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Spatio-temporal variations in climate, primary productivity and efficiency of water and carbon use of the land cover types in Sudan and Ethiopia

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HIGHLIGHTS

- Interaction between climate and vegetation ecosystems is complex and still unclear.
- Correlating climate variability and vegetation productivity provides useful insights.
- Spatio-temporal variations in climate, NPP, WUE and CUE using remote sensing data
- NPP, WUE and CUE vary widely among land covers in different climate conditions.
- This variation should be considered in policy-making for water and food security.

GRAPHICAL ABSTRACT

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ABSTRACT

The impact of climate variability on the Net Primary Productivity (NPP) of different land cover types and the reaction of NPP to drought conditions are still unclear, especially in Sub-Saharan Africa. This research utilizes public-domain data for the period 2000 through 2013 to analyze these aspects for several land cover types in Sudan and Ethiopia, as examples of data-scarce countries. Spatio-temporal variation in NPP, water use efficiency (WUE) and carbon use efficiency (CUE) for several land covers were correlated with variations in precipitation, temperature and drought at different time scales, i.e. 1, 3, 6 and 12 months using Standardized Precipitation Evapotranspiration Index (SPEI) datasets. WUE and CUE were estimated as the ratios of NPP to actual evapotranspiration and NPP to Gross Primary Productivity (GPP), respectively. Results of this study revealed that NPP, WUE and CUE of the different land cover types in Ethiopia have higher magnitudes than their counterparts in Sudan. Moreover, they exhibit higher sensitivity to drought and variation in precipitation. Whereas savannah represents the most sensitive land cover to drought, croplands and permanent wetlands are the least sensitive ones. The inter-annual variation in NPP, WUE and CUE in Ethiopia is likely to be driven by a drought of time scale of three months. No statistically significant correlation was found for Sudan between the inter-annual variations in these indicators with drought at any of the time scales considered in the study. Our findings are useful from the view point of both food security for a growing population and mitigation to climate change as discussed in the present study.

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1. Introduction

Net Primary Productivity (NPP) is defined as the amount of atmospheric carbon that is captured by plants and transformed into biomass (Zhao and Running, 2010). The total amount corresponding to the photosynthesis process is called Gross Primary Productivity (GPP). The difference between NPP and GPP is referred to as respiration (Ardö, 2015), which is the amount of carbon previously assimilated by the plant and subsequently used for maintenance of the biomass or for growth. Monitoring of the variability in primary production is critical due to the fact that NPP provides vital services for human survival (Ardö, 2015). Reduction in NPP potentially jeopardizes food security and may increase global warming since a reduction in NPP might decrease the available carbon sinks (Zhao and Running, 2010). Whereas the spatial variation of NPP depends on vegetation type, soil, climate conditions and human activities, the temporal variation of NPP depends mostly on the variability of climatic factors (Li et al., 2016). Several climate factors control the NPP, such as temperature, precipitation and shortwave solar radiation (Li et al., 2016). Temperature and precipitation have more influence on NPP in arid and semi-arid areas whereas solar radiation is the main controlling factor in humid and semi-humid areas (Liu et al., 2015). Temperature plays a role in raising NPP (Zhao and Running, 2010). Although the period from 2000 through 2009 was the warmest decade in the records since 1880 (NOAA, 2016), Zhao and Running (2010) found that global NPP has declined by 0.55 petagram carbon (Pg C) during the same decade. They suggested that a drying trend in the southern hemisphere was the main driver for this reduction. There has been a debate regarding these findings as to whether there was a decrease in NPP or whether this decrease was due to artifacts from the applied model (Samanta et al., 2011; Zhao and Running, 2011). If NPP is affected by climate as suggested in that model; then, NPP should have decreased during this period (Medlyn, 2011).

Ecosystems differ in their responses to climate variability (Knapp and Smith, 2001). Different plant species respond differently to drought conditions based on their physiological and structural characteristics in order to prevent loss of water (Van Der Molen et al., 2011). Understanding how land cover types respond to drought and to climate variability can promote more efficient management of these land covers and can, in turn, assist significantly in securing water and food in the future.

Many studies have been conducted on this matter, yet most of them have focused on the climate driver of the NPP variation on a global scale (e.g. Huang et al., 2016; Liu et al., 2015). Recent analyses showed that semi-arid areas are a main control of global NPP variations (Huang et al., 2016; Ahlström et al., 2015). However, it is important to examine whether the same pattern of NPP found by Zhao and Running (2010) on a global scale also applies on regional and local scales (Chen et al., 2013). As the scaling of the relevant processes is typically non-linear, different patterns are likely to emerge at the regional or local scale. Drought is expected to be more severe in the future (Ault et al., 2014). Therefore, it is important to investigate the effect of drought on primary productivity and efficiency of the land cover types in terms of water and carbon use. Analysis of these interactions at regional and national levels is useful and provides essential information for land cover management and climate policy-making (Peng et al., 2017; Liu et al., 2015). Recently, a country-scale analysis of the relationship between NPP and drought was published by Peng et al. (2017). The data used in their work were Moderate Resolution Imaging Spectroradiometer (MODIS) NPP and the drought Standardized Precipitation Evapotranspiration Index (SPEI). They found that countries show different trends in NPP for the period 2000 to 2014, and only 35 countries accounted for >90% of the global NPP.

On the continental scale, Africa has witnessed an increase in NPP during the same period, i.e. from 2000 through 2009, by 0.189 Pg C. This was mostly due to a decrease in vapor pressure deficit (Zhao and Running, 2010). African ecosystems produce around 20% of the total global NPP (Ciais et al., 2011), and a large fraction of the inter-annual variability in the global carbon cycle is due to ecological processes on the African continent (Williams et al., 2007). Monitoring the variation in vegetation productivity, WUE and CUE, and correlating this variation with climate variability for large areas is a challenge, particularly against the backdrop of the given limitations of ground data, especially in the countries of Sub-Saharan Africa, for instance, where ground weather stations are few and sparsely distributed.

WUE and CUE are useful indicators for the assessment of the pattern of water use and carbon sequestration by plants. WUE is defined as "The rate of carbon uptake per unit of water lost" (Tang et al., 2014). It can be calculated by different approaches according to the purpose of investigation (Ito and Inatomi, 2012). Here, WUE is defined as the amount of water evaporated for every g carbon/m^2 of NPP produced, i.e. NPP/ET$_a$, where ET$_a$ is the actual evapotranspiration (Kuglitsch et al., 2008). CUE is defined as a ratio of NPP to GPP. The earliest conception of the CUE is that it ideally equals 0.5 (DeLucia et al., 2007; Zhang et al., 2009). However, CUE should not be considered as a constant value since the driving processes of photosynthesis and respiration are nonlinearly governed by different environmental drivers; thus, the ratio of these fluxes varies. Photosynthesis and respiration are primarily governed by the absorbed photosynthetically active radiation (APAR) and temperature, respectively. Several researchers noted that CUE might vary depending on climate factors (e.g. precipitation and temperature) and geographical location (Zhang et al., 2009). Plants are considered carbon sinks. Examining the variability of CUE is thus important for climate change and CO_2 emissions studies (Chen et al., 2013). Also, a better understanding of WUE and CUE may lead to a better management of ecosystems (Tang et al., 2014; Zhang et al., 2009).

Variability in primary productivity affects food availability and food security. At the same time, the magnitude of primary production strongly affects the carbon cycle (Zhao et al., 2005). However, lack of continuous ground observation hinders the long-term analysis of the dynamics of vegetation development. Luckily, many remote sensing or model based public-domain data sources nowadays provide continuous spatial climate observations and other key environmental variables (e.g. LAI, biomass, soil moisture). The general availability of these public-domain data sources provides a unique opportunity for examining the climate-plant productivity relationship, which is essential for a reproducible analysis of the impact of climate variation on primary productivity. However, in comparison with climatic variables, only few public-domain databases provide data on primary productivity. MODIS data, such as the primary productivity (MOD17) product, are often used to detect the variability of primary productivity as well as analyzing the WUE and CUE of land cover types or entire ecosystems and their association with climate conditions. For a summary of the most important studies, refer to Table 1.

To the best of our knowledge, apart from the study of Peng et al. (2017) who studied the impact of drought on NPP on a country scale for the whole globe, no other study was conducted to analyze the response of NPP, WUE and CUE of different land cover types to drought and climate variability in Sub-Saharan Africa based upon generally available datasets. In this study, inter-annual variations in climate conditions and drought on different time scales for the period from 2000 through 2013 were correlated with inter-annual variation in NPP, WUE and CUE in various land cover types in Sudan and Ethiopia. The two selected countries are examples of Sub-Saharan countries with severe data-scarcity and high vulnerability to climate variation and food insecurity. Understanding the spatio-temporal variability of NPP, WUE, and CUE is essential to achieve a better land management in these countries and to improve food security.

2. Materials and data

2.1. Study area and its importance

East Africa is one of the most challenging areas for managing natural resources due to many factors. It is a region highly vulnerable to climate