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Design of a GIS and multi-criteria based land evaluation procedure for sustainable land-use planning at the regional level

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ABSTRACT

Design: of comprehensive, standardized land evaluation tools is challenged by constraints of scale, data availability, validity, and mathematical translation and combination of diagnostic indicators. This study aims to design a GIS-based multi-criteria land suitability analysis that integrates agro-ecological aptitude, environmental impact and socio-economic feasibility criteria in a step-wise procedure combining recent advances in indicator selection, evaluation and weighing – exploiting information from various data sources – with functional mathematical combination procedures. The procedure involves: (1) selection of diagnostic land characteristics, (2) design of the corresponding evaluation criteria and consequent scoring of the diagnostic characteristics, (3) arithmetic combination of the scored characteristics into partial performance indices for agro-ecological aptitude, environmental impact and socio-economic feasibility, and (4) classification of the performance indices into aptitude, impact, and feasibility classes and determination of the overall land suitability class of the proposed land use. The tool's performance and applicability proved successful in a case study, identifying expansion zones for rubber in Quang Tri province, Vietnam. Local expert knowledge, relevant literature sources, factor-yield relationships and the discriminating power of different land characteristics within the given environment were successfully integrated to select, score and weigh diagnostic land characteristics. Explicit distinction between factors and constraints depending on the fuzziness of their spatial patterns, and between limiting and non-limiting factors depending on their impact and interaction, furthermore allowed to apply the most relevant arithmetic combination procedures.

1. Introduction

Global driving forces in land-use planning are either needs for improved, resource-use efficient management, or demands for a revised land-use pattern, dictated by changing environmental or socio-economic circumstances. In 1996, the Food and Agriculture Organisation (FAO) defined land-use planning as the systematic assessment of land and water potential, land-use alternatives and socio-economic conditions in order to adopt the best land-use options (FAO, 1996). The definition highlighted the ecological, socio-economic and environmental aspects that need to be taken into account in the planning process. Land evaluation has always been considered a core component of land-use planning (FAO, 1996; Roetter et al., 2005; Baja et al., 2007). In 2007, the FAO land evaluation framework concepts and methodological approaches have been revised and expanded, taking into account much more explicitly the different functions and services offered by land and soil, threats to sustainable land uses, and limitations finding its origin in economic and societal conditions (FAO, 2007).

Land-use planning implies weighing trade-offs among conflicting goals. Multi-criteria analysis (MCA) is a methodology by which the relative merits of different options (e.g. land uses or land management practices) can be compared by using a range of quantitative and qualitative criteria (Center for International Forestry Research, 1997). The relative importance of these criteria is typically expressed using weights, whereas the performance of the land use under consideration for each criterion is generally expressed as a score or suitability class. Weights can be assigned

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subjectively or objectively using, for instance, expert knowledge in a pairwise comparison method (Giap et al., 2005) or a principal component analysis of yield-determining factors (Kosaki et al., 2012), respectively. In combination with a Geographical Information System (GIS), the MCA can be performed in a spatially explicit way. Such GIS-based multi-criteria analysis (GIS-MCA) consists of different step-wise procedures to analyze a single objective or many objectives, affected by spatially-distributed diagnostic factors (e.g. environmental conditions) that are evaluated based on the selected criteria.

GIS-MCA has been applied in many fields of science including environment, geography, soil science, land-use planning and society (Joerin et al., 2001; Lachassagne et al., 2001; Roetter et al., 2005; Malczewski, 2006; Bell et al., 2007; Karnatak et al., 2007). Van Der Merwe (1997) developed a multi-criteria evaluation model for application in the IDRISI GIS package to evaluate suitability for four land-use categories (commercial agriculture, small farming, urban development, nature conservation) according to appropriately measured and weighted criteria. Ceballos-Silva and Lopez-Blanco (2003) evaluated land suitability for specific crops using a pair-wise comparison method developed by Saaty (1977) to determine the weights, and a score scale from 0 to 5 based on ecological criteria. Giap et al. (2005) applied MCA to evaluate land suitability for shrimp farming considering factors and constraints in Hai Phong, Vietnam. They distinguished factors, being measures of the suitability of the criterion relative to the activity under consideration, and constraints, referring to restrictions that limit the alternatives under consideration in a binary manner. The relative importance of a particular factor was used to weigh and rate its suitability, using the analytical hierarchy process (AHP). In Mexico, Malczewski (2006) applied GIS-MCA using ordered weighted averaging combination method for a land-use suitability analysis. In addition, he incorporated the concept of fuzzy (linguistic) quantifiers. Also Baja et al. (2007) proved that GIS and MCA are powerful tools for dealing with various types of land-use modeling using compromise programming integrated with a raster GIS. The analysis considers conflicting objectives in space. Compromise programming applies the principle of distance functions, whereby a decision maker would seek a solution as close as possible to the ideal situation. The results depend on the definition of a reference point, a point with maximum benefit and minimum cost for every criterion, and the choice of a distance metric. The programming is used to calculate an overall (composite) score for each alternative (objective). Liu et al. (2013) developed a self-adapting fuzzy inference system for the evaluation of agricultural land in Hubei Province, China. They integrated a genetic algorithm with a multi-criteria evaluation based fuzzy inference system to construct a self-adapting system that calibrates its evaluation criteria by self-learning from land sample points. Such approach reduces the subjective uncertainty which characterizes ordinary fuzzy inference systems, but strongly depends on the quality of the dataset with respect to sample size, representativeness, and relevance of the considered criteria, for which they still depend on expert knowledge.

The aim of this study is to design a GIS-based multi-criteria land suitability analysis, integrating the three key aspects agro-ecological aptitude, environmental impact and socio-economic feasibility. The procedure combines recent advances in indicator selection, evaluation, weighing, and mathematical combination, exploiting information from various data sources. Despite the early recognition that agro-ecological, environmental and socio-economic aspects are all important in land evaluation, researchers are still struggling to integrate these naturally data-consuming assessments into standardized, comprehensive tools having local, regional, or global validity and facing the challenges of scale, data availability, and the correct mathematical translation and combination of various diagnostic indicators. The GIS-MCA designed for this purpose, however, integrates various environmental and socio-economic criteria with the agro-ecological aptitude, explicitly deals with constraints of data availability, and requires the user to take an informed decision on the most appropriate mathematical combination method depending on the characteristics of the factors under consideration. This is expected to improve the comprehensiveness and reliability of the analysis. The tool can be used as a stand-alone program or in a multiple objective analysis to develop a land-use plan for different land-use types, based on a set of production scenario's and preferences. Its performance and applicability is illustrated in a case study, identifying expansion zones for rubber cultivation in the Quang Tri province, Vietnam.

2. Materials and methods

2.1. GIS-based multi-criteria analysis procedure

The GIS-MCA procedure for the land-use type under consideration can be subdivided into four different stages (Fig. 1): (1) selection of diagnostic characteristics, making a distinction between factors and constraints, (2) design of the corresponding evaluation criteria or so called land-use requirements and consequent scoring of the diagnostic characteristics, (3) arithmetic combination of the scored characteristics into partial performance indices, and (4) classification of the partial performance indices into aptitude, impact, and feasibility classes followed by determination of the overall land suitability classes of the proposed land use.

2.1.1. Selection of the diagnostic factors and constraints

The evaluation procedure considers 3 key aspects: agro-ecological aptitude, environmental impact, and socio-economic feasibility. For each of these aspects, physical and socio-economic characteristics of the studied environment that directly or indirectly influence the productivity, sustainability or feasibility of the land use, need to be identified. Selection of such diagnostic land characteristics is based on (1) availability of local experimental data relating these characteristics to land productivity, (2) local cropping guidelines, or (3) expert knowledge from local and international experts, in decreasing order of preference. Among the diagnostic characteristics, a distinction is made between factors and constraints depending on their spatial patterns. Constraints are Boolean indicators characterized by sharp mapping unit boundaries distinguishing those land units that can be considered suitable for the specific land-use scenario from those that cannot. Land cover for instance, could be considered as a constraint if it includes nature reserves that are protected from land use change. Factors on the other hand, change gradually with respect to their aptitude, impact or feasibility, and thus show fuzzy boundaries, such as for instance the factors reflecting chemical soil fertility. The decision whether a characteristic is to be used as a factor or constraint strongly depends on the boundary conditions and land-use scenarios adopted, and can be changed in order to reflect multiple objectives.

2.1.2. Design of evaluation criteria and scoring of the factors and constraints

The selected land characteristics need to be evaluated with respect to their impact on productivity, sustainability and feasibility of the land use(s) under consideration. Design of these evaluation criteria relies on (1) measured or empirical relationships between land performance and the selected factors/constraints (e.g. factor-yield relationships, universal soil loss equation), or (2) local and international expert knowledge. Criteria