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Research article

Markov chains and cellular automata to predict environments subject to desertification

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ABSTRACT

The foremost objective of this study was to analyze the performance of a Markov chain/cellular automata model for predicting land use/land cover changes in environments predisposed to desertification. The study area is the Vieira river basin, located in Montes Claros (MG, Brazil). Land use/land cover prognosis was performed for the year 2005 so that this result could be compared with the ranked image for the same year, taken as ground truth. Kappa indices were used to evaluate the change level that occurred between these two cases. Results from cellular automata were evaluated from those of the Markov chain model. The latter proved to be efficient in the quantitative prediction of changes in land use/land cover. Regarding the cellular automata, an average performance was noted in the spatial distribution of classes. Specifically, with regard to desertification, the use of the CA-Markov model was effective at estimating the total area of the most susceptible class to this process, Bare Soil; however, it was inefficient in its spatialization. Even with the caveats related to the performance of cellular automata, the overall prediction capacity of CA-Markov models can be considered as good.

1. Introduction

Desertification is a process of land degradation, limited to dry regions. Its possible incidence is restricted to arid, semiarid, or dry subhumid areas. Among several factors considered as causes of desertification, climate change and anthropic activities are highlighted (Brasil, 1998). Recognized as one of the main causes of desertification, several human practices have exceeded the productive land capacity, characterized by inappropriate soil management, including grazing, erosion, salinization, continuous use of fire, extractivism, mining, and deforestation (Adamo and Crews-Meyer, 2006; D'Angelo et al., 2000; Huang et al., 2009; Mabbutt, 1992; McClure, 1998; Rhodes, 1991; Santini et al., 2010).

Desertification affects over 100 countries and is present on all continents, especially in arid and semiarid regions that occupy approximately one-third of the land surface and are subject to the occurrence of this process. It is worth mentioning that one-sixth of the world's population lives in these areas (Matallo Jr, 2001). Despite these alarming numbers, there is a surprising lack of consensus on the appropriate form of evaluating desertification (Verón et al., 2006).

Owing to the intrinsically spatial nature, studies on desertification have benefited directly from recent advancements in the areas of remote sensing and geographical information systems (GIS). Using these techniques, the CA-Markov model combines the Markov chain and cellular automata (CA), where the probabilities of possible land use changes supplied by a Markov chain are spatialized by CA. Several authors studied desertification employing the CA-Markov model and considered this model as viable and efficient in predicting trends concerning the behavior of this land degradation process (Huo-ping et al., 2009; Lu et al., 2009; Muller and Middleton, 1994; Wu et al., 2010). Recent studies highlight that the association between Markov chain and cellular automata makes it possible to predict the probability of trends in land use evolution, such as the phenomenon of desertification (Jiang and Lin, 2018; Joseph et al., 2018; Varghese and Singh, 2016; Xu et al.,

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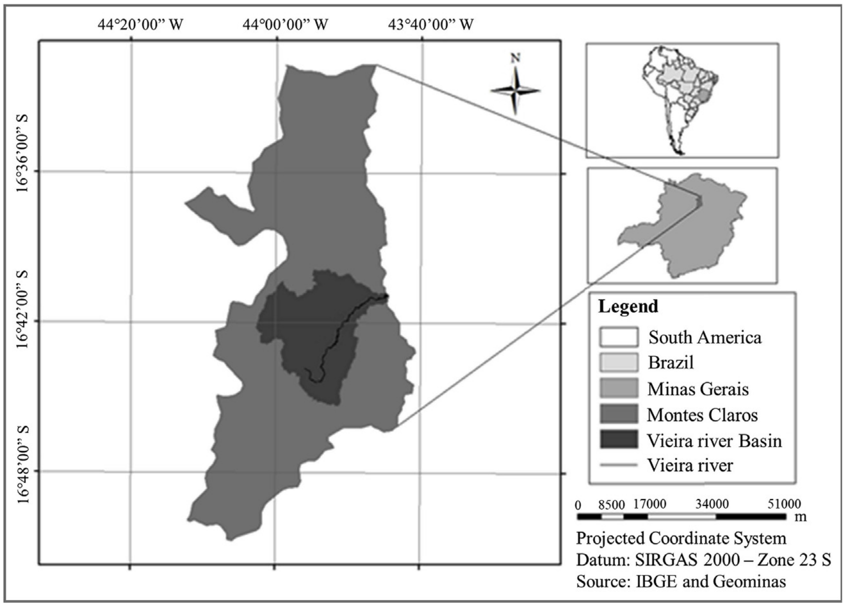

Fig. 1. Location of vieira river basin in Montes Claros (MG, Brazil).

2016, 2014).

Given the climatic delimitation of Brazil, the northeast region and the north of Minas Gerais state are considered susceptible to desertification. These are the semiarid and dry sub-humid areas of the country; therefore, they are prone to the occurrence of this degradation process (Brasil, 2005, 1998). Hence, the foremost objective of this study was to analyze the performance of a CA-Markov model for predicting land use/land cover changes in environments predisposed to desertification.

2. Material and methods

2.1. Study area

The Vieira river basin is located in the municipality of Montes Claros in the northern region of Minas Gerais state, Brazil. The study area covers approximately 580 km^2 and is located at 43° 54′ 38″ longitude and 16° 32′ 52" latitude (Fig. 1).

The climatic ranking of integrating municipalities of dry sub-humid areas in the country includes the municipality of Montes Claros; consequently, according to the desertification concept, this municipality is also considered susceptible to the occurrence of this process (Brasil, 1998, 2010).

The adopted methodological processes are shown in the flowchart (Fig. 2) and described below.

2.2. Study area delimitation

The Vieira river basin was delimited using ArcGis® software, from a dataset (1° × 1°) of the Shuttle Radar Topography Mission (SRTM) base (NASA, 2009). To eliminate existing spurious depressions in these datasets, we used the *Fill* command. Next, we applied the *Flow direction* command to the filled out digital elevation model (DEM) to obtain the drainage direction for each cell. Then, the *Flow Accumulation* command was used to determine the flow accumulated, which corresponds to the number of cells situated upstream of a certain cell. Finally, the Vieira river basin was delimited by employing the *Watershed* command, from an interactively defined point, corresponding to the place in which the Vieira river flows into the Verde Grande river. All these tools are in the ArcToolbox, *Spatial Analyst* option, in the *Hydrology* set of ArcGis® software.

2.3. Land use and occupation

To determine the land use/land cover of the Vieira river basin, we selected two images from the LANDSAT-5 satellite, TM sensor, and orbit/point 218/72 (NASA Landsat Program, 2012). Dated September 9, 1995, September 22, 2000, and July 18, 2005, these images have 30 m cells.

Bands 3, 4, and 5 were used for RGB composition of images. These bands, which originally had geographical coordinates and World Geodetic System (WGS-84) datum, were then projected to the Universal Transverse Mercator (UTM) coordinate system, Zone 23 S, and horizontal datum SIRGAS 2000.

For co-registration of images, another image from the LANDSAT-5 satellite, orthorectified, from June 26, 1997, was also adopted for same scene. This orthorectified image presented better quality georeferencing when compared with the others and was taken as a reference to adjust the other four images. Similar to the other images, bands 3, 4, and 5, RGB composition, and UTM coordinates system, datum SIRGAS 2000, and Zone 23 S were also used. The tool used for co-registration was *Georeferencing* in ArcGis®.

Next, the Vieira river basin was extracted from LANDSAT compositions and used as a mask, using the *Extract by Mask* tool of ArcToolbox. These new images were then submitted to a supervised classification. Using the toolbar *Image classification*, training samples were collected in each previously determined class: Urban Area, Forest, Cropland/Pasture, and Bare Soil. Note that for Forest, we considered natural vegetation and eucalyptus culture areas. Maximum likelihood estimation was adopted for the supervised ranking, which performs a pixel-by-pixel ranking at a 5% probability level.

Two other maps were adopted as reference for the ranking. The first is in the study carried out by Leite et al. (2011), where a land use map was prepared for the same area of the Vieira river basin. The second was the native land cover and reforestation mapping carried out in 2005 by the State Institute of Forests (IEF, MG) in partnership with the Federal University of Lavras (UFLA) (Scolforo and Carvalho, 2006).

The accuracy of rankings was evaluated by Kappa index, using training samples, in ArcGIS®. Kappa can be qualitatively evaluated according to the ranking proposed by Landis and Koch (1977), where a Kappa coefficient lower than 0.00 is considered awful quality, 0.01–0.20 is considered bad, 0.21–0.40 is considered reasonable, 0.41–0.60 is considered good, 0.61–0.80 is considered very good, and