Environmental Modelling & Software 40 (2013) 51–64

Contents lists available at SciVerse ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Connotative land degradation mapping: A knowledge-based approach to land degradation assessment

Luis A. Bojórquez-Tapia [a,*], Gustavo M. Cruz-Bello [a], Laura Luna-González [b]

[a] Laboratorio Nacional de Ciencias de la Sostenibilidad, Instituto de Ecología, Ciudad Universitaria, UNAM, Apartado Postal 70275, 04510 México, Distrito Federal, Mexico
[b] Instituto de Geología, UNAM, Circuito Exterior, CU, 04510 México DF, Mexico

A R T I C L E I N F O

Article history:
Received 18 April 2011
Received in revised form
13 July 2012
Accepted 15 July 2012
Available online 27 August 2012

Keywords:
GIS-MCDA
ANP
Fuzzy pattern recognition
Geo-visualization
Land degradation
Mexico

A B S T R A C T

Land degradation mapping is a problem-solving task that aims to provide information for allocating budgets and materials to counter the deterioration of land resources. Typically, it entails the implementation of a set of indicators in a GIS to appraise the severity of land degradation across a territory. Nevertheless, the selection of these indicators has proved to be challenging in practice and often this selection reflects one particular and thus limited perspective of land degradation. Because land degradation is intrinsically complex and involves decisions by many agencies and individuals, land degradation mapping should be used as a learning tool through which managers, experts and stakeholders can re-examine their views within a wider semantic context. In this paper, we introduce an analytical framework, called Connotative Land Degradation Mapping, which aims to depict the meaning of a multiplicity of interacting drivers and effects The CLDM entails the implementation of (1) geographic information systems and multicriteria decision analysis (GIS-MCDA), and (2) geo-visualization. The approach is illustrated through a case study of two urban watersheds in central Mexico. Results showed that the main land degradation drivers in the study area were related to natural processes, which were exacerbated by human activities. The output of the CLDM enabled a better communication of the land degradation issues and concerns in a way relevant for policymakers.

1. Introduction

Land degradation has been defined as a natural or human-related process that transforms land resources to undesirable states (Stocking and Murnaghan, 2000; Zuquette et al., 2004). That is, the quality and productivity of the land decline to a point that no longer can sustain ecological and economic functions (Choudhury and Jansen, 1998; Eswaran et al., 2001; Gregorich et al., 2001; Hill et al., 2005; Lal, 2002). In extreme conditions, land degradation cannot be reversed under the prevailing socioeconomic and technological conditions (Little, 1994). Examples of land degradation are loss of soil fertility, erosion, increment of flood incidence, desertification, soil salinization, soil compaction, and removal of vegetation (Birch-Thomsen et al., 2001; Dale et al., 2005; Rozelle et al., 1997).

Mapping land degradation entails the implementation of an analytical geo-spatial model to appraise and categorize the severity of land degradation across a territory. One key purpose of these maps is to enable agencies to optimally allocate budgets and materials to counter the deterioration of land resources. Typically, results show the diverse degradation hazards as homogeneous spatial units that are derived from the synthesis of the proper indicators. From a geo-computational perspective, the combination of geographic information systems and multicriteria decision analysis (GIS-MCDA) has proved useful in land degradation mapping (e.g., Dragan et al., 2003; Qi and Altinakar, 2010).

The complexity of land degradation in a region is however difficult to grasp, let alone to map. In theory, indicators of land degradation provide a comprehensive and consistent picture about the processes that affect the land's intrinsic properties. Couclelis and Gottsegen (1997) argue nevertheless that "people read meaning into maps that go beyond the literal identification of the entities and relations represented." That is, map reading is not only re-constructing a purportedly objective geographic context, but rather a nontrivial cognitive task in which different readers may interpret the same map differently, depending on their skills and backgrounds.

Much of the debate around the notion of land degradation, centers over the connotation, rather than the denotation, assigned

* Corresponding author. Tel.: +52 55 5622 9002; fax: +52 55 5616 1976.
E-mail addresses: luis@multicriteria.org, bojorquez@ecologia.unam.mx (L.A. Bojórquez-Tapia).

1364-8152/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envsoft.2012.07.009

by different groups of people to certain contested geographic entities. In actual practice, the attributes selected as inputs for land degradation indicators largely determine the way in which geographic entities are represented and interpreted (Deng and Wilson, 2006). Consequently, concepts such as land degradation are highly polysemous because they are based upon notions of "quality" and "productivity" which are inescapably embedded within cultural and economic value judgments (Warren, 2002a),

Accordingly, it is not enough for policymaking to delineate a *bona fide* geographical entity, such as a physiographic land unit, because its true meaning arises by its *fiat* representation as, for example, "pristine habitat at risk," "natural hazard" or "severe land degradation." Such fiat representations depend upon whether the map users are conservationists, emergency services, or farmers. Importantly, fiat representations may lead to legally binding issues if maps are interpreted by some authorities Hence, the incorporation of such fiat representations into a land degradation map that is useful for policymaking and planning requires the implementation of an analytical approach capable of synthesizing different subjective or experiential understanding of nonexperts (e.g., policymakers, managers, etc.) along with scientific knowledge about land degradation drivers and processes.

One key challenge in mapping land degradation is therefore how to depict the meaning of a multiplicity of interacting drivers and effects. These include geomorphologic (e.g., mass movement, flooding), pedologic (e.g., wind and water erosion), and socioeconomic (e.g., land cover change, subsidence induced by groundwater extraction) processes that affect the land's intrinsic properties. Following Couclelis and Gottsegen (1997), we posit that eliciting this meaning requires the implementation of a "connotative land degradation mapping" approach or CLDM. That is, a formal evaluation of both the connotation (semantic context) of geographic entities and the denotation (definition and delimitation) of geographic entities in terms of the severity of the decline of land resources' quality and productivity.

In this paper, we present the CLDM as was implemented to depict priority areas in terms of land degradation in two urban watersheds in central Mexico. The overall approach entailed the development and implementation of geographic visualization – or geo-visualization. One major advantage of geo-visualization is its capacity for engaging map users (either experts or lay persons) in identifying the mapping output that denotes or conveys the most meaningful spatial representation of geographic phenomena (Blaser et al., 2000; Couclelis and Gottsegen, 1997; Hallisey, 2005; Vitek et al., 1996). From a computational perspective, the CLDM entailed the implementation of a what is technically known as site search analysis (see Malczewski, 2004, 2006) to enable a group of experts and managers (1) evaluate units of observation (either pixels or polygons) in terms of the condition of a set of land degradation drivers, and (2) assign those units of observation to meaningful land degradation categories.

In the section that follows, we provide a brief overview of the geo-computational approaches and geo-visualization. Next, we introduce in detail the methodological steps of CLDM and then illustrate the approach through our case study. In the discussion and conclusions, we examine the utility of the overall approach and how CLDM enhances the ability of experts and planners to characterize a variety of complex land degradation processes into meaningful information for planning and policymaking.

2. Overview

In general, geo-computational methods in geomorphologic mapping can be divided broadly into three categories, depending on how they integrate input data from digital terrain models, spectral (remotely sensed) map layers, and ancillary information. First, physonomic methods follow the notion of "you map what you see" when delimiting landforms, and use quantitative data to complement and refine such delimitations (e.g., Bocco et al., 2001, 2005; Jabbar and Chen, 2006; López-Blanco and Villers-Ruiz, 1995; Zuquette et al., 2004). Second, numerical approaches are based upon the application of *a priory* rules to train algorithmic classifiers of landforms (e.g., Bolongaro-Crevenna et al., 2005; Drăguţ and Blashke, 2006; Moreno et al., 2005; Van Asselen and Seijmonsbergen, 2006). And third, approaches based upon artificial intelligence procedures aim at mimicking human reasoning in the delineation of landforms through techniques such as heuristic knowledge, neural networks and fuzzy pattern recognition (e.g., Bojórquez-Tapia et al., 2009; MacMillan et al., 2000, 2004; Neaupane and Piantanakulchai, 2006).

Yet, these approaches have one important shortcoming. They focus on what Couclelis and Gottsegen (1997) refer to the definition and delimitation – or denotation – , instead of the semantic – or context connotation – of geographic entities. As pointed out by Duncan (2006), these methods can be labeled as "ontologically shallow" because they fail to explicitly recognize that priorities in planning and policymaking are socially constructed and hence "issues are seen to be constantly rising and falling in prominence." Because of their limited scope, they tend to fail in policymaking whenever they are implemented within a context of the distinctly epistemological implications among stakeholders, experts, and planners, such as when there are strong differences in access or familiarity to data and technical information.

The relevance of connotation of geographic entities for planning resides not only in the vague definition of some geographic entities such as landforms (Fisher, 2000; Smith and Mark, 2003), but also in the fact that some concepts, such as land degradation, may actually encompass a family of complex processes and thus turn to be highly polysemous. Because land degradation implies a need for remedial action, it is not enough to delineate, for example, a "lacustrine plain" as a bona-fide landform. In land degradation mapping, it is also critical to depict such lacustrine plain as a fiat representation of "fragile wetland", "flood hazard" or "land reclamation area." Thus, a practical justification for depicting the connotation of geographic entities is the demand for spatial representations of land degradation processes that can be prioritized for planning and decision making. The connotation of geographic entities enables the production of land degradation maps that are purposeful spatial representations for planning and decision making.

Geo-visualization is a key tool for depicting the significant connotations associated with geographic entities and relations (Couclelis and Gottsegen, 1997). The definitive goal of visualization is to achieve a more complete understanding of geographic phenomena. It entails an iterative process of comparing observations with knowledge (Hallisey, 2005). The advantage of geo-visualization resides in its capacity to engage the powerful human information-processing abilities associated with vision in problem solving (Blaser et al., 2000; Couclelis and Gottsegen, 1997; Hallisey, 2005; Vitek et al., 1996).

Regarding land degradation, geo-visualization can be used as a tool to synthesize the inherent subjectivity about the prioritization of land resources along with quantitative data concerning specific geographic entities. The resulting geospatial displays are used not only to explore data but also to depict the nuances in meaning of concepts such as "floods," "land cover change," or "dust storms." Hence, geo-visualization enables the construction of new knowledge so that the final spatial representation effectively identifies the causal mechanism and structures that lead to the deterioration of land resources.