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# Wavelet-based detection of bush encroachment in a savanna using multi-temporal aerial photographs and satellite imagery

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ABSTRACT

Although increased woody plant abundance has been reported in tropical savannas worldwide, techniques for detecting the direction and magnitude of change are mostly based on visual interpretation of historical aerial photography or textural analysis of multi-temporal satellite images. These techniques are prone to human error and do not permit integration of remotely sensed data from diverse sources. Here, we integrate aerial photographs with high spatial resolution satellite imagery and use a discrete wavelet transform to objectively detect the dynamics in bush encroachment at two protected Zimbabwean savanna sites. Based on the recently introduced intensity-dominant scale approach, we test the hypotheses that: (1) the encroachment of woody patches into the surrounding grassland matrix causes a shift in the dominant scale. This shift in the dominant scale can be detected using a discrete wavelet transform regardless of whether aerial photography and satellite data are used; and (2) as the woody patch size stabilises, woody cover tends to increase thereby triggering changes in intensity. The results show that at the first site where tree patches were already established (Lake Chivero Game Reserve), between 1972 and 1984 the dominant scale of woody patches initially increased from 8 m before stabilising at 16 m and 32 m between 1984 and 2012 while the intensity fluctuated during the same period. In contrast, at the second site, which was formely grass-dominated site (Kyle Game Reserve), we observed an unclear dominant scale (1972) which later becomes distinct in 1985, 1996 and 2012. Over the same period, the intensity increased. Our results imply that using our approach we can detect and quantify woody/bush patch dynamics in savanna landscapes.



## Introduction

Savannas are ecosystems co-dominated by a continuous grass layer and scattered trees (Frost et al., 1985). Savannas account for a fifth of the terrestrial surface (Scholes and Archer, 1997) and contribute up to 30% to global net primary production (Grace et al., 2006). In addition, savannas support the largest diversity of mammals on Earth and constitute a major source of livelihood for more than half of the total human population in Africa through agriculture, grazing as well as fuelwood harvesting (Scholes and Archer, 1997; Sankaran et al., 2005). In this regard, knowledge on savanna ecosystems and their dynamics is important.

The ability of the savanna to provide services to society is dependent on the persistence of a stable mosaic of grasses and trees, which is now undergoing transformation due to widespread bush encroachment being experienced on a global scale (Wigley et al., 2009). Bush encroachment is the gradual increase in woody plant species in previously grassland-dominated, tree-grass-dominated areas or tree-grass co-dominated ecosystems (Archer, 1990, 1994; Sankaran et al., 2004; Khavhagali and Bond, 2008; van Auken, 2009). Bush encroachment is widely hypothesised to be driven by a combination of factors that range from overgrazing by domestic livestock to global ones that include elevated atmospheric $CO_2$ concentrations, increased nitrogen deposition and climate change (van Auken et al., 1985; Archer et al., 1995; Briggs et al., 2005; Wigley et al., 2009). The increase in woody species in savannas largely results in reduced rangeland carrying capacity for livestock and wildlife (Archer, 1994; Timberlake, 1994; Rohner and Ward, 1997; Kraaij and Ward, 2006; Wiegand et al., 2006). Thus, an understanding of the process of bush encroachment is important as a preamble to the development of methods for the detection and characterisation of the process.

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As mentioned earlier, the development of methods that allow for the detection and characterisation of bush encroachment hinges upon the understanding of its progression in the first place. Archer (1995) provides a conceptual framework for understanding the progression of bush encroachment in savanna ecosystems which can be conveniently be subdivided into 3 key stages, i.e. initiation, cluster development and coalescence of woody clusters. The initialisation of bush encroachment starts with the dispersal and invasion of woody species in a previously grass dominated landscape. Next, clusters develop around established individual woody plants as a result of facilitation through nucleation process enhanced by avifauna dispersal (Yarranton and Morrison, 1974) and increased resource availability through trapping of nutrients under wood canopy (Schlesinger et al., 1990). Finally, with further recruitment of woody species around the focal woody plant, there is enlargement of young and old clusters resulting in coalescing of discrete clusters (Archer, 1995). However, we assert that the process of bush encroachment is a non-linear ecological process. For instance, drought years may result in the contraction of woody clusters and expansion of the herbaceous layer while years of above normal rainfall may result in enhanced woody plants recruitment (Roques et al., 2001; Sankaran et al., 2005; Angassa and Oba, 2007). Thus, the dynamic changes in these two life forms are influenced by recruitment of invading woody species in response to changes in rainfall regimes (Wiegand et al., 2006).

Traditionally, the study of bush encroachment involves the use of fieldwork and aerial photography. For the latter, studies have mainly used manual digitising (Ansley et al., 2001) and grey-scale partitioning or level slicing (Lahav-Ginott et al., 2001) to detect bush encroachment in savanna ecosystems. While these methods have enabled the determination of tree or tree cluster location and size, they have often failed to determine the window size, i.e., scale at which bush encroachment occurs, yet all ecological processes such as bush encroachment are intrinsically scale dependent (Wiens, 1989; Wiegand et al., 2006). Only recently, have ecologists started having interest in developing and applying methods that can objectively quantify the scale dependency of ecological processes. In that regard, variograms (He et al., 2006) and recently wavelets have been applied to the quantification of spatial scale of vegetation structure in forests (Bradshaw and Spies, 1992) and savanna (Strand et al., 2006, 2008). However, to date these studies have not been adopting any analytical framework that can simultaneously incorporate vegetation density or cover and linear dimension (scale). This has made it difficult to characterise vegetation dynamics in landscapes such as the savannas where ecological processes consist of a largely multi-scale structure. Recently Murwira and Skidmore (2005) developed the intensity-dominant scale approach which may be able to simultaneously handle changes in cover and scale. However, to the best of our knowledge application of the intensity-dominant scale approach to understanding bush encroachment is still in its infancy.

The intensity-dominant scale approach is based on two key concepts, i.e., intensity and dominant scale. Intensity is the maximum variance exhibited when a spatially distributed landscape property such as vegetation cover is measured with a successively increasing window size or scale and dominant scale is the scale or window size at which the intensity is displayed. In the case of a tree-grass co-dominated landscape intensity would coincide with the maximum variance in cover which would normally occur at the window size defining the woody patch and grass patch discontinuity. Thus, the dominants scale is predicted to correlate well with the spatial extent or dominant linear dimension of either woody or grass patches within the study sites while intensity coincides with the contrast in the density of woody and grass cover.

In the context of bush encroachment we envisage several predictions based on the intensity-dominant scale approach. Firstly, during the initiation phase of bush encroachment when woody clusters are few, we predict a large dominant scale that reflect the large size of the grassland and a low intensity as a result of low woody cover and grass cover contrast. Next, during the cluster development stage, we predict a decrease in the dominant scale due to increasing woody patch size resulting from further recruitment of woody plants. At this stage, intensity is expected to increase due to the increased contrast between grassland background and tree clusters. In fact, intensity is expected to be highest when the two life forms co-dominate. Finally, with further progression of bush encroachment coalescence and canopy closure, we predict that intensity decreases reflecting near homogeneity or dominance in woody cover. However, since bush encroachment is non-linear, we predict that both the dominant scale and intensity fluctuate between low and high. In this regard, it is reasonable to hypothesise that the intensity-dominant scale framework can be used to track tree and grass spatial dynamics resulting from bush encroachment in a savanna ecosystem. Like earlier-mentioned, although the intensity-dominant scale approach has been successfully used to characterise spatial heterogeneity in different landscapes (Murwira and Skidmore, 2005; Pittiglio et al., 2011), the issue of whether this method can be used to characterise the process of bush encroachment has not yet been tested.

In this study, we test whether the intensity-dominant scale approach implemented using a wavelet transform can be used to detect bush encroachment using historical aerial photographs and satellite images in two protected savanna landscapes in Zimbabwe. Specifically, based on the recently developed intensity-dominant scale approach, we test the hypotheses that: (1) the encroachment of woody patches into the surrounding grassland matrix causes a shift in the dominant scale. This shift in the dominant scale can be detected using a discrete wavelet transform regardless of whether aerial photography and satellite data are used; and (2) as the woody patch size stabilises, woody cover tends to increase thereby triggering changes in intensity. The quantification of tree-grass dynamics is a first step towards understanding the magnitude and direction of change as well as insights into the possible mechanisms that drive bush encroachment.

## Materials and methods

### *Study area*

The study was conducted at two study sites, i.e., Lake Chivero Game Reserve located at latitude 17° 55′ and longitude 30° 48′ and Lake Kyle (Mutirikwi) game reserve located at 20° 06′ of latitude and longitude 30° 58′. These two sites were selected because they were established around the same time (Kyle 1961 and Chivero 1962) and have typically similar vegetation and herbivore species. Consumptive human activities are prohibited in game reserves, making the two study sites ideal for studying wood/bush encroachment and densification in a natural setting.

### *Lake Chivero Game Reserve*

The game reserve was established in 1962 and occupies 1867 ha (Zimbabwe Parks and Wildlife Authority). Within this reserve, a 1.024 km × 1.024 km site was selected for this study.

Fig. 1 shows the aerial photographs and GeoEye satellite images of the study site.

The mean annual rainfall at Lake Chivero Game Reserve is 829 mm (Zimbabwe Meteorological Services Department). The precipitation regime is highly variable in both space and time. The predominant vegetation in Lake Chivero Game Reserve is the miombo woodland (*Brachystegia spiciformis* and *Julbernada globiflora*) that is found in association with *Terminalia sericea,*