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Deserts do not advance, they are created: Land degradation and desertification in semiarid environments in the Middle Atlas, Morocco

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ABSTRACT

Semiarid Mediterranean regions are highly susceptible to desertification. This study investigated the influence of increasing anthropogenic pressure on land degradation in highly vulnerable semiarid environments in the Mediterranean region. Remote sensing imagery was used to identify changes in land cover between 1984 and 2007, which indicated a clear trend of land degradation, and that the most important features were the transformation of forest to shrubland, the conversion of shrubland to grassland, and, the degradation of grassland to bare land, the last stage of degradation. The largest amount of degraded land was in the administrative fraction that was characterized by high population and livestock numbers, as well as the large number of settlements on rangeland. Bayesian Model Averaging showed that the probability of land degradation was highest near settlements, water points, and in areas that had gentle slopes. Furthermore, landscape pattern analysis revealed a reduction in the area occupied by *Genista pseudopilosa*, and an increase in the fragmentation of patches of *Artemisia herba alba*. The land degradation, which was triggered by high livestock pressure, might be irreversible, and restoration to initial conditions impossible because of the level of degradation; essentially, in areas where the degradation has reached a very advanced stage.

1. Introduction

Land degradation is a complex phenomenon that results from a combination of potentially interacting factors (e.g., climate variations, human activities) (Le Houérou, 1984) and involves various processes including vegetation cover loss (Le Houérou, 1996; Alados et al., 2006; Vicente-Serrano et al., 2012). The international scientific community has recognized the high risk of land degradation in arid and semiarid regions because of the marked abiotic constraints, human perturbations, and overexploitation (Le Houérou, 1996; Del Barrio et al., 2016). The latter two of which can trigger the loss of vegetation cover and the productive capacity of the ecosystem in these areas (Alados et al., 2004; Vicente-Serrano et al., 2012).

Among the semiarid regions of the world, those in the western Mediterranean are highly prone to desertification because of climate variability and demographic disequilibrium, which directly and indirectly affect land degradation through associated changes in land use (Le Houérou, 1996; Alados et al., 2011; Puigdefàbregas and Mendizabal, 1998).

In the semiarid rangelands of the Maghreb, livestock grazing is one of the main economic activities, both in terms of the number of individuals employed and its distribution throughout the region (Slimani et al., 2010). Those semiarid rangelands cover approximately 385 km^2 and represent 25% of the region's productive food raising area (Le Houérou, 1993; Abaab, 1994). More than one quarter of the region's population derive their livelihood directly from the rangeland-based activities of mixed farming and herding (Le Houérou, 1993). In precolonial times, populations in settlements and nomadic people built a complex network of relationships, which had positive and negative effects on ecosystems, but with a positive balance for the stability of the entire region (Del Barrio et al., 2016). Since they gained independence from colonial rule, however, the Maghreb countries have undergone substantial changes after exposure to new socioeconomic forces that have reshaped the landscape (Del Barrio et al., 2016). The most significant are a dramatic increase in population, the technological intensification of agriculture, and the progressive sedentarization of nomads (Del Barrio et al., 2016; Aidoud et al., 1998; Alados et al., 2006). The environmental impacts include the degradation of steppes and rangelands because of livestock overgrazing and the encroachment by agriculture on steppes and rangelands to meet the needs of growing

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populations (Puigdefàbregas and Mendizabal, 1998; Del Barrio et al., 2016).

In Morocco's Middle Atlas Mountains, livestock grazing has been the dominant traditional activity in relatively sustainable conditions for several centuries (Artz et al., 1986). Traditionally, this activity relied on the customary law developed by the people living in these areas (Ben Chrifa and Johnson, 1990; El Aich and Waterhouse, 1999). Grazing was managed by a tribe council "Jmaa", which selected a chief of grass, "Almghar N'Tuga", to make final decisions on the use of common grazing lands and on all other grazing matters such as transhumance and the deferred grazing of an area "Agdal" (Artz et al., 1986; Bernhard, 2002). After the independence, however, changes in administrative policies and socioeconomic conditions affected negatively the pastoral system in the Middle Atlas (Appendix; Ben Chrifa and Johnson, 1990; Swearingen and Ben Chrifa, 1996). Continuous human population growth and the increasing livestock numbers have led to forceful sedentarization of nomads in the rangelands and increased demand for agricultural land. Further increases in human pressure might lead to irreversible changes in the area, with restoration to initial conditions impossible because of the level of land degradation (Le Houérou, 2001, 2006; Alados et al., 2011).

It can be difficult to assess the land degradation process because broad temporal and spatial perspectives are necessary for an accurate assessment of the magnitude of the process (Vicente-Serrano et al., 2012). In that respect, remote sensing might be the most appropriate method because satellite images can provide spatially distributed quantitative and objective data (Hammi et al., 2010; Vicente-Serrano et al., 2012). In particular, Landsat imagery can be used to identify processes with the appropriate degree of detail (Vicente-Serrano et al., 2012). Moderately high spatial resolution and multi-spectral bands make those data suitable for detecting changes in land cover at reasonable scale (Cohen and Goward, 2004; Vicente-Serrano et al., 2012).

Recent studies in the Sahel (Hein and de Ridder, 2006; Prince et al., 2007), Patagonia (Jobbagy et al., 2002), Spain (Valderrama et al., 2016), and Inner Mongolia (Bai et al., 2008) have used satellite imagery as input data to quantify land degradation; however, few studies have used satellite images to assess land degradation processes in arid or semiarid environments in the Maghreb (but see Hanafi and Jauffret, 2008; Hirche et al., 2011; Del Barrio et al., 2016). The objectives of this study were to identify recent land degradation and to quantify the magnitude and spatial variability of the degradation in the semiarid environments of the Middle Atlas, Morocco. In addition, we investigated whether an increase in grazing pressure was a significant factor in the overall development and the spatial patterns of land degradation in the region. The findings of this study can provide guidance for other semiarid and arid regions and can be used to inform decisions on land management and restoration.

2. Material and methods

2.1. Study area

The study area was in Timahdite, a rural municipality in Morocco's Middle Atlas that has four administrative fractions: Ait Ben Hcine, Ait Ben Yakoub, Ait Hcine ou Hand, and Ait M'hamed (Fig. 1).

In the area, elevation ranges between 1500 and 2450 m, and the climate is semiarid, with hot summers (August mean high = 31 °C) and cold winters (January mean low = −3 °C). The annual average rainfall is 695 mm; most of it occurring in spring and winter (Climate data for cities worldwide; www.climate-data.org).

The study area included state-owned forests, privately owned fields that produced winter wheat and barley, and collective grazing lands that supported several grass and shrub complexes. Types of land cover included natural forests of cedar (*Cedrus libanotica* ssp. *atlantica*) and green oak (*Quercus ilex*), shrublands (*Juniperus thurifera*, *Genista pseudopilosa*, *Artemisia herba helba*, *Bupleurum spinosum*), grasslands (which were dominated by *Festuca ovina*, *Poa bulbosa, Carex* sp., *Euphorbia* sp. and *Ononis* sp.), wetlands, and arable farmlands.

Livestock farming, especially sheep herding, has been the most important economic activity in the area. Traditionally, it was regulated by the collective management system of rangelands (Agdal) and double transhumance (i.e., sheep pasture in the highlands in summer and overwinter in the lowlands); however, increases in human and livestock populations since the 1970's have increased the number of sedentarized herders on the grazing lands, which has led to the abandonment of double transhumance. Today, sheep farming based on sylvo-pastoral resources remained the main agricultural activity.

2.2. Image classification and land cover dataset

The analysis was based on four cloud-free Landsat-5 Thematic Mapper images derived from the U.S. Geological Survey (USGS). The images were taken in early and late summer in 1984 and 2007 (i.e., 8 Jun and 27 Aug 1984; 31 May and 27 Aug 2007) at a spatial resolution of 30 m, and were used to produce land cover maps for 1984 and 2007. The use of multi-date imagery allowed vegetation phenological information to be included, which can improve the classification (Brandt et al., 2013; Gartzia et al., 2014). The atmospheric and topographic corrections were based on ARCTOR 3 algorithms implemented in the ATCOR software (http://www.rese.ch/products/atcor/atcor3/). Following Gartzia et al. (2013), we used 21 layers for the supervised classification: The six bands of the reflective spectrum (except the thermal band) of early- and late-summer images, Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), and five topographical features (elevation, slope, north-south aspect, east-west aspect, insolation) that were derived from the 30-m resolution digital elevation model obtained from the ASTER Global Digital Elevation Map (http://asterweb.jpl.nasa.gov/gdem.asp). More than 1000 training samples were used to define land cover classes in the field, which were used in the non-parametric random forest (RF) classifier (for more details on the supervised classification, see Gartzia et al., 2014). RFs have been used to detect and classify land cover elsewhere (e.g., Gartzia et al., 2014). Those classifiers offer advantages over traditional classifiers; particularly they do not overfit the data (Gartzia et al., 2014).

The land cover maps (Fig. 2) included nine categories: dense forest (canopy density of ≥70%), sparse forest (canopy density < 70%), xerophytic shrubland, shrubland dominated by *Genista pseudopilosa*, shrubland dominated by *Artemisia herba alba*, grassland dominated by herbaceous vegetation, wetland, and bare land.

The accuracy of the classified map for 2007 was tested using another 1000 randomly selected pixels and Cohen's Kappa Index of Agreement was calculated. After confirming the accuracy (Cohen's Kappa = 0.94) of the supervised classification of the 2007 land cover map, the 1984 imagery was classified based on the random forest parameters derived from the supervised classification of the 2007 land cover map.

2.3. Quantifying land degradation

To create a map of changes in land cover classes, the maps for 1984 and 2007 were overlaid. The map of changes was summarized by calculating change rates (probabilities of change), which were calculated using the following formula:

$$P_{ij} = A_{j2007}/A_{i1984}$$

where P_{ij} is the probability that a section changes from class i to class j, A_{j2007} is the area of the class j in 2007 that was i in 1984, and A_{i1984} is the area of the class i in 1984.

Our primary focus was to quantify land degradation; therefore, we considered only the following types of change: (1) i = {dense forests}