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Long and short term population dynamics of acacia trees via remote sensing and spatial analysis: Case study in the southern Negev Desert

S. Isaacson [a,*], J.E. Ephrath [b], S. Rachmilevitch [b], S. Maman [d], H. Ginat [c], D.G. Blumberg [a]

[a] *Geography and Environmental Development, Ben-Gurion University of the Negev, Beer Sheva, Israel*
[b] *French Associates Institute for Agriculture and Biotechnology of Drylands, Jacob Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sede Boker, Israel*
[c] *Dead-Sea and Arava Science Center, Israel*
[d] *Homeland Security Institute, Ben-Gurion University of the Negev, Beer Sheva, Israel*

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ABSTRACT

Monitoring vegetation dynamics in hyper-arid zones is important because any decrease in the already sparse vegetation cover in these areas could considerably affect the entire ecosystem. The new generation of high spatial resolution satellite (HSR) sensors is suitable for monitoring trees in arid regions because of the distinct and separate objects that trees represent in these environments. The main limitation of modern HSR sensors is the lack of a historical archive that would otherwise enable meaningful landscape change detection, especially in arid regions where tree population dynamics are naturally very slow. This study uses spatial analysis to gain information regarding the long- and short-term dynamic processes affecting the acacia tree population in Wadi Ktora, in the southern Arava Valley, Israel. The data is extracted from a single HSR aerial photograph composed of three spectral bands in the visible and infrared spectrum (green, red, and near infrared).

A map of individual acacia trees that is extracted from a colour infrared aerial photograph of Wadi Ktora from 2010 enables the examination of spatial distribution patterns for both tree size and foliage health. Tree size distribution is used as an indicator of long-term (decades) hydrologic spatial processes affecting the acacia population. The tree health distribution is used as an indicator for short-term (months to a few years) hydrologic spatial processes, such as the paths of recent flash floods events. Comparing the distributions of tree size and normalized difference vegetation index (NDVI) enables differentiation between the long-term and short-term processes that brought the population to its present state.

Using spatial statistic grouping, the distribution of the trees in the wadi (ephemeral stream) is divided into three distinct categories: (1) large trees with high NDVI values, (2) large trees with low NDVI values, and (3) small trees with medium NDVI values. Using the resulting classification, we divided the wadi into three sections, each representing a unique combination of long- and short-term hydrologic processes affecting the acacia trees. We suggest that the lack of spatial correlation between tree size and health status is a result of spatio-temporal changes in the water supply.

1. Introduction

Hyper-arid zones are characterized by sparse vegetation cover. Thus, monitoring the vegetation dynamics in hyper-arid zones is important because any reduction in the vegetation cover of these areas can lead to a considerable reduction in the carrying capacity of the ecological system (Saltz et al., 1999). Trees such as acacias play a significant role in desert ecosystems by moderating extreme environmental conditions. Therefore, acacia trees in arid zones are considered to be ‘keystone species’, having a major influence on the biodiversity of both plant and animal species (Munzbergova and Ward, 2002; Noy-Meir, 1973). Acacia trees are long-lived trees with an estimated average lifespan of 200 years. Older individuals aged around 300–400 years have been reported (Andersen and Krzywinski, 2007a; Chesson et al., 2004). They can even tolerate several years of drought (Andersen and Krzywinski, 2007b). The hardiness and long lifespan of these trees make them good representatives and indicators of long- and short-term climate fluctuations in desert ecosystems.

The distribution of acacia trees in Israel is influenced by water supply and temperature regimes (Halevy and Orshan, 1972). Due to low rainfall, the acacia trees in southern Israel are usually restricted to ephemeral stream beds (wadis) as these possess a higher soil moisture content than the surrounding landscape (Noy-Meir, 1973; Shmida et al., 1986). Spatial analyses of tree distribution at the drainage basin scale contributes to a better understanding of the hydrologic regime because

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* Corresponding author.
E-mail address: sivanisa@post.bgu.ac.il (S. Isaacson).

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water is the main limiting factor in such areas (Schick, 1974). That is, the spatial distribution of trees and their characteristics within the wadi may reflect the spatial variance of water availability within different segments of the wadi.

Deserts are characterized by high spatial and temporal variability in precipitation, and in turn, high spatial and temporal variation in vegetation cover (Noy-Meir, 1985, 1973). Field surveys are limited in their spatial extent and number of samples and therefore often resort to extrapolation for a more complete picture. However, spatial interpolation and extrapolation in areas with great variability, such as deserts, have low accuracy and credibility. The full coverage provided by remote sensing images is beneficial in these cases for capturing true spatial variability without the use of interpolation methods (Eisfelder et al., 2012). Images acquired by satellites and airborne imaging systems (together henceforth termed 'remote sensing images') can provide information that enables the expansion of the spatial and temporal environmental databases. At the time of this study, remote sensing images have been acquired for over 50 years and provide a powerful tool for long-term monitoring, especially in arid zones where access is limited, long-term ground data are rarely available (Dall'Olmo and Karnieli, 2002; Tueller, 1987), and population dynamics (e.g., rare recruitments events, tree growth and decomposition of dead trees) are extremely slow (Martin, 2000; Shmida et al., 1986). Nevertheless, remote sensing studies in arid environments have been criticized for focusing mainly on biomass density changes rather than more detailed changes in vegetation structure (i.e., biodiversity) and population dynamics (Ward, 2009).

Most studies on desertification have been performed on global to regional scales and at low (250–1000 m) to medium (30–100 m) spatial resolutions (Eisfelder et al., 2012). However, because of the mixed pixel effect, local information can be lost, especially in arid regions where spatial heterogeneity is high and vegetation distribution is typically sparse (Alsharrah et al., 2015). To detect individual trees and monitor changes in a sparsely distributed tree population, high spatial resolution imagery is essential. Panchromatic, high resolution aerial photos and satellite images have been used in various studies of acacia trees in hyper-arid regions (Andersen, 2006; Andersen and Krzywinski, 2007a; BenDavid-Novak and Schick, 1997; Lahav-Ginott et al., 2001).

The new generation of multi-spectral, high spatial resolution (HSR) sensors have enabled a new approach to image classification: object-based image analysis. This approach is particularly suitable to trees in arid regions because of the distinct and separate objects that trees represent there (Chávez and Clevers, 2012). HSR images with NIR band have great potential for monitoring trees in arid environment studies (Chávez et al., 2013; Moustakas et al., 2006; van Coillie et al., 2016). However, the main limitation of the new generation HSR sensors such as IKONOS, QuickBird2, GeoEye-1, and WorldView-2 is the absence of a historical archive that would otherwise enable detection of meaningful change over time, especially in arid regions, which have a very slow natural dynamic rate.

A new technique is proposed in this study to overcome the lack of HSR historical archives and long-term monitoring in arid regions. By using spatial analysis tools, we extract historical eco-hydrological insights from one contemporary Colour Infrared (CIR; green, red and NIR) image. This approach enables us to expand the time scope of field monitoring and reveals the spatial and temporal changes of tree populations in arid regions. The CIR image enables us to extract information about photosynthetically active biomass that is often quantified or indexed through vegetation indices such as normalized difference vegetation index (NDVI) (Pettorelli et al., 2005; Tucker, 1979).

The main goal of this research was to study both the long-term and short-term spatial processes affecting the acacia population within different segments of the wadi by delineating the spatial distribution of different parameters of acacia trees within a single CIR aerial photograph.

2. Rationale

The response time of plants to a change in water supply varies significantly between different functional types in arid lands (Williamson et al., 2012). This difference has been used in various studies to identify long-term changes in the ecosystem, mainly the transition between shrubland and grassland dominance (Peters et al., 2012; Williamson et al., 2012). Rather than the comparison between two functional types, we suggest a comparison of two different tree attributes that differ in their response times to water supply: (1) tree size and (2) tree foliage health status as measured by NDVI. These attributes are used in this study as indicators of water availability over the long term and short term, respectively.

1) Tree size (canopy area) – A long-term indicator of the water supply regime. Field monitoring conducted previously in the research site during 2000–2010 revealed that acacia trees of all sizes can remain the same size (as measured by trunk circumference) or even shrink over the period of a decade when limited amounts of water are available (Isaacson, 2011). Since water is the limiting factor in these ecosystems, acacia tree size is therefore primarily associated with age and water supply. Therefore, considering the longevity and slow growth rate of these trees, we consider tree size as an accumulated indicator of long-term (decades-scale) hydrological processes. It should be noted, that in Israel, human influences on trees such as pollarding, pruning and livestock browsing is not common and hence do not affect canopy size (Ashkenazi, 1995).
2) NDVI – A short-term indicator of the water supply regime. NDVI is widely used in ecological remote sensing studies to estimate photosynthetically active biomass, i.e. green biomass (as reviewed in Pettorelli et al., 2005). Green biomass, in contrast to tree size, has a much faster response to changes in the water supply, as reflected by greenness values such as the NDVI (Heumann et al., 2007; Vicente-Serrano et al., 2013). This response to water is prominent for most desert plants in arid ecosystem where water is the limiting factor (Noy-Meir, 1973). For long-lived trees, like the acacia, that experience summer leaf defoliation, we assume that the physiological status of the leaves reflects water availability within the scope of a month to a few years.

3. Data and methods

3.1. Study area and remote sensing data

The study area is located in the Southern Arava Rift Valley, Israel, located about 20 km north of the Gulf of Eilat. Rain events in this hyper-arid region are rare and flash floods may occur once every few years. The mean accumulated annual rainfall for the area is 30 mm but varies significantly both in time and space (Goldreich and Karni, 2001). A clear decrease in the accumulated annual precipitation in this area has been recorded since 1995 (Ginat et al., 2011). This decline has resulted in the decrease in the number of flash flood events to nearly zero and, consequently, has led to a reduction of water availability to perennial plants along the wadis. This sequence of dry years was broken with a regional flood event in January 2010.

During March 2010, two months after the flood event, a CIR aerial photograph was acquired with a 0.1-m spatial resolution. The image contained three spectral bands: green, red and NIR. The Wadi Ktora is an ephemeral riverbed incised in alluvium in the southern Arava Valley (Fig. 1). Its drainage basin covers a total area of 25 km^2. The aerial photograph covers 1.5 km^2 of the downstream portion of the drainage basin. This section of the wadi includes a channel with braided-type morphology, i.e., a network of small channels separated by small islands. The flow direction of the main channel is north-west to south-east. The channel is narrow in the northern part of the study area (area I, Fig. 1); the main channel of flow is located in the north and north-east part of the wadi (area I and II, Fig. 1). This channel is