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Examining the NDVI-rainfall relationship in the semi-arid Sahel using geographically weighted regression

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ABSTRACT

The Sahel of Africa is an eco-sensitive zone with complex relations emerging between vegetation productivity and rainfall. These relationships are spatially non-stationary, non-linear, scale dependant and often fail to be successfully modelled by conventional regression models. In response, we apply a local modelling technique, Geographically Weighted Regression (GWR), which allows for relationships to vary in space. We applied the GWR using climatic data (Normalized Vegetation Difference Index and rainfall) on an annual basis during the growing seasons (June–September) for 2002–2012. The operating scale of the Sahelian NDVI–rainfall relationship was found to stabilize around 160 km. With the selection of an appropriate scale, the spatial pattern of the NDVI-rainfall relationship was significantly better explained by the GWR than the traditional Ordinary Least Squares (OLS) regression. GWR performed better in terms of predictive power, accuracy and reduced residual autocorrelation. Moreover, GWR formed spatial clusters with local regression coefficients significantly higher or lower than those that the global OLS model resulted in, highlighting local variations. Areas near wetlands and irrigated lands displayed weak correlations while humid areas such as the Sudanian region at southern Sahel produced higher and more significant correlations. Finally, the spatial relationship of rainfall and NDVI displayed temporal variations as there were significant differences in the spatial trends throughout the study period.

1. Introduction

The normalized difference vegetation index (NDVI) is the most widely used surrogate for vegetation greenness in a wide range of studies spanning regional to global scales (Anyamba and Tucker, 2005; Vrieling et al., 2013). The variability of NDVI is a function of prevalent climatic conditions such as rainfall and temperature, and this relationship is well established at various spatial and temporal scales (Fabricante et al., 2009; Udelhoven et al., 2009; Wang et al., 2010). Rainfall is a particularly important predictor of vegetation distribution in the transition zone from humid to arid environments (Martiny et al., 2006; Huber et al., 2011). In most studies that characterize the relationship between vegetation and rainfall, NDVI is modelled as a function of rainfall using global linear models calibrated using ordinary least squares (OLS) regression methods. However, the NDVI-rainfall relationship varies spatially and temporally depending on land cover, soil type, vegetation composition and structure, microclimatic conditions and human impact (Propastin et al., 2008). As such, models that assume stationarity may fail to capture the true nature of the relationship between variables making the validity of their results questionable.

The Sahel region of Africa comprises various land cover categories and complex ecosystems, and is known to be sensitive to environmental change (Nicholson et al., 1990; Huber et al., 2011). The Sahel underwent a protracted drought from the mid-1960s through the mid-1980s in which there were several humanitarian crises. Eklundh and Olsson (2003) reported a recovery from this period and observed increases in satellite-derived NDVI from the mid-1980s onwards. This increase in landscape greenness was called the "greening of the Sahel" (Olsson et al., 2005), and was the result of increases in herbaceous and tree cover (Dardel et al., 2014; Brandt et al., 2015). The primary mechanism behind this observed greening is the increase in rainfall (Hickler et al., 2005), and, to a lesser extent, improved land use activities (Olsson et al., 2005; Lee et al., 2015).

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The majority of studies that examine the Sahelian NDVI-rainfall relationship are based on linear per-pixel time series analysis of NDVI and rainfall. However, the spatially variable relationship between these parameters has not been explored in depth. As such, this study attempts to model the complex relations between NDVI and rainfall by using a local non-parametric regression method known as geographically-weighted regression (GWR) (Fotheringham et al., 2003). GWR is commonly used in human geography (Fotheringham et al., 2001; Hu et al., 2012) and has recently become popular in ecology (Wang et al., 2005; Propastin et al., 2008; Gaughan and Waylen, 2012). GWR allows the relationships between dependent and explanatory variables to vary over space and directly deals with non-stationarity. The outputs of this method are useful for descriptive purposes and to detect areas of model misspecification or variability that would otherwise be lost in a global model. Thus, the objective of this study is to explore the NDVI – rainfall spatial relationship in the Sahel between 2002 and 2012, with a focus on vegetative growing season. The extremities of this period were chosen because of the large difference in total rainfall received in the region −2002 was a dry year and 2012 was a wet year (Fig. 1).

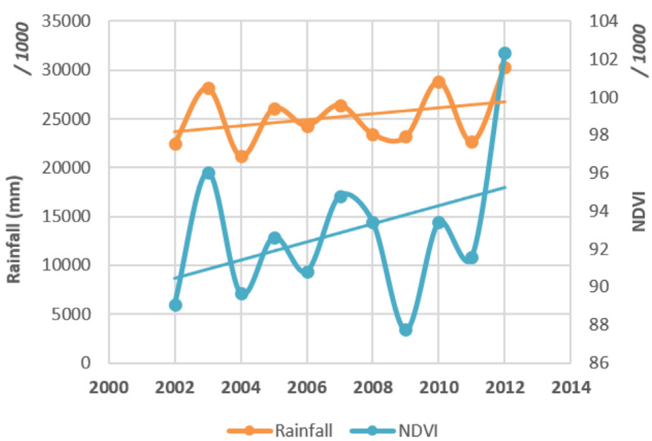

Fig. 1. Annual sums of monthly NDVI and monthly rainfall layers between 2002 and 2012 based on the GIMMS and CHRIPS datasets, respectively.

This enables the analysis of temporal variability in the spatial relationships, and the detection of areas where the Sahel is particularly sensitive to variations in rainfall by mapping the local regression results.

2. Study area

The Sahel is a 3.3 million km^2 region that separates the hyper-arid Sahara Desert in the north from the humid Sudano-Guinean zone in the south. The majority of the rainfall is distributed over 2–4 months during the summer growing season (June–September) whereas rainfall during the rest of the year is negligible (Brandt et al., 2015). The dominant land cover categories of the Sahelian belt based on the Global Land Cover (GLC) SHARE classification (Latham et al., 2014) are shown in Fig. 2. Most Sahelian plants have the C_4 photosynthetic pathway, and are acclimatized to warm, arid environments. These are primarily composed of herbaceous vegetation (Fig. 2). The canopy cover ranges between 3 and 10%, and is predominantly composed of trees that have the C_3 photosynthetic pathway.

3. Material and methods

3.1. Normalized difference vegetation index – NDVI

The independent variable in this study is the NDVI and is computed as:

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

where, NIR and RED denote spectral reflectance in the near infrared (800–1000 nm) and red (620–750 nm) portions of the electromagnetic spectrum. The index ranges between −1 (water bodies) and 1 (dense vegetation). We utilized NDVI derived from the Advanced Very High Resolution Radiometer (AVHRR) instrument on board the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites. The dataset is the third generation (3g) NDVI product developed by the Global Inventory Monitoring and Modelling System (GIMMS) project. The data are provided as

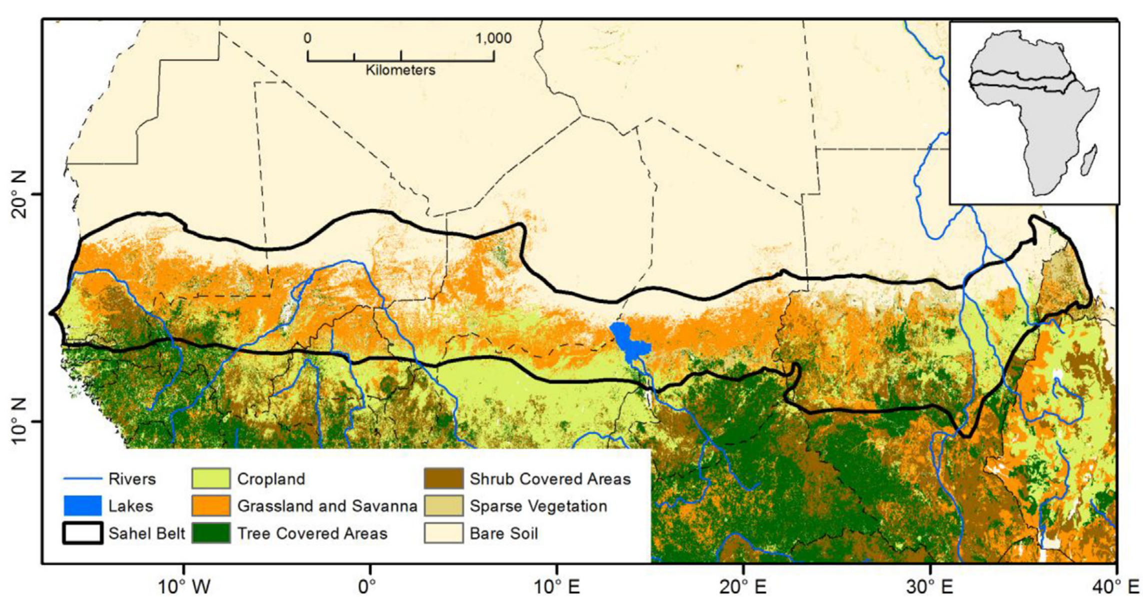

Fig. 2. Land cover of the Sahel based on the GLC-SHARE classification scheme from the Food and Agriculture Organization of the United Nations.