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Analysis of vegetation seasonality in Sahelian environments using MODIS LAI, in association with land cover and rainfall

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ABSTRACT

Present-day Sahelian vegetation in a highly anthropized semi-arid region is assessed from local to regional scales, through the joint analysis of MODIS LAI (1 km^2 and 8-day resolutions), daily rainfall, morphopedological and land cover datasets covering the period 2000–2008. The study area is located in northwest Senegal and consists of the "Niayes" and the northwestern "Peanut Basin" eco-regions, characterized by market gardening and rain-fed cultivated crops, respectively. The objectives are i) to analyse at pixel scale LAI time series and their relation to vegetation and soil types, ii) the estimation of phenological metrics (start of season SOS, end of season EOS, growing season length GSL) and their inter-annual variability, iii) to recognize the vegetation responses to rainfall trends (mean annual precipitation, MAP; frequency of rainy events, K; combination of MAP and K, called F).

Pixel-scale analyses show that LAI time series 1) describe the actual phenology (agreeing with ground-truth AGHRYMET data), and thus can be used as a proxy for Sahelian vegetation dynamics, 2) are strongly dependent on soil types. Median maps of SOS and EOS suggest an increase of the GSL from Saint-Louis to Dakar, in agreement with both the North-South rainfall gradient and the intensification of agricultural practices around Dakar. Significant correlations (R: 0.64) between annual variation coefficient of LAI and MAP for both herbaceous crops and natural vegetation are highlighted; this correlation is reinforced (R: 0.7) using the rainfall distribution factors K and F. Rainfall thresholds allowing the SOS can be defined for each type of vegetation. These thresholds are estimated at 0–5 mm, 20 mm and 40 mm for natural herbs, herbaceous crops and shrublands, respectively.

If previous works revealed the close link between the MAP and the SOS, our results highlight that LAI dynamics are also controlled by rainfall distribution during the Monsoon season. In this study, climatic indicators are proposed for estimating vegetation dynamics and monitoring SOS. Coupling Earth Observation data, such as MODIS LAI, with rainfall data, vegetation and soil information is found to be a reliable method for vegetation monitoring and for assessing the impact of human pressure on vegetation degradation.

1. Introduction

The Sahel has experienced a rainfall decline over the last decades (Gonzalez, 2001; Nicholson, 2000). Although a recent shift to a wetter regime has been observed (Nicholson, 2005; Olsson et al., 2005), except for western Sahel (Lebel and Ali, 2009), the major droughts (1972–1973 and 1983–1984 events) that occurred within the 1968–1993 dry period led to a decrease in water resources, to the land cover degradation, and had severe impacts on crop productivity and populations (Tschakert, 2007).

The determination of the predominant factor responsible for land degradation is still questionable. Gonzalez (1997) suggested the predominance of climatic factors when Tappan et al. (2000, 2004) put the emphasis on traditional land-use practices, such as crop expansion in association with an intensification of deforestation. However, for the UNCCD (United Nations, 1994), the observed Sahelian vegetation results from a complex combination of both anthropogenically induced degradation effects and climatic trends. From local to regional scales, parameters such as soil types, vegetation communities, inter-annual variations in rain-use efficiency are also responsible for biomass productivity variations (Diouf and Lambin, 2001; Hiernaux et al., 2009; Tottrup and Rasmussen, 2004).

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Assessing land cover changes is one of the bases for modelling vegetation seasonality in response to climatic changes. One means of assessing the seasonality of Earth's vegetated surfaces is to use remotely sensed data (Tucker et al., 1985). Among the array of available Earth Observation products, the *Leaf Area Index* (LAI) product provided by the MODerate resolution Imaging Spectroradiometer (MODIS) proved to be a significant biophysical parameter for crop yield assessment (Doraiswamy et al., 2005). This product is obtained from solar reflectances by radiative transfer model inversions, and is defined as one-sided green leaf area per unit ground area (Myneni et al., 1997). Among the few studies validating the MODIS LAI product in semi-arid environments, good correlations between *in situ* LAI measurements and MODIS LAI in the Southern Kalahari (Privette et al., 2002) and in Central and North Senegal (Fensholt et al., 2004) have been reported. At the African continent scale, the LAI product was used for discriminating vegetation types and proved to contain major information for characterizing plant phenological properties, i.e. the timing and the dynamics of the vegetation-growing season (Kaptue et al., 2010): the LAI spatial pattern indeed matches the vegetation cover distribution and the LAI time series follows the intra-annual dynamics of vegetation cycle, conditioned by local environmental conditions such as rainfall or topography. For Fensholt et al. (2004), MODIS LAI product retranscribes the "real-world LAI" and thus may be used as a vegetation status proxy.

In the last decades, an array of methods has been developed for determining the timing of the growing season (Kang et al., 2003; Schwartz, 1998; White et al., 2002; Zhang et al., 2003) from remotely sensed time series. The vegetation dynamics may be defined by the identification of phenological key dates, usually the green-up (Start Of the growing Season, SOS), the maturity, the senescence (End Of the growing Season, EOS) and the Growing Season Length (GSL). In semi-arid regions, vegetation phenology is mainly controlled by water availability (Kramer et al., 2000). Green leaves indeed often follow rainfall events (De Bie et al., 1998; Peñuelas et al., 2004). In cropland areas, growth and harvest dates were also revealed to be controlled by the distribution and amounts of precipitation during the rainy season (Omotosho, 1992), as well as the number and frequency of dry-days within the monsoon season (Proud and Rasmussen, 2011). A quantitative understanding of the relation between climatic trends and growing season seasonality may improve the ability to predict food production and anticipate biomass reduction (Brown and de Beurs, 2008).

The aim of this study is to assess vegetation dynamics under anthropized semi-arid environments through the joint analysis of MODIS LAI, rainfall, geomorphological and land cover datasets over the period 2000–2008 (Fig. 2). The study area is located in Northwest Senegal and consists of the "Niayes" and the north-western "Peanut Basin" Eco-regions (Tappan et al., 2004). This region was chosen to analyse the links between vegetation seasonality, soil characteristics and rainfall for two main reasons. First, this area constitutes a representative case of degraded Sahelian vegetation (Tappan et al., 2004). Second, daily rainfall data provided by the "Direction Nationale de la Météorologie" (DNM, Dakar) was available at four rain gauge stations. This dataset permitted us to analyse the spatial and temporal vegetation responses to rainfall.

The main objectives reported in this paper are as follows (Fig. 2):

- Study of the vegetation seasonality from LAI time series.
- Estimate of phenological metrics, their spatial variations and their inter-annual variability.
- Analysis of the vegetation responses to rainfall amount and distribution.

The first objective concerns the detailed analysis of LAI time series, and is performed at local scale. Cross-correlations between LAI time series, types of vegetation (including *in situ* agricultural information) and rainfall patterns are discussed for selected LAI pixels.

The second objective aims at deriving phenological information from LAI time series at regional scale. The derivation of SOS and EOS dates, as well as GSL, is performed using the methodological approach proposed by Zhang et al. (2003), which consists of fitting two simple sigmoid function to remote sensing time series to extract the phenological information.

Finally, the third objective relies on the assessment of the influence of rainfall patterns (annual amount of rain and frequency of rainy events) on the timing and the performance of the vegetation types encountered in the study area. These correlations are analysed only around the four rain gauge stations, with a particular focus on the assessment and characterization of the rainfall-phenology relationships according to vegetation and soil types.

2. Study area

2.1. Geographical setting

The study area is located in northwest Senegal, in a 40 km wide strip of land along the Senegal coastland, stretching over 180 km between the cities of Dakar and Saint-Louis (Fig. 1). The topography presents live sand dunes ranging between 0 and 50 m above sea level and reaching an altitude of 126 m near the plateau of Thiès. The study area covers two eco-regions characterized by differences in geomorphological setting (Stancioff et al., 1986), floral composition and land use practices (Tappan et al., 2004). The Long Coast eco-region defines a narrow 5–30 km wide land strip along the northern Senegalese coastline, and consists of a succession of sandy dunes and organic-hydromorphic soils, also referred to as peat soils, in depressions (Tappan et al., 2004). The north-western part, the "Peanut Basin" eco-region is composed of eolian sands on which have developed ferruginous tropical sandy soils, the latter being brown, deep, structureless and well-drained (Tschakert and Tappan, 2004). Southwards, ferruginous tropical soils are developed on marno-calcareous formations (near Thiès, Fig. 1).

2.2. Vegetation

Global information on vegetation spatial distribution for the two studied eco-regions is shown in Fig. 1 (source Globcover Land Cover -GLC- map, see the description of the product in section 3.3). The Long Coast eco-region is characterized by the presence of niayes, which are microecosystems in inter-dunal depressions, and Savanna shrub in surrounding sandy dunes. The location of the niayes is reported in Fig. 1 (from the Global Land Cover Network -GLCN- database, http://www.glcn.org/dat_0_en.jsp website). Since the beginning of the 1970s, the natural vegetation of the niayes has progressively been replaced by market gardening (Tappan et al., 2004). Representing less than 1% of the study area, the vegetation dynamics of these particular irrigated environments are not discussed in the study.

Vegetation in the Peanut Basin essentially consists of a patchwork of crops and sparse shrublands. Rainfed millet (85–90 day growth cycle) and peanut (90–105 day growth cycle) systems are used in yearly rotation (Affholder, 1995).

3. Datasets

3.1. Precipitation data

Daily rainfall data was provided by the "Direction Nationale de la Météorologie" (DNM, Dakar, Senegal). Four rain gauge stations