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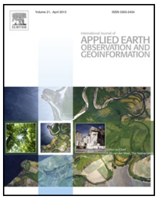

Remote sensing of vegetation cover dynamics and resilience across southern Africa

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ABSTRACT

Southern Africa supports a significant portion of the world's floral biodiversity but predicted changes in climate are likely to cause adverse impacts on the region's ecosystems and biodiversity. Knowledge regarding the resilience of vegetation cover is important for understanding the potential impact of anthropic or climatic change. The length of time vegetation cover takes to recover from disturbances can provide an indication of ecosystem resilience. We investigated spatial and temporal patterns in the persistence of vegetation cover across southern Africa (1982–2006) and used persistence probability plots to estimate decay times of NDVI trends as a means to characterise the potential resilience of key southern African biomes. Patterns of positive and negative NDVI trend persistence were spatially coherent, indicating collective dynamic behaviour of vegetation cover. Persistence probability plots indicated differences in resilience between biomes. Mean recovery times from negative NDVI trends were shorter than for positive trends in the Savanna and Nama Karoo, whereas the Succulent Karoo exhibited the shortest mean lifetime for positive NDVI trends and one of the longest mean lifetimes for negative trend survival, implying potentially slow recovery from environmental disturbance. The results show the potential of satellite-time series data for monitoring vegetation cover resilience in semi-arid regions.

1. Introduction

Changes in vegetation cover as a consequence of predicted anthropogenic climate change, or other land-use related pressures (e.g. fires, overgrazing and land abandonment) may have a substantial effect upon the world's ecosystems (e.g. ; Midgley & Thuiller, 2011; Schaphoff et al., 2006; Scholze et al., 2006). Like much of the African continent, southern Africa is considered highly vulnerable to future climatic change (Fauchereau et al., 2003; Thomas et al., 2005; IPCC, 2007). An increased frequency and intensity of extreme climatic events, such as droughts, is likely to cause major changes in vegetation cover, with attendant socio-economic implications (Reynolds et al., 2007). There is a growing research impetus to identify ways to detect early signs of climate change and identify regions and ecosystems of high vulnerability (Midgley & Thuiller, 2011).

Vegetation responses to an environmental perturbation depend upon the frequency and magnitude of the disturbance, the relationships between the perturbing factors (e.g. temperature, precipitation, land use; Hutyra et al., 2005) and the resilience of the ecosystem concerned. Quantification of the persistence and resilience of vegetation cover, across various spatial and temporal scales, will facilitate a greater understanding of both baseline vegetation dynamics and the responses of ecosystems to human activities or natural stresses (Gunderson, 2000).

Different definitions of resilience exist with the ecological literature (Gunderson, 2000), although the most common definition considers ecological systems to exist close to a stable steady-state (Holling, 1996). Therefore, resilience can be defined as the ability of a system to return to a stable steady-state following a perturbation. The time taken for the vegetation to recover can be used as one measure of vegetation resilience (Tilman & Downing, 1994; Ives, 1995; Mittelbach et al., 1995). The vegetation recovery time is inversely proportional to the level of resilience (Wissel, 1984). Under quasi-stable conditions, healthy vegetation is expected to be more resilient, whereas environmental stresses can reduce resilience and cause persistent decreases in vegetation activity (Lanfredi et al., 2004; Simoniello et al., 2008). Despite its simplicity, this definition of resilience is often used for large-scale studies of vegetation dynamics, particularly those relying on remotely sensed data where vegetation cover is often characterised as either being present or absent.

Spatial coverage and the availability of time-series data render remote sensing systems an ideal tool with which to consider such large-scale vegetation dynamics. The NOAA-AVHRR (National

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Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer) sensors currently provide the most comprehensive time-series of satellite data for monitoring regional-scale changes on the Earth's surface. Specifically, the Normalised Difference Vegetation Index (NDVI), which derived from red and near infrared reflectance bands of the AVHRR sensor, is an established satellite vegetation index commonly used as a surrogate for vegetation biomass, cover and vitality (e.g. Tucker, 1979; Myneni et al., 1997). AVHRR data have previously been used to study trends in greenness in arid and semi-arid areas, both globally (e.g. Nemani et al., 2003; Xiao and Moody, 2005; Beck et al., 2011; de Jong et al., 2011; Fensholt et al., 2012) and at a regional level (e.g. Hellden and Ottrup, 2008; Huber and Fensholt, 2011).

The aim of this paper is to characterise vegetation dynamics and resilience across southern Africa between 1982 and 2006 using AVHRR data, and to assess the potential of this approach for monitoring the vulnerability of key African biomes to environmental change. We followed a method developed by Lanfredi et al. (2004), which provides an estimation of the persistence probability of vegetation cover. From this, timescales of vegetation cover recovery can be deduced and related to vegetation resilience. Using AVHRR-NDVI data, we investigate spatial patterns in the persistence of vegetation cover at the regional and biome scale across Botswana, South Africa, Namibia, Swaziland and Lesotho and use the estimated decay times of NDVI trends as a means of characterising biome specific resilience. In doing so, this study will be the first to apply this specific technique to arid and semi-arid regions and biomes such as the Succulent Karoo of western South Africa. The range of biomes across the study area, which are characterised by different plant physiologies and structural characteristics, in conjunction with significant climatic gradients and varying degrees of climatic variability, also make this a useful region in which to test this approach to resilience analysis.

2. Study area

The study area encompasses five countries and a diversity of environmental conditions. Seven major biomes are recognised across this region, five of which (Fynbos, Succulent Karoo, Nama Karoo, Grassland and Savanna) are the focus here. These biomes are largely differentiated on the basis of dominant plant life form, which in turn reflects marked gradients in rainfall seasonality and summer aridity across the sub-continent (Rutherford, 1997; Dlamini, 2011; Wessels et al., 2011). Substrate (soil) has little influence on biome-scale categorisations (Rutherford, 1997), although some exceptions do exist (e.g. Succulent Karoo/Fynbos). Mean annual rainfall is extremely variable across the study area, ranging from c. 800 mm per annum in south east South Africa, to <50 mm per annum in hyper-arid Namibia. Isohyets, which are orientated in a broadly east–west manner in more tropical latitudes, become increasingly north–south orientated in central South Africa and the south-western parts of the subcontinent, which reflects the increasing significance of the mid-latitude anticyclones relative to the ITCZ (Intertropical Convergence Zone) in driving atmospheric stability and rainfall patterns (Lindesay, 1998).

There is little conclusive evidence for long-term increases or decreases in southern African precipitation throughout the twentieth century (Richard et al., 2001; Hoffman et al., 2009). Some evidence has been reported for a drying trend in the early twentieth century in South Africa (Hoffman et al., 2009), along with an increased frequency of drought and extreme events during the period subsequent to the late 1960s and into the 1980s (Fauchereau et al., 2003). The relatively sparse data available for such analyses should be noted. The problem of limited data is further compounded by high inter-annual climatic variability, which is particularly characteristic of arid regions (Muller et al., 2008; Kane, 2009). Coefficients of variation in mean annual rainfall generally increase from east to west, exceeding 40% along the western margins of South Africa (Schulze, 1997). In such environments single storm events can make substantial contributions to the annual rainfall total (e.g. Muller et al., 2008). Cyclical temporal variability in rainfall has been identified at a range of frequencies, ranging from the (2–3 year) Quasi Biennial Oscillation (QBO) to a consistently identified 18 year variability cycle (Tyson, 1986; Mason and Jury, 1997). Summer-rainfall zone variability has been linked with the El Niño Southern Oscillation (ENSO; Lindesay, 1988; Washington and Todd, 1999; Rouault and Richard, 2003) with areas of NW/SE orientated lower level convergence, which are ordinarily responsible for considerable rainfall in the summer rainfall zone, shifting towards Madagascar and reducing summer rainfall during El Niño events (Washington and Todd, 1999). The most severe droughts in South Africa during the study period occurred in 1983 and 1992 (Rouault and Richard, 2003).

3. Methodology

3.1. Satellite vegetation index

We used 25 years (1982–2006) of GIMMS (Global Inventory Modelling and Mapping Studies) AVHRR-NDVI data for the initial determination of vegetation cover persistence across southern Africa because of the long record of this NDVI product (i.e. from 1982 to 2006 for the entire planet; Tucker et al., 2004). The GIMMS NDVI data have a nominal spatial resolution of 8 km and are provided every 16 days. The data were obtained from the Global Land Cover Facility (www.landcover.org) and are calibrated and corrected for variations in solar and view zenith angle, and the presence of stratospheric aerosols associated with the El Chichon and Mt Pinatubo volcanic eruptions (Tucker et al., 2005). Annual Maximum Value Composites (MVC) (Holben, 1986) were created and used as a surrogate value for the level of vegetation cover. To account for the timing of peak NDVI in the southern hemisphere, the annual MVC–NDVI composites were based on hydrological year, i.e. October to September as opposed to a calendar year. The hydrological year is designated by the calendar year in which it ends.

3.2. Ancillary data

Southern African biome data, based on the categorizations identified by Rutherford (1997), were made available in vector format by the South African National Biodiversity Institute (http://www.plantzafrica.com). The map contains 7 major biomes (Fig. 1). Monthly high resolution ($0.5^\circ \times 0.5^\circ$) gridded precipitation data were also obtained from the University of East Anglia Climatic Research Unit dataset (CRU TS 3.0; Harris et al., 2013).

3.3. Persistence analysis

Spatial patterns of NDVI change were generated through an analysis of the persistence of NDVI trends (Lanfredi et al., 2004). An initial reference map was produced by constructing a linear NDVI trend surface $s(x, y, t)$ over the reference period (1982–1991). Pixels (x, y) for which the trend sign was positive over this initial period ($t = t_i$) were assigned a value of +1, otherwise a value of −1 was assigned. Using a yearly time step, NDVI values were then added and a new trend surface was created. If the addition of an additional year cleared an existing trend (i.e. the slope is set to zero), we assumed that the current status of the vegetation was statistically equivalent to the initial reference level (i.e. recovery). In practice, because of the noised nature of the NDVI