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Assessing desertification risk in the semi-arid highlands of central Mexico

Rocio Becerril-Piña [a], Carlos Alberto Mastachi-Loza [a, *], Enrique González-Sosa [b], Carlos Díaz-Delgado [a], Khalidou M. Bâ [a]

[a] Centro Interamericano de Recursos del Agua, Facultad de Ingeniería, Universidad Autónoma del Estado de México, C.U. Cerro de Coatepec, C.P. 50110, Toluca, Mexico
[b] Facultad de Ingeniería, Universidad Autónoma de Querétaro, C.U. Cerro de las Campanas, C.P. 76010, Querétaro, Mexico

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ABSTRACT

This study presents the integration of a set of indices representing four desertification factors: vegetation, soil, climate and anthropic disruptors. The Desertification Trend Risk Index (DTRI) adds the mean slope of each factor in a time series, thereby classifying the risk of desertification according to four categories: low, medium, high and extreme. This index is based on Landsat images and population data from 1993 to 2011, as well as climatological data from 1980 to 2010. An analysis using a combination matrix is also presented to identify the driving forces in each category. In addition, a change vector analysis (CVA) is performed to evaluate changes in land use in the semi-arid highlands of central Mexico. The results show that the semi-arid areas of the municipalities of Querétaro, Santa Catarina, Corregidora, Apaseo el Alto and Celaya represent extreme alert regions. In general, anthropic activities such as changes in land use and deforestation are the primary driving forces in the desertification process in the region. Based on the results of this study, the use of the DTRI is recommended as a low-cost and easily applied tool to assess and monitor desertification.

1. Introduction

Strategies to evaluate desertification have evolved along with the concept itself. And several debates have occurred about whether human activities or climate variability cause this phenomenon, until arriving at an understanding that it is the result of a synergic effect (Ibáñez et al., 2008). Desertification is land degradation (soil, vegetation and groundwater) in arid, semi-arid and dry sub-humid regions due to a variety of factors, particularly climatic variations and human activities (UNCCD, 1994). It leads to a reduction or loss in economic productivity and in the complexity of the earth's ecosystems—including soil, vegetation and other biotic components—and affects ecological, bio-geochemical and hydrological processes (Reynolds et al., 2005).

Dry lands cover about 30% of the earth's surface and over 250 million persons are thought to be directly affected by the desertification process (Reynolds et al., 2007). Approximately 65% of the land in Mexico is dry (xeric, hyper-arid, arid, semi-arid and sub-humid) (UNESCO, 2010), and is home to 30% of the country's population. According to data from SEMARNAT-CP (2003), 45% of the soil is undergoing some type of degradation, primarily due to changes in land use related to agriculture, over-grazing and urbanization.

The interaction of direct and indirect factors such as climate, characteristics of the soil, vegetation cover, socioeconomic conditions (Helldén and Tottrup, 2008) and a system's susceptibility to desertification contribute to the risk and vulnerability to this phenomenon. The analysis of desertification is multidisciplinary, involving scientific and political approaches that have made it possible to develop different methods based primarily on indicators. The OECD (2003) defines an indicator as a parameter, or a value derived from parameters, that provides information and describes the state of a phenomenon. A parameter is considered a property that is measured or observed. Several proposals have been developed in recent years to measure risk and vulnerability based on a set of indicators and indices (Birkmann, 2006). Nevertheless, given the availability of data and the technical knowledge of each

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* Corresponding author.
E-mail addresses: rocio111mx@yahoo.com.mx (R. Becerril-Piña), mastachii@hotmail.com (C.A. Mastachi-Loza), egs@uaq.mx (E. González-Sosa), cdiazd@uaemex.mx (C. Díaz-Delgado), khalidou@uaemex.mx (K.M. Bâ).

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country, a group of universal or minimum desertification indicators cannot be defined (Enne and Zucca, 2000).

2. Evaluation of desertification

Many studies have been limited to the application of statistical indicators, nonetheless these approaches are not sufficient to analyze a dynamic phenomenon such as desertification. Other researchers have focused on the analysis of the spatial–temporal evolution of environmental and socioeconomic components (Santini et al., 2010). For example, remote sensing is an efficient technique in terms of time and cost and has become a valuable tool to monitor surface processes, with great potential for the evaluation of desertification (Collado et al., 2002; Qi et al., 2012). In addition, combating desertification requires the ongoing monitoring of vulnerable areas in order to understand the desertification process (Huang and Siegert, 2006). Several authors (Ghosh, 1993; Dawelbait and Morari, 2012) have demonstrated the feasibility and potential of using high-resolution satellite data such as Landsat TM to analyze the desertification process. One of the most important environmental applications of remote sensing is the calculation of vegetation indices based on a combination of red and infrared spectral bands that highlight areas with more vegetation cover over those with bare soil. Although certain indices reflecting changes in vegetation cover are used as a direct indicator of the degradation of the land, evaluations based on growth and changes in vegetation are not very feasible due to the characteristics of vegetation in semi-arid ecosystems (Yang et al., 2005). In terms of soil properties, the desertification process is often determined by a physicochemical sampling of soil, a method that requires several samplings in order analyze the process spatially and temporally, which is not always possible. Meanwhile, some spectral indices have been able to detect changes in the physical structure of the topsoil (Xiao et al., 2006).

Desertification has always been closely associated with arid conditions, which are expressed as a function of precipitation and temperature. One of the most used climatic indices is the Aridity Index (AI), which is based on the P/ET$_0$ ratio (where P is precipitation and ET$_0$ is reference evapotranspiration). This index is considered to be an indicator of hydric availability (UNEP, 1992), for which a region with an AI less than 0.65 is considered dry land. On the other hand, climatic variability is not the only factor driving land degradation processes. It is therefore important to consider anthropic effects for example, by using the spatial distribution of a population, assuming that human activities and their growth as well as population distributions are significant factors involved in desertification (Salvati and Bajocco, 2011; Qi et al., 2012).

In spite of the importance of this phenomenon, few studies exist to characterize, evaluate and monitor desertification in Mexico. Thus, an imminent need exists to analyze this process on the spatial–temporal scale in order to identify critical areas and levels of desertification. Therefore, the objectives of this study were to: 1) determine the rate of land cover changes, 2) integrate indices through a trends analysis based on climatological and population data and 3) identify areas at risk of desertification and the driving forces in the study area.

3. Study area

This study focused on the semi-arid region of Mexico because of its large manufacturing industry and significant contribution to the economic activity and Gross National Product of the country. It is also one of the most densely populated regions nationwide. The study also considers that four of the most serious problems facing humanity converge in dry lands: availability of water, migration, food insecurity and degradation (Díaz-Padilla et al., 2011). The following aspects were taken into account to delimit the study region: 1) location of the bio-geographic province of the highlands (CONABIO, 1997), which is a classification scheme used as a standard for planning and preserving the biological diversity of the country; 2) distribution of the semi-arid climate under the Köppen climate classification modified by García & CONABIO (1998), defined by the historical monthly average temperatures and the historical monthly average rainfall; and 3) distribution of the semi-arid hydric regime, which is in function of the annual average water deficit and the wet period length. The latter was based on the UNESCO (2010) document that mapped arid, semi-arid and sub-humid regions in Latin America and the Caribbean, which is used as a common indicator to characterize the availability of water resources according to a climatic perspective.

The semi-arid highlands of central Mexico is located in the north-central region of the country. It has a semi-arid climate with a mean annual precipitation of 400–800 mm, a mean annual temperature of 25 °C and a mean elevation of 2059 masl. It includes portions of the states of Aguascalientes, Jalisco, Guanajuato and Querétaro (102°29′ to 99°16′W and 22°16′ to 20°16′N) with an approximate area of 23,401 km^2 and a population of 4,007,632 inhabitants (INEGI, 2010). Large urban and agro-industrial populations are located in this region, such as the City of Querétaro, Aguascalientes, Lagos de Moreno, San Juan del Río, Celaya, and Dolores Hidalgo, among others. A supervised classification performed with Landsat TM images from the year 2011 determined that 48.8% of the area was grass–shrub, 30% seasonal crops, 9.8% irrigation, 6.9% urban zones and 0.3% water bodies. The most common vegetation was xerophile, including grass, mesquite (*Prosopis* sp.) and huisache (*Acacia* sp.), among others (Mastachi-Loza et al., 2010). Oak and pine forests (4.2%) were also present, primarily in the regions with higher elevations (Fig. 1).

4. Materials and methods

The methodology to evaluate the risk of desertification was based on a spatial–temporal analysis of indicators captured by desertification trend risk maps. Fig. 2 indicates the aims of this study, which were to 1) evaluate the intensity of changes in the land using a vector change analysis (VCA) and 2) construct a desertification trend risk index by integrating vegetation, soil, climate and anthropic indices.

4.1. Image processing and data generation

Landsat TM images (http://earthexplorer.usgs.gov) were used to build three mosaics for the years 1993, 2000 and 2011 using five scenes (path/row 27/45, 27/46, 28/45, 28/46 and 29/45) (Fig. 1) with a spatial resolution of 30 m. Dry months (November–March) were analyzed in order to take advantage of low cloud cover and minimize the uncertainty of the results. The satellite information and databases were processed using the geographic information system Idrisi Selva (Clark Labs) and ArcMap (ESRI).

The preliminary treatment of the images consisted of converting digital numbers to radiance (Eq. (1)) and reflectivity (Eq. (2)) for each band (p_λ) based on the metadata of the images (Chander et al., 2009).

$$L_\lambda = \left(\left(L_{MAX_\lambda} - L_{MIN_\lambda}\right)/(Q_{calmax} - Q_{calmin})\right)(Q_{cal} - Q_{calmin}) + L_{min} \tag{1}$$