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Monitoring desertification in a Savannah region in Sudan using Landsat images and spectral mixture analysis

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ABSTRACT

Two Landsat images, acquired in 1987 and 2008, were analyzed to evaluate desertification processes in central North Kurdufan State (Sudan). Spectral Mixture Analysis (SMA) and multitemporal comparison techniques (change vector analysis) were applied to estimate the long-term desertification/re-growing of vegetation cover over time and in space.

Site-specific interactions between natural processes and human activity played a pivotal role in desertification. Over the last 21 years, desertification significantly prevailed over vegetation re-growth, particularly in areas around rural villages. Changes in land use and mismanagement of natural resources were the main driving factors affecting degradation. More than 120,000 km^2 were estimated as being subjected to a medium-high desertification rate. Conversely, the reforestation measures, adopted by the Government in the last decade and sustained by higher rainfall, resulted in low-medium re-growth conditions over an area of about 20,000 km^2.

Site-specific strategies which take into account the interactions of the driving factors at local scale are thus necessary to combat desertification, avoiding any implementation of untargeted measures. In order to identify the soundest strategies, high-resolution tools must be applied. In this study the application of spectral mixture analysis to Landsat data appeared to be a consistent, accurate and low-cost technique to identify risk areas.

1. Introduction

Desertification is defined as land degradation in arid, semiarid and dry sub-humid areas due to climate variation and/or human activity (UNCCD, 1994). The three major land use systems prone to desertification in arid and semiarid areas are rangeland, rain-fed croplands and irrigated lands. Degradation of vegetation cover by overgrazing and the cutting of woody plants for fuelwood, buildings, bush fencing and other purposes is the common desertification process in rangeland (Mustafa, 2007). On rain-fed croplands, wind and water erosion are accelerated by cropland preparation, which involves removal of the native vegetation cover, woodcutting or grass burning. High concentrations of salts in the root zone associated with the introduction of irrigation in dry areas (secondary salinization) have caused desertification due to salts rising with the rise in ground water level (Singh, 2009).

Four aspects must be evaluated in order to render the desertification process measurable (FAO-UNEP, 1984): status, which is defined as the state of a particular piece of land at a specific time compared with its condition in the past; rate, which refers to the change in the condition over time; inherent risk, which is a measure of the vulnerability of landscape to a desertification process; and hazard, which is the overall rating considering the previous three aspects. To make the assessment easier, several Authors have attempted to determine appropriate indicators. Environmental indicators over large areas must be measurable and suitable for regular updating. Few of the proposed indicators are specifically for dryland degradation alone, because it is difficult to separate the effects of climatic factors from those of human activities in such areas (Diouf and Lambin, 2001; Mabbutt, 1986; Rubio and Bochet, 1998).

Difficulties have also arisen because the interpretation of the UNCCD desertification definition can differ greatly according to the choice of indicators. Soil erosion and sedimentation, perennial plant cover and biomass have been used as indicators of the desertification status (Le Houerou, 2006). However a recent survey among 90 experts has recognized the long-lasting loss of vegetation cover and productivity over time and in space as the key indicator/variable of desertification (Hellden, 2008).

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One of the most effective tools for desertification assessment is remote sensing. It has long been suggested as a time and cost efficient method for observing dryland ecosystem environments (Hassan and Luscombe, 1990), monitoring land cover degradation, as well as characterizing the dynamism of sand dunes (Collado et al., 2002).

Most remote sensing in arid regions has concentrated on optical remote sensing techniques which use data from sensors that collect radiation in the reflected solar spectrum. Two main approaches are usually followed (Dawelbait and Morari, 2008; Smith et al., 1990): a) calculation of vegetation indices; b) image classification.

A relationship between plant biomass and a standardized vegetation index can be established (Tucker, 1979). Vegetation indices, reviewed by Jackson et al. (1983), Tueller and Oleson (1989) and others, are generally based on ratios of the radiance in the red and infrared spectral bands, chosen to maximize the reflectance contrasts between vegetation and other materials. The Normalized Difference Vegetation Index (NDVI) has been most commonly used to map spatial and temporal variation in vegetation (Tucker, 1979). NDVI is sensitive to pixel-level changes in greenness and fraction of photosynthetically active radiation absorbed but is not differentially sensitive to change in vegetation cover versus vegetation condition (i.e. the vigour, photosynthetic capacity or stress of vegetation canopy or cluster). This means that when an NDVI change occurs, it cannot be readily determined whether or not it was caused by altered vegetation cover or condition of cover (Asner, 2004). Moreover, NDVI has only limited success in providing accurate estimates of shrubland cover in arid areas and limited utility in an arid ecosystem. This is due to spectral variability of background materials such as soil and surface litter and the strength and variation of soil spectral albedo, which causes nonlinearity in the relationship between NDVI and vegetation characteristics (Asner, 2004; Huete, 1988; Huete et al., 1992).

Image classification usually relies on statistical methods including maximum-likelihood, clustering and discrimination analysis or methods based on principal components analysis (PCA) (Smith et al., 1990). PCA is used to identify a change in heterogeneity. However, to obtain an accurate measurement the pixel size must be smaller than the scale of variability of at least one of the principle landscape elements (e.g. grasslands).

Spectral mixture analysis (SMA) is a sub-pixel classification technique which could be use to unmix the soil-plant canopy measurements into the respective soil, vegetation, and non-photosynthetic vegetation (Smith et al., 1990). SMA depends on the spectral response of land cover components. The spectral response in remote sensing from open canopies is a function of the number and type of reflecting components, their optical properties and relative proportions (Adams et al., 1995). SMA appears to be the most efficient technique to obtain information on vegetation cover, soil surface type and vegetation canopy characteristics in semiarid areas because the scale of variability of the principle landscape elements in semiarid areas is larger than the pixel size in most of the remote sensing satellite imageries (Adams et al., 1995; Dawelbait and Morari, 2008; Okin and Robert, 2004).

Sudan is a developing country where desertification is widespread. UNEP considers that three compounding desertification processes are underway (UNEP, 2007): climate-based conversion of land types from semi-desert to desert, mainly due to a reduction in annual rainfall; degradation of existing desert environments, including wadis and oases, principally caused by deforestation, overgrazing and erosion; conversion of land types from semi-desert to desert by human action (deforestation, overgrazing and cultivation) even if rainfall may still be sufficient to support semi-desert vegetation. These processes are relatively difficult to distinguish, separate and quantify on the ground (Diouf and Lambin, 2001).

Specific studies are therefore necessary in order to define the driving variables affecting the processes and adopt efficient site-specific strategies to combat desertification. Since limited funds are provided to Sudanese research institutions, remote sensing can be a reliable tool to study desertification without incurring high costs (e.g. Ali and Bayoumi, 2004; Dafalla and Casplovics, 2005; Khiry, 2007).

This paper aimed to a) test the application of SMA to Landsat images as a tool to study the desertification phenomenon and b) individuate and quantify the driving variables influencing land degradation in a savannah region in the central part of Sudan.

2. Material and methods

2.1. Study site

The study site is located in the north of Umrowaba in North Kordodan State, central Sudan, in the Sahelian eco-climatic zone (between latitude 12°56′35″ and 13°3′49″N and longitude 31°0′51″ and 31°58′51″ E) (Fig. 1). The climate is semiarid with annual rainfall ranging from 200 to 750 mm, concentrated during a few summer months (June to September/October), with a peak in August. Mean annual temperature is about 20 °C, but the daytime temperature can rise as high as 45 °C during summer.

The soil is a Cambric Arenosols (FAO-UNESCO, 1997), coarse sandy, of Aeolian origin with high infiltration rates and inherent low fertility. Sand sheets and sand dunes stabilized by vegetation are the main natural formations. Natural vegetation consists of trees (*Acacia* spp.), bushes and grass, *Aristida pallida* Steud. on crests of dunes, *Eragrostis termula* Tnismert. in the troughs and *Cenchrus biflorus* Roxb., which grows after crop cultivation. Rangeland and rain-fed croplands are the most important land use systems. The main crops are sorghum (*Sorghum vulgare* Pers.), millet (*Panicum miliaceum* L.), sesame (*Sesamum indicum* L.) and watermelon (*Citrullus lanatus* (Thunb.) Matsum & Nakai). The rainy season usually leads to a short growing period (from June to October) followed by a long dry season with a reduction in green vegetation. The peak of biomass is observed at the end of the rainy season (September–October).

2.2. Data acquisition and preprocessing

Landsat Thematic Mapper (TM5) and Landsat Enhanced Thematic Mapper plus (ETM+7) scenes acquired on September 15th 1987 (TM5 Sep 15) and October 18th 2008 (ETM+7 Oct 18) were analyzed. The dates coincided with the end of the rainy season and were selected for monitoring the potential long-term processes of desertification, since both of them were acquired in periods of comparable rainfall amount (5 mm in September 1987 and 8 mm in October 2008) even considering the antecedent months (e.g. 113 in August 1987 and 92 mm in August 2008).

Landsat images were selected because they are free of charge, with high monitoring frequency and cover areas appropriate for monitoring the environment in a large geographic zone. Landsat TM5 and ETM+7 have a temporal revisit time of 16 days and a spatial resolution of 30 m with six visible/near infrared bands and one thermal band. The gaps in ETM+7 scan-line corrector (SLC)–off were filled using the localized linear histogram mach (LLHM) method (Scaramuzza et al., 2004). Landsat 7 ETM + SLC − off, November 3rd 2008 was used to fill the gaps since the time lag between the two images was only 15 days and the gaps were not overlapping.

ETM+7 Oct 18 was co-registered to TM5 Sep 15 to undertake comparative analysis. Images were not referenced to a standard