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ScienceDirect
Landscape and Urban Planning 81 (2007) 200–212
LANDSCAPE AND URBAN PLANNING
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A Land Suitability Index for Strategic Environmental Assessment in metropolitan areas

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Received 3 July 2006; received in revised form 27 November 2006; accepted 28 November 2006
Available online 29 December 2006

Abstract

This paper presents the Land Suitability Index (LSI), a transparent, modular hierarchical system of cartographic indices aimed at delivering Strategic Environmental Assessment (SEA) of developmental land uses for regional planning (European Directive 2001/42/EC). The LSI evaluates land suitability by combining three main sub-indices concerning (i) the vulnerability of the biosphere, lithosphere, and hydrosphere to impacts arising from implementing development proposals; (ii) the natural heritage value of the target area; and (iii) its contribution to terrestrial ecological connectivity. We have used the LSI to evaluate the impact of municipal urban plans in the Barcelona Metropolitan Region (BMR). For this case study, we provide redundancy and sensitivity analyses, and a partial validation using independent studies. Results showed noticeable inconsistencies between the municipal plans and the values of the LSI and its main sub-indices. There was moderate redundancy between sub-indices but considerable sensitivity to changes in input variables. Validation showed a high degree of coincidence with previous, independent, studies as regards connectivity. The quantitative and cartographic approach adopted by the methodology facilitates conveying the results to planners and policy makers. In addition, successive iterations to check the impact related to different alternative planning scenarios can be quickly performed. We therefore propose its application to other metropolitan areas.

Keywords: Land Suitability Indices; Ecological connectivity; Land vulnerability; Natural heritage; Regional planning; Barcelona

1. Introduction

Land suitability assessment is the process which determines the fitness of a given tract of land for a defined use (Steiner et al., 2000), usually among multiple, competing uses. Initially, this tool was developed as a means for planners to provide a more holistic view of the target environment from a set of spatially independent factors. Land suitability assessment is a context-dependent, multi-criteria evaluation of land capacity for development, based on the opinion of experts who define the most desirable factors and their optimal values and weights for this purpose (Jiang and Eastman, 2000; Stoms et al., 2002). Since McHarg (1969), land suitability assessment has become a standard practice in land use planning. The wide acceptance of GIS applications has permitted the development of spatially explicit approaches based on mapping parameters characterizing the land surface (Fabos et al., 1978). However, such approaches have not provided significant advances in perhaps the most important constraint of these methods: the lack of standard methodologies. In particular, the difficulties concern the choice and conceptual definition of indicators and of the mathematical model of which they form part (Andrearsen et al., 2001).

The application of the European Directive 2001/42/EC on Strategic Environmental Assessment (SEA) to land use and regional planning is facing serious challenges. One of the main difficulties of applying SEA is that many regional plans frequently fail to take proper account of environmental factors.

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doi:10.1016/j.landurbplan.2006.11.005

Thus it is difficult to assess the land suitability, and to compare the impacts associated to different alternatives (Sadler and Verheem, 1996; Partidário and Clark, 2000; Bonde and Cherp, 2000). Quantitative socio-environmental indices, already in use for aquatic systems (Paul, 2003), may be a good option to assess the impact on land of diverse alternative plans, with the aim of more sucessfully integrating sustainability factors in the new generation of land use plans. There have been various attempts to establish regional parameters to provide planning tools (Ramos et al., 2000; Lugeri et al., 2000). Most of these methods are based on mapping parameters characterizing the land surface. But the development of these cartographic indices is not trivial: land is a complex system resulting from the interaction of physical, biological, and anthropological phenomena operating over different scales of time and space (O'Neill, 1989).

Landscape ecological theory has provided a working scale and a set of quantitative tools (namely landscape indices or metrics) to characterize landscapes (Turner and Ruscher, 1988; Li, 2000) and to measure a region's landscape change through time (Reed et al., 1996). It is widely accepted that a general association exists between landscape pattern and ecological processes (Forman, 1995; Tischendorf, 2001). However, concepts and methods of landscape ecology also are useful for land planning and design (Nassauer, 1999; Corry and Nassauer, 2005). Indices might be a way to evaluate the consequences offered by a given plan in relation to a current scenario (Opdam et al., 2001), or they could be used to evaluate alternative plans for a particular landscape (Gustafson, 1998). In either case, they are evaluative tools for regional planning (Botequilha and Ahen, 2002).

This paper proposes a Land Suitability Index (LSI) for SEA incorporating some of these concepts inherited from landscape ecology and from general ecological theory as well. This is a complex, multimetric index which tries to describe nature as the heterogeneous, dynamic, multi-scale, hierarchically organized reality suggested by Margalef (1997), and to summarise its main structural, functional, and hierarchical features. In keeping with this hypothesis, we present the index as a tool for conducting SEA in metropolitan areas, focusing on the region of Barcelona. We justify the incorporation of a new index to the battery of parametric methodologies known at international level as there is a need for objective criteria (i) when deciding the geographic situation of a specific territorial intervention, and (ii) when determining the quantitative effect associated to different alternatives in the course of evaluation.

2. Methods

2.1. Our Land Suitability Index proposal

Our work addresses the necessity to have quantitative indices for SEA of regional or county land use plans. We define land suitability as the capacity of land for admitting development uses (namely urban, industrial, residential, extractive, transportation/circulation, etc.). We then propose a holistic index for land suitability assessment (LSI hereafter), based on a hierarchically organised set of indices in this work. The final objective of the algorithm is to provide an auxiliary tool for land planning, which is sufficiently straightforward and quantitative, and has cartographic applications, so that it can be used interactively by planners and decision makers.

The development of the LSI essentially followed the steps proposed by Paul (2003) for multimetric indices aggregating or combining environmental information across indicators, namely: (i) select individual components by a group of experts; (ii) calculate indicator values from individual components; (iii) aggregate the indicator values in partial indices and these in three sub-indices; (iv) aggregate the sub-indices in the overall index; and (v) interpret the index values for SEA purposes. The first three steps are detailed later in specific sub-sections per sub-index. Steps four and five consisted of LSI construction based on three axes representing (i) the suitability of the physical environment (Δ_{TVI}) as regards the impact of human activity on the biosphere, lithosphere, and hydrosphere; (ii) the suitability of the biological environment (Δ_{NHI}) according to its natural heritage value; and (iii) the suitability of the functional environment (Δ_{ECI}) inferred from its contribution to terrestrial ecological connectivity. These three axes are combined to give LSI as follows:

$$\mathrm{LSI} = 1 + 4\left[\frac{\log(\Delta + 1)}{\log K_{\Delta}}\right]$$

where $\Delta = \Delta_{\mathrm{TVI}}\,\Delta_{\mathrm{NHI}}\,\Delta_{\mathrm{ECI}}$

where K_{Δ} is the maximum value of Δ ($K_{\Delta} = 65$). This formula permits us to standardise the values of LSI between 1 and 6, with a normal distribution of such values. The final step was to assign these values to six ordinal categories.

The three factors of Δ are respectively inferred from sub-indices which have previously been calculated to assess land impact, not land suitability. These sub-indices are the Territorial Vulnerability Index (TVI), the Natural Heritage Index (NHI), and the Ecological Connectivity Index (ECI) described later. The LSI is then built on these sub-indices, which are in turn based on a hierarchical structure of partial indices and indicators, after their transformation from land impact to land suitability (Fig. 1) following pre-defined rules (summarised in Fig. 2).

Now, we present the basic steps for developing the three sub-indices making up the LSI, which measure the territorial vulnerability, the natural heritage value, and the ecological connectivity.

2.2. The Territorial Vulnerability Index

The TVI is a combination of bio-physical variables constituting the regional matrix (Marull, 2003; Folch and Marull, 2004), understood as a complex system comprising the biosphere, lithosphere, and hydrosphere. The algorithm quantifies the ecosystem's potential resilience (Gunderson and Holling, 2002) to the potential impacts of various urban and/or infrastructural plans.

The TVI is a sub-index which results from a hierarchical system with six ordinal indicators (I_{i}) with five possible categories (0, excluded; 1, low; 2, medium; 3, high; 4, very high). These indicators are constituents of three partial indices quanti-