Available online at www.sciencedirect.com
SCIENCE DIRECT®
Remote Sensing of Environment 101 (2006) 554–566
Remote Sensing of Environment
www.elsevier.com/locate/rse

Characterization of shrub distribution using high spatial resolution remote sensing: Ecosystem implications for a former Chihuahuan Desert grassland

Ian O. McGlynn *, Gregory S. Okin [1]

Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904-4123, United States

Received 10 October 2005; received in revised form 18 January 2006; accepted 28 January 2006

Abstract

Patchiness is often considered a defining quality of ecosystems in arid and semiarid regions. The spatial distribution of vegetation patches and soil nutrients coupled with wind and water erosion as well as biotic processes are believed to have an influence on land degradation. A geostatistical measure of spatial "connectivity" is presented to directly measure the size of patches in the landscape from a raster data set. Connectivity is defined as the probability that adjacent pixels belong to the same type of patch. Connectivity allows the size distribution of erodible patches to be quantified from a remote sensing image or field measurement, or specified for the purposes of modeling.

Applied to high-resolution remote sensing imagery in the Jornada del Muerto Basin in New Mexico, the spatial distribution of plants indicates the current state of grassland-to-shrubland transition in addition to processes of degradation in this former grassland. Shrub encroachment is clearly evident from decreased intershrub patch size in coppice dunes of 27.8 m relative to shrublands of 65.2 m and grassland spacing of 118.9 m. Shrub patches remain a consistent 2–4 m diameter regardless of the development of bush encroachment. A strong SW–NE duneland orientation correlates with the prevailing wind direction and suggests a strong aeolian control of surface geomorphology.

With appropriate data sets and classification, potential applications of the connectivity method extend beyond vegetation dynamics, including mineralogy mapping, preserve planning, habitat fragmentation, pore spacing in surface hydrology, and microbial community dynamics.

Keywords: Connectivity; Spatial distribution; Shrub encroachment; Aeolian geomorphology; Desert vegetation; Chihuahuan Desert; Mesquite

1. Introduction

Shrub encroachment is a global phenomenon documented in arid and semiarid regions of Africa, Australia, and North America (Archer, 1995; Fensham et al., 2005; Roques et al., 2001). In the Chihuahuan Desert grasslands of North America, shrub encroachment has been especially pronounced, with significant transformation of vegetation community structure occurring in the last 150 years. Populations of grasses, primarily black grama (*Bouteloua eriopoda*) once dominated 90% of the region but have diminished to less than 25% (Buffington & Herbel, 1965; Gibbens et al., 2005). Drought-resistant shrub cover, primarily comprised of creosote (*Larrea tridentata*) and mesquite (*Prosopis glandulosa*), has increased by a factor of 10 over the same period, replacing the native grasses (Gibbens et al., 2005; Rango et al., 2000; Reynolds et al., 1999). Causes of shrub encroachment and grassland deterioration such as rainfall variability, elevated CO_2, changes in fire regime, seed dispersal and livestock grazing have been suggested (Archer et al., 1995; Scanlon et al., 2005), but the definitive cause of the transformation remains unknown (Archer, 1995; Bahre & Shelton, 1993; Dougill & Thomas, 2004).

The change in the spatial distribution of vegetation is an important aspect of shrub invasion. Shrubs create "islands of fertility" by trapping soil resources beneath their canopies (Schlesinger et al., 1990; Whitford, 1992). The transition from grass to shrub cover increases the scale of spatial heterogeneity and the dominant small-scale processes can be reflected through the position of individual plants (Schlesinger & Pilmanis, 1998). Thus, the ability to quantify the spatial distribution of plants could indicate the current state of

* Corresponding author. Tel.: +1 434 924 6421; fax: +1 434 982 2137.
E-mail addresses: imcglynn@virginia.edu (I.O. McGlynn), okin@virginia.edu (G.S. Okin).
[1] Tel.: +1 434 924 3324; fax: +1 434 982 2137.

0034-4257/$ - see front matter
doi:10.1016/j.rse.2006.01.016

transition in addition to processes of degradation in semiarid mixed-shrub grasslands.

Remote sensing provides an opportunity to monitor and understand spatial patterns of vegetation and to inform the understanding of biotic and abiotic processes related to those patterns. The physical and spectral properties associated with vegetation cover and surface morphologic structures observed by remote sensing are being continuously refined (Bradley & Mustard, 2005; Okin & Painter, 2004; Okin et al., 2001; Weeks et al., 1996) especially with the incorporation of spatial patterns of vegetation (Caylor et al., 2004; Okin & Gillette, 2001; Privette et al., 2004; Scholes et al., 2004).

High spatial resolution remote sensing enables direct imaging of plant individuals that are at least the size of the ground resolution of the remote sensing image. This capability makes possible demographic studies of vegetation such as Schlesinger and Gramenopoulos's (1996) use of archival photographs to show that there were not climate-induced changes in woody vegetation in the Sudan from 1943 to 1994, and with individual-based monitoring of vegetation change in the Jornada Basin (Rango et al., 2002).

The ability to image individual plants with high resolution remote sensing opens up the possibility of effective use of geostatistical methods for describing the distribution of plants. Phinn et al. (1996) and Okin and Gillette (2001) have shown that traditional variograms can provide an accurate measure of average plant spacing in shrublands of the Chihuahuan Desert. Nonetheless, variograms provide limited information about the landscape. In particular, because variograms are calculated on the basis of pairs of data separated by some distance (lag), this method cannot provide information about conditions between these pairs. In landscapes where the connectedness of soil or vegetation patches (providing conduits for wind, water, seeds, small mammals, etc.) is important, a different geostatistical metric of two-dimensional landscape structure is advisable.

A new application of geostatistical techniques is presented to evaluate the connectivity of plant and soil patches. This connectivity function calculates the probability that contiguous pixels belong to the same class, or in this application, the probability that contiguous pixels are or are not occupied by shrubs.

In this study, we present the use of connectivity to provide spatial information about patch size and anisotropy and show that the results are robust for patchy landscapes. Using an object-oriented classification on digitized orthophotos of our field site in New Mexico, individual 1 m pixels are separated into shrub and not-shrub classes. We then apply the connectivity statistic to the classified images to characterize the spatial nature of shrub encroachment and the spatial characterization of individual shrub patches. As a geostatistical measure, the use of connectivity is independent of the choice of classification scheme. The progressive nature of shrub encroachment is evaluated through the comparison of shrub and intershrub patch characteristics amongst differing areas of establishment. Specifically, we present the theory and definition of connectivity geostatistics, provide validation of connectivity based on stochastic simulation, and demonstrate the utility of connectivity using a case study to examine the variability of spatial distribution of vegetation in the Jornada Basin of New Mexico.

2. Material and experimental methods

2.1. Connectivity

We used a geostatistical measure of the connectedness of patches in the landscape called "connectivity." For a raster data set, connectivity is defined as:

$$C(\vec{h}) = \frac{1}{n}\sum_{n}\left(\prod_{\vec{h}} I_i\right) \tag{1}$$

where C is the connectivity, $\vec{h}$ is the lag vector with length $|h|$, n is the number of consecutive sets of pixels along $\vec{h}$ in an image, and I_i is an indicator variable equal to 1 for pixels that belong to the class of interest and 0 otherwise. The connectivity at $\vec{h}=0$ is denoted as C_0 and is equal to the fraction of pixels in an image that belong to the class of interest. For example, if "shrub" is the class of interest, then pixels that are classified as "shrub" are given a value of 1, and all other pixels are given a value of 0. In this case, C_0 will be equal to the fraction of pixels that are classified as "shrub", or in other words, the fractional shrub cover.

Connectivity may also be interpreted as a probability. In the case of C_0, the connectivity is the probability that any pixel in an image belongs to the class of interest. $C(\vec{h})$ is the probability that any set of consecutive pixels along $\vec{h}$ all belong to the class of interest (Fig. 1). When interpreted as probabilities, it is intuitive that connectivity always decreases with increasing lag distance, $|h|$.

In practice, the decrease in connectivity with $|h|$ approximates an exponential decay function (Fig. 2). Thus, to derive a single statistic for the spatial scale of landscape connectedness

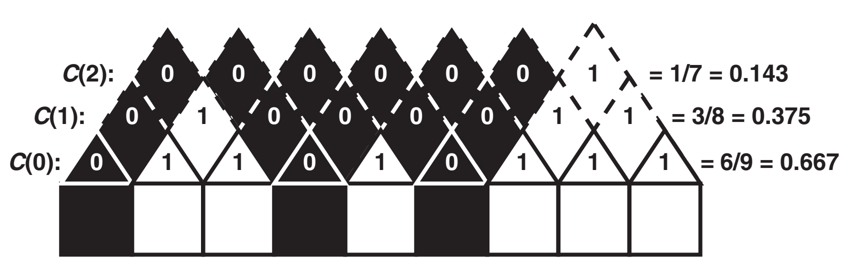

Fig. 1. Connectivity is calculated on the number of consecutive sets of pixels in an image, as 1 for pixels that belong to the class of interest and 0 otherwise with increasing lag distance, as demonstrated for 1, 2, and 3 pixel distances.