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Spatially-explicit sensitivity analysis for land suitability evaluation

Erqi Xu [a,b], Hongqi Zhang [a,*]

[a] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China
[b] Graduate University of Chinese Academy of Sciences, Beijing 100049, PR China

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A B S T R A C T

Land suitability evaluation (LSE) is an important step in land-use planning. Using multi-criteria decision-making (MCDM) techniques based on geographic information systems is a flexible and effective approach for this evaluation process. Implementation of sensitivity analysis to validate and calibrate the MCDM can enhance the understanding of the LSE results and assist in making informed planning decisions. The main limitation of sensitivity analysis in MCDM applications is a lack of insight into the spatial dimensions. To address this issue, this paper presents a new framework that incorporates the spatial configuration information from sensitivity analysis for MCDM. The framework consists of a land suitability evaluation and a spatially explicit sensitivity analysis. The sensitivity analysis couples spatial visualization and summary indicators, which include a traditional metric (i.e., the mean of the absolute change rate, MACR) and a novel spatially explicit metric (the Earth Mover's Distance, EMD). The newly reclaimed region of Yili in China was studied as the representative area. We assumed that the weights were the only source of uncertainty and used a one-dimensional sensitivity analysis. This experiment indicated that the expert LSE results for wheat are robust but relatively sensitive in local areas to changes in the weights. Our results confirm that the MACR and EMD can effectively identify sensitive parameters based on various sensitivity aspects. The EMD explores the new information from the spatial dimensions, which differs from traditional methods for sensitivity analysis. This approach provides a suitable framework based on a spatially explicit sensitivity analysis for the effective implementation of MCDM for robust LSE results.

Introduction

Agricultural production activities are the foundation of human survival and development. With the growth in the population and the reduction of arable lands, ensuring effective use of arable land to meet the growing demand for food requires rational land use management and planning. Land suitability evaluation (LSE) is an important step in this planning. Because the Food and Agricultural Organization (FAO) recommended an approach for LSE based on climatic, terrain, and soil properties data (FAO, 1976), multi-criteria decision-making (MCDM) techniques have been widely applied to combine information from different criteria for the LSE. The interest of researchers in integrating geographic information systems (GIS) with MCDM has grown steadily (Ceballos-Silva & López-Blanco, 2003; Hossain & Das, 2010; Kumar, Patel, Sarkar, & Dadhwal, 2013; Nisar Ahamed, Gopal Rao, & Murthy, 2000; Pereira & Duckstein, 1993; Tenerelli & Carver, 2012). However, GIS-based MCDM is a multi-disciplinary and multi-step process that can result in many sources of uncertainty (Burgman, 2005; Chen, Wood, Linstead, & Maltby, 2011; Wood, Beresford, Barnett, Copplestone, & Leah, 2009), including criteria selection, input data accuracy, standardization method, weight calculation, and aggregation method (Elaalem, Comber, & Fisher, 2011; Reshmidevi, Eldho, & Jana, 2009).

The uncertainties can be classified as aleatory or epistemic (Helton, 1993; Refsgaard, van der Sluijs, Højberg, & Vanrolleghem, 2007). Particularly, the weight assigned to each criterion is one of the most sensitive parameters in MCDM and is a potential source of considerable uncertainty (Larichev & Moshkovich, 1995). For example, the Analytical Hierarchy Process (AHP) (Saaty, 2008) is one of the most popular methods for calculating criteria weights in MCDM via an expert pair-wise comparison matrix (Hossain & Das, 2010; Marinoni, 2004; Ohta et al., 2007; Vaidya & Kumar, 2006). Using their weights, the criteria can be subsequently aggregated into a single imprecise MCDM estimation point, which results in uncertainties with no confidence (Benke, Pelizaro, & Lowell, 2009). Meanwhile, multiple decision-makers are able to set different weights and thus derive a variety of MCDM results for various

* Corresponding author. Tel.: +86 10 64889106.
E-mail address: zhanghq@igsnrr.ac.cn (H. Zhang).

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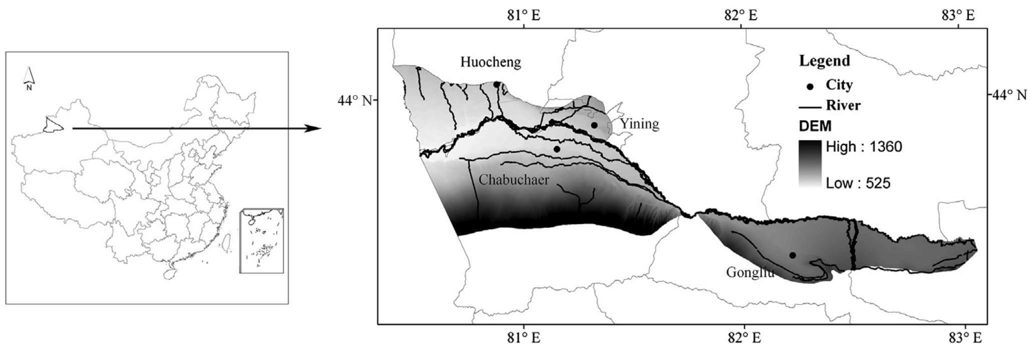

Fig. 1. Location of the newly reclaimed region Yili.

policy targets (Al-Mashreki, Akhir, Rahim, Lihan, & Haider, 2011; Chen et al., 2011; Roura-Pascual, Krug, Richardson, & Hui, 2010). Therefore, the robustness of the LSE results should be evaluated for effective implementation in land-use planning (Fuller, Gross, Duke-Sylvester, & Palmer, 2008; Ligmann-Zielinska & Jankowski, 2008). For this purpose, use of the uncertainty and sensitivity analysis is helpful in the validation and calibration of MCDM (Delgado & Sendra, 2004; Merritt, Croke, & Jakeman, 2005; Zoras, Triantafyllou, & Hurley, 2007).

Until now, sensitivity analysis has received only minimal attention in previous MCDM studies, although this situation is changing (Chen, Yu, & Khan, 2010; Delgado & Sendra, 2004; Ligmann-Zielinska, Jankowski, & Watkins, 2012; Lowell, Christy, Benke, & Day, 2011). It should be noted that the most critical shortcoming of sensitivity analysis is a lack of insight into the spatial dimensions (Chen et al., 2010; Feick & Hall, 2004). This situation therefore requires spatial visualization techniques and spatially explicit methods applied in the sensitivity analysis to create effective information for the planning decision process, i.e., GIS techniques and simulation algorithms (Ligmann-Zielinska & Jankowski, 2008; Mosadeghi, Warnken, Tomlinson, & Mirfenderesk, 2012; Pannell, 1997). Spatial visualization can display the uncertainties of the evaluation results graphically based on the uncertainty of the input parameters and enhance the experts' and decision-makers' understanding of the possible risk in identification of parameter sensitivity in MCDM (Blaser, Sester, & Egenhofer, 2000; BojóRquez-Tapia, Cruz-Bello, & Luna-González, 2012; Chen et al., 2011; Hallisey, 2005; Vitek, Giardino, & Fitzgerald, 1996).

Few studies have attempted to develop a spatial sensitivity analysis for MCDM. Feick and Hall (2004) presented a method for investigating the spatial dimension of the sensitivity of multi-criteria weights. Chen et al. (2010) presented a visualized approach for analyzing the dependency of MCDM output on weight changes and identifying those criteria that are especially sensitive to weight changes in a given spatial dimension. Chen et al. (2011) used an indicator-based method to visually explore the influence of uncertainties on MCDM with the application of the Catchment Evaluation Decision Support System in the Tamar catchment. Ligmann-Zielinska et al. (2012) employed a Monte Carlo simulation and output variance decomposition to represent output uncertainty in spatial form. Tenerelli and Carver (2012) set up a land capability model for assessing the potential of perennial energy crops and performed an uncertainty analysis of the model with a spatial distribution. Ligmann-Zielinska and Jankowski (2012) presented an approach for adjusting the criteria preferences based on distance measures using the explicit consideration of a locational structure.

However, the aforementioned studies focused primarily on spatial visualization of the sensitivity analysis and used traditional statistical methods to summarize the sensitivity results. Traditional methods for calculating the sensitivity indicators of outputs under uncertainty simulation, i.e., change percentage (Maguire, Goodchild, & Rhind, 1991), rank order (Benke, Steel, & Weiss, 2011; Butler, Jia, & Dyer, 1997), standard deviation (Heumann, Walsh, & McDaniel, 2011; Lowell et al., 2011; Pelizaro, Benke, & Sposito, 2011) and correlation coefficient (Tenerelli & Carver, 2012), consider the outputs of MCDM as discrete and independent elements and ignore the spatial configuration of the evaluation results. Evaluating spatially explicit LSE results in sensitivity analysis requires insight into the spatial information of the sensitivity analysis. Fortunately, the Earth Mover's Distance (EMD), which is a spatial metric used in image retrieval and histogram comparison (Rubner, Tomasi, & Guibas, 2000), provides an opportunity to consider the spatial dimension of sensitivity analysis.

The objective of this study is to present a new framework that incorporates the spatial configuration information of sensitivity analysis. We evaluated the LSE based on GIS-MCDM with weights calculated using the AHP. The framework examined the sensitivity of different criteria with changes in weights via spatial visualization of the uncertainty outputs and summary sensitivity indicators generated by traditional and spatially explicit methods.

Materials and methods

Study area

The newly reclaimed region located in the valley of Yili lies roughly between 80°22′14″ and 83°3′54″E and 43°22′37″ and 44°8′22″N (Fig. 1) and is one of seven important land resource development regions established by the Ministry of Land and Resources of the People's Republic of China. Land resource development engineers aim to achieve a balance of arable lands and improve the land productivity. The Yili River valley, with a better match of soil and water resources, is a limited potential region for land resource development in Western China. Therefore, this region requires effective land-use planning to both combat desertification and improve the quality of newly cultivated lands.

The study area belongs to Yining, Chabuchaer Autonomous County, Huocheng County, and Gongliu County in the administrative region. The region covers an area of ca. 5000 km^2, with elevations ranging from 661 m to 1572 m and lies within the temperate continental semi-arid climate zone with a mean annual temperature of 8–9 °C, a mean annual precipitation of 200–500 mm, a mean annual evaporation of 1200–1900 mm, and water resources that are the richest in Xinjiang. Land-use types primarily include grassland and farmland with a partial distribution of sand and saline areas. The soil types primarily consist of sierozem with a partial distribution of kastanozem above an altitude of 850 m. Other soil types include