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Can vegetation productivity be derived from greenness in a semi-arid environment? Evidence from ground-based measurements

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ABSTRACT

Trends of biomass production and land processes in the Sahel have been widely studied since the droughts of 1970s. Satellite data have been an important source of information because of limited *in situ* data. Previous studies relied on the assumed existence of a relationship between vegetation productivity and the NDVI, in particular the annually integrated NDVI (iNDVI). This study examines this assumption and its limitations, based on *in situ* time series measurements of biomass, species composition, NDVI and soil moisture at the Dahra test site in northern Senegal. It is shown that, there are large differences between the NDVI – vegetation productivity relationships, and these differences can be linked to species composition. There is moderate correlation between NDVI and above-ground net primary productivity (ANPP) at the peak season ($r^2 = 0.39$). In particular, the species *Zornia glochidiata* is characterized by high peak NDVI and low ANPP, compared to other common species such as *Cenchrus biflorus* and *Aristida adscensionis*. It is concluded that spatial and temporal variations in species dominance is likely to add noise to the relationship between NDVI and biomass. However, the seasonal cyclic fraction of the NDVI – "small seasonal integral" – reduces such noise.

1. Introduction and research questions

The Sahel is one of the most studied ecoregions in Africa. Environmental trends have been examined by natural and social scientists since the so-called Sahel crisis in the 1970s, both in order to quantify and explain the changes taking place, often under the heading of land degradation, and in order to provide inputs to the management of the region (Begue et al., 2011; Diouf and Lambin, 2000; Prince et al., 2007). Among the many themes studied, changes in the productivity of semi-natural vegetation in rangelands, taking up a major part of the Sahel, have attracted special interest, because of the large economic importance for the livestock sector, and because vegetation productivity is a key indicator of land degradation (Nicholson, 2000; Ridder et al., 1982).

The *in situ* data available for studying changes (and spatial differences) in productivity of the herbaceous vegetation in rangelands is quite limited, and most studies have relied on the use of satellite data (Tucker et al., 1985). The use of medium to high resolution satellite data, such as Landsat MSS/TM/ETM and SPOT HRV data, is hampered by the widespread cloud cover in the growing season in combination with the low revisit frequency of these systems. Instead moderate to coarse resolution systems, such as NOAA AVHRR, SPOT VGT and MODIS (Aqua-Terra), offering daily coverage, have been used. In terms of methodology, most studies have been based on use of vegetation indices, and in particular the NDVI integrated over the growing season (Anyamba and Tucker, 2005; Budde et al., 2004; Fensholt et al., 2009), as a proxy for vegetation productivity (Tucker and Sellers, 1986; Prince, 1991a,b; Millich and Weiss, 2000; Rasmussen, 1998a,b). In order to minimize the atmospheric influence on the NDVI signal, various techniques are used, including Maximum Value Compositing (Holben, 1986), best index slope extraction (Viovy and Arino, 1992), step-wise logistic regression (Zhang et al., 2003), and curve fitting (Jonsson and Eklundh, 2002). Long-term temporal trends in ANPP (above-ground net primary productivity) may be extracted using

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techniques such as linear regression or Theil-Sen trend analysis (Kalácska et al., 2004).

It is well documented that the relationship between integrated NDVI and herbaceous ANPP is far from perfect. For instance, Tucker et al. (1985), Prince (1991a) and Prince et al. (1995) find a moderate linear relationship between the satellite observations of vegetation indices and the seasonal primary production in early studies of the applicability of NOAA AVHRR data for vegetation monitoring in the Sahel. Many factors may cause noise in the relationship; Pettorelli et al. (2005) mention the noise associated with the cloud cover effect, effects of the over-smoothing of data or increase in highs and lows on the trend curve of NDVI due to processing methods. Other studies have pointed to the importance of the soil background brightness variations caused by changes in soil moisture content over the growing season (Tucker et al., 1985). Also studies suggest that the relationship depends on species composition (IPCC, 2007; Olsson et al., 2005) which is the focus on the current study. While many botanical studies focus on vegetation class change analysis (Couteron and Kokou, 1997; GEMS, 1988; Gonzalez, 2001; Lykke and Fog, 1999), few discuss spatial and inter-annual variation in dominance of herbaceous species as a function of rainfall and grazing pressure (Hiernaux et al., 2009a; Miehe et al., 2010). However, if pre-drought botanical accounts of rangeland vegetation are compared to contemporary studies, it is clear that perennial species have been on the retreat while annuals, like those mentioned above, have taken over. The causes for the changes in the Sahel vegetation remain uncertain because of an incomplete understanding of the coupling between rainfall temporal distribution and productivity (IPCC, 2007; Prince et al., 1998). The lack of explained productivity variance by rainfall for certain areas is signaling that greening cannot be fully explained by increased rainfall (Monteith, 1972; Olsson et al., 2005). A study from Niger (Boulain et al., 2009) covering a 2-year period showed that inter-annual variations in fallow vegetation development was more dependent on the temporal rainfall distribution (and thereby soil moisture content) along the growing season than on the rainfall starting date. Miehe et al. (2010) studied the rainfall pattern and grazing on plant composition in North Senegal over a 27 year period and concluded that grazing had a significant influence on the herbaceous plant composition. Hence, interpretation of vegetation dynamics in the Sahel may reflect complex combined effects of human land use and climate variability (Rasmussen et al., 2001; Seaquist et al., 2009).

The method for ANPP estimation from NDVI satellite data, described above, is a purely statistical approach. Alternatively, a method based on satellite data providing inputs to a process-based model may be applied. The most widely used is the Light Use Efficiency (LUE) modeling approach (Fensholt et al., 2006a; Seaquist et al., 2003; Turner et al., 2003). Here NDVI can be used to estimate the fraction of photosynthetically active radiation absorbed by the vegetation (fAPAR). In this model a factor representing the efficiency of the conversion of absorbed radiation into energy in the plant material is included. This efficiency factor may depend on a number of factors, including water stress and several species dependent factors (Huber et al., 2011). This supports the idea that different species can have different relationships between integrated NDVI and ANPP.

When producing maps of vegetation productivity with global coverage, such as the product being generated from the MODIS data stream, the NDVI – ANPP relationship is assumed to be biome-specific, and thus the method requires worldwide maps of broad biome classes (Running et al., 2004). These predefined classes of vegetation are by no means spatially detailed enough to capture variations in species dominance within a biome, nor do they take temporal variations into account.

Temporal variations and trends in ANPP, determined from NDVI time-series, may be explained by reference to rainfall variations/trends or to other factors, such as land use/cover change. It is, however, worth noting that as explained above, such variations and trends may alternatively be explained by variations/trends in the dominance of various herbaceous species (Tappan et al., 2004). Much of the recent literature agrees that 'the Sahel is greening' over the period (1981–2010) covered by the NOAA AVHRR time series (Anyamba and Tucker, 2005; Fensholt and Rasmussen, 2011; Herrmann et al., 2005; Heumann et al., 2007; Myneni et al., 1997; Olsson et al., 2005). This does not rule out that certain areas experience little change or even a decrease (Wezel and Haigis, 2000). As the scale of analysis decreases towards the spatial resolutions of LANDSAT, SPOT and ASTER (10–30 m) or even finer, the picture becomes more nuanced, and it may be suggested that the greater variation in observed trends at higher spatial resolutions is partly caused by the greater spatio-temporal variability of species dominance at finer scales.

This study intends to highlight this effect by studying it at the scale of few meters by using *in situ* measurements of NDVI ANPP and soil moisture from four growing seasons. The measurements were carried out at the Dahra test site in Senegal (Fensholt and Sandholt, 2005) over the growing seasons of 2006, 2008, 2009 and 2010.

The study addresses the following research questions:

1. Does herbaceous species composition and changes in phenology, influence the NDVI (and in particular the iNDVI) – biomass (and in particular the ANPP) relationship?
2. Can shifts in species dominance between growing seasons be explained by soil moisture variability?
3. What is the significance of the answers to the first two questions for the usefulness of satellite-based estimation of ANPP? Study area

The study site is located in Dahra in the Ferlo-region in the semi-arid northern part of Senegal (lat 15.40; long −15.43) (Fig. 1). The short rainy season stretches from late July to October and the average annual precipitation is 350 mm, but interannual variations are large. The average annual air temperature is about 26 °C, with monthly averages reaching a minimum of 21 °C and a maximum of up to 34 °C. The vegetation is characterized as open grassland similar to many other parts of the Sahel (Hanan et al., 1991; Moreau et al., 2003). Fine-leaved annual grasses of the *Poaceae* family mostly C4 plants, with a maximum height of 60 cm dominate the herbaceous layer in the region *Schoenefeldia gracilis*, *Dactyloctenium aegypticum*, *Aristida mutabilis* and *Cenchrus biflorus* (Valenza and Diallo, 1972) but widely spaced perennial grasses with a maximum height of 80 cm can also be found (Ridder et al., 1982) in the so called tiger bush. Several species of the *Fabaceae* family, mostly C3 plants are present. Species such as *Zornia glochidiata*, *Alysicarpus ovalifolius* and *Cassia tora* are frequent in the study area. Tree and shrub canopy cover generally does not exceed 5% and is dominated by four species; *Balanites aegyptiaca*, *Acacia Senegal*, *Acacia tortilis* and *Boscia senegalensis* (Diallo et al., 1991). The soil type of the site can be characterized as a poorly developed soil formed on sandy parent material of dunes or fluvial deposits with less than 3% clay, FAO (1995).

2. Materials and method

2.1. Test site measurements

The site from where the *in situ* measurements of NDVI and soil humidity are collected is located in a rangeland area, within a state