation to potential evapotranspiration (P/PET) to indicate water-limiting conditions for plant growth (Nemani et al., 2003). The range of minimum temperature, water availability and solar radiation variables (-5–5 °C, 0–0.75 and 0.1–1, respectively) were rescaled to 0–1 to show the degree of limits for the productivity (Nemani et al., 2003).

Second, 3000 random points of natural vegetation cover were created to tabulate the three constraints and NPP. The points were separated by a minimum distance of 5 km to avoid spatial autocorrelation. From these samples, 75% were used for training the NPP model and 25% were used for validation. Third, multivariate regression was used to assess the relationship between NPP and the climatic variables (water availability, solar radiation and minimum temperature). The regression model was also used for identifying which environmental variable has more influence on natural vegetation NPP. The relative impact of these variables for NPP of each vegetation cover was determined by standardized coefficients (beta). These coefficients were measured in standard deviations unlike the regression coefficients that are in the units of the variables. Finally, the model was used for simulating potential NPP over agricultural lands of Ethiopia, aiming to provide a proxy for identifying the original natural vegetation in these areas. The simulated productivity map classified based on threshold in order to show how the natural vegetation affected by agricultural expansion. These thresholds were set based on the average simulated NPP value of each class. That is, the threshold was made by taking the half way between the two consecutive land cover classes' average simulated NPP after the value sorted ascending order,. Finally, accuracy assessment was made in order to validate the classification using a stratified random sample of the simulated NPP and the current natural vegetation cover of Ethiopia (1000 points per class).

2.1. Climatic data

Water is one of the most important factors for plant growth and limiting conditions are often driven by precipitation (Nemani et al., 2003). Besides precipitation, low temperatures can limit productivity. Minimum temperature is important to control the stomatal conductance (the measure of the rate of passage of carbon dioxide (CO_2) entering or water vapor exiting through the stomata of a leaf) for plant growth especially during the growing season (Mu et al., 2007). In this study, Coupled Model Intercomparison Project Phase 5 (CMIP5) Global high-resolution of WorldClim data (http://www.worldclim.org), mean annual precipitation and mean annual minimum temperatures were used as climatic variables. These data