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A Land Suitability Index for Strategic Environmental Assessment in metropolitan areas

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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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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:

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

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

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-

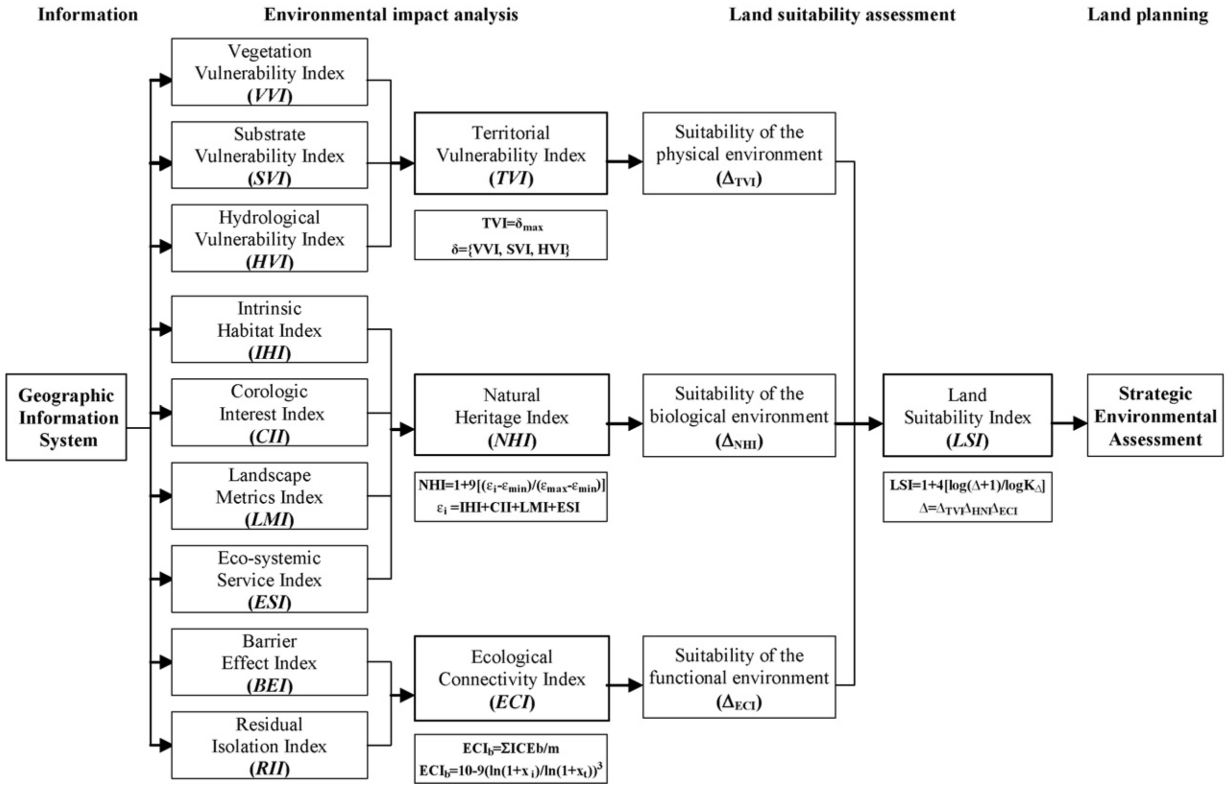
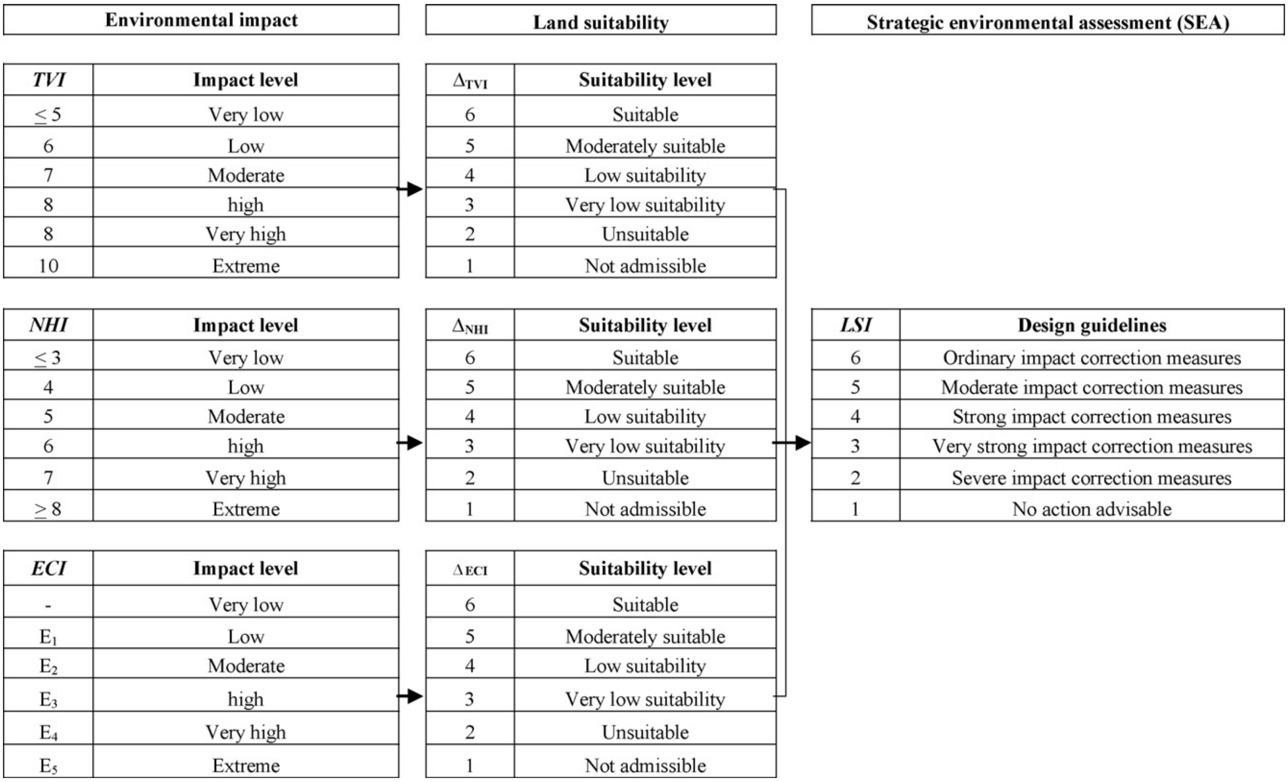


Fig. 1. Methodological schema of the system of indices for SEA making up the Land Suitability Index.



Environmental impact

TVI	Impact level
≤ 5	Very low
6	Low
7	Moderate
8	high
8	Very high
10	Extreme

NHI	Impact level
≤ 3	Very low
4	Low
5	Moderate
6	high
7	Very high
≥ 8	Extreme

ECI	Impact level
-	Very low
E_1	Low
E_2	Moderate
E_3	high
E_4	Very high
E_5	Extreme

Land suitability

Δ_{TVI}	Suitability level
6	Suitable
5	Moderately suitable
4	Low suitability
3	Very low suitability
2	Unsuitable
1	Not admissible

Δ_{NHI}	Suitability level
6	Suitable
5	Moderately suitable
4	Low suitability
3	Very low suitability
2	Unsuitable
1	Not admissible

Δ_{ECI}	Suitability level
6	Suitable
5	Moderately suitable
4	Low suitability
3	Very low suitability
2	Unsuitable
1	Not admissible

Strategic environmental assessment (SEA)

LSI	Design guidelines
6	Ordinary impact correction measures
5	Moderate impact correction measures
4	Strong impact correction measures
3	Very strong impact correction measures
2	Severe impact correction measures
1	No action advisable

Fig. 2. Calculation rules from land impact to land suitability on the basis of the TVI, NHI, and ECI sub-indices of the Land Suitability Index, and associated planning guidelines for SEA.

fying the vulnerability of vegetation (VVI), substrate (SVI) and hydrosphere (HVI). We formalized TVI as the maximum value of the three partial indices for a given point in the region:

$$\begin{aligned}&\mathrm{TVI} = \delta_{\max}\\&\text{where}\ \delta = \{\mathrm{VVI},\ \mathrm{SVI},\ \mathrm{HVI}\}\end{aligned}$$

A brief explanation of each of the constituent partial indices is given below:

(i) The Vegetation Vulnerability Index (VVI) summarises the difficulty that plant communities have in recovering after alterations to the natural environment. It is made up of two indicators: I_1, vegetation fragility (estimated from intrinsic attributes such as plant life-form and ecological range); and I_2, topographic-climatic constraints (inferred from climatic and digital elevation models). We considered that vegetation vulnerability in the Mediterranean region results from the concurrence of both factors weighted similarly. Thus, we calculated VVI as a product, following the algorithm:

$$\mathrm{VVI} = 2 + \frac{8\ \log(I_1 I_2)}{k_1}$$

where $k_1 = \log 16$. This algorithm standardizes the values of VVI to a normal distribution between 1 and 10.

(ii) The Substrate Vulnerability Index (SVI) provides a measure of the risk of surface and substrate instability that may result from urban and infrastructure alterations to the earth substrate (Baeza and Corominas, 2001). This index is made up of two indicators, inferred from expert knowledge using lithology: I_3, substrate erosion; and I_4, substrate instability. In this case, we considered that substrate erosion potential was much more important than substrate instability, and we assigned the factor weights accordingly:

$$\mathrm{SVI} = 2 + \frac{8\ \log\left(I_3^2 I_4\right)}{k_2}$$

where $k_2 = \log 64$. As in the case of VVI, this algorithm standardizes the values of SVI to a normal distribution between 2 and 10. If soil maps were available, soil erosion could be included as a third component and the algorithm would have to be adjusted accordingly.

(iii) The Hydrological Vulnerability Index (HVI) provides an integrated measure of the vulnerability of the quality and quantity of surface and ground water, as a result of impacts of urban schemes development and land use changes. It is comprised of two indicators based on rough hydrological information and expert knowledge: I_5, the vulnerability of surface water; and I_6, the vulnerability of ground water. We considered in this case that one factor (surface water) should be weighted more than the other (ground water), and we assigned the factor weights accordingly:

$$\mathrm{HVI} = 2 + \frac{8\ \log\left(I_5^2 I_6\right)}{k_3}$$

where $k_3 = \log 64$. The resulting values followed a normal distribution between 1 and 10.

2.3. *The Natural Heritage Index (NHI)*

The NHI is a sub-index synthesizing the bio-geographical and ecological variables concerning natural heritage (Marull et al., 2004). Based on the assumption that habitats are a good indicator of the environmental conditions and their associated biodiversity, the NHI has been constructed without using detailed information on the species distribution, which is usually scarce, lacking either significant species or portions of the study area. It does not include geological heritage values (geotopes) because this information was not available, although we plan to take them into consideration whenever possible.

The NHI is based on previous criteria of environmental assessment (see Justus and Sarkar, 2002 for a review), but it aims to overcome some limitations of most traditional approaches to the evaluation of natural heritage, such as the undervaluing of certain extensive agroecosystems in Mediterranean regions which have a significant value for biodiversity. It tries to achieve this by combining the intrinsic value of habitats, their chorological significance and their landscape functions. It also introduces a fourth criterion, namely the environmental services rendered to society by the natural systems. It is based on 16 indicators (I_n) hierarchically organised in four partial indices. All the indicators have been transformed to ordinal variables with five possible categories (0, excluded; 1, low; 2, medium; 3, high; 4, very high). Partial indices have been constructed by adding up the values of the indicators concerned and re-scaling the final result to 10 ordinal values from 1 (lowest) to 10 (highest) and including the 0 value for excluded (urban) areas.

Unlike TVI, we considered that each indicator involved in each partial index increased the value of natural heritage with a similar weight, thus we organised the partial and the global indices as a sum of terms. All the sums were performed so as to obtain a normal distribution of index values from 0 to 10. We then defined NHI as the sum, rescaled from 0 to 10, of four partial indices

$$\begin{aligned}&\mathrm{NHI} = 1 + 9\left(\frac{\varepsilon_\mathrm{i} - \varepsilon_{\min}}{\varepsilon_{\max} - \varepsilon_{\min}}\right)\\&\varepsilon_\mathrm{i} = \mathrm{IHI} + \mathrm{CII} + \mathrm{LMI} + \mathrm{ESI}\end{aligned}$$

where $\varepsilon_{\min}$ and $\varepsilon_{\max}$ correspond, respectively, to the minimum and maximum values of NHI in the study area.

We considered four partial indices for the NHI, with a variable number of indicators:

(i) The Intrinsic Habitat Index (IHI) covers the floral and vegetational value of habitats, regardless of their state of conservation by means of five indicators inferred from the habitats by experts: I_1, species diversity; I_2, species rarity; I_3, vegetation distribution range; I_4, vegetation successional state; and I_5, vegetation fragility.

$$\mathrm{IHI} = 1 + 9\left(\frac{\alpha_\mathrm{i} - \alpha_{\min}}{\alpha_{\max} - \alpha_{\min}}\right)$$

where α_i is the sum of the indicators for each point in the region, while $\alpha_{\min}$ and $\alpha_{\max}$ are the minimum and maximum values, respectively, in the study under consideration.

(ii) The Chorologic Interest Index (CII) provides a measure of bio-geographic and other aspects bearing on the distribution of habitats in a region. It is comprised of five indicators inferred by expert knowledge and GIS calculation: I_6, bio-geographic value; I_7, regional spread; I_8, topographic diversity; I_9, spatial aggregation; and I_{10}, spatial eccentricity.

$$\mathrm{CII} = 1 + 9\left(\frac{\beta_{\mathrm{i}} - \beta_{\min}}{\beta_{\max} - \beta_{\min}}\right)$$

where β_{i} is the sum of the indicators in each point of the region, while $\beta_{\min}$ and $\beta_{\max}$ are the minimum and maximum values, respectively.

(iii) The Landscape Metrics Index (LMI) is based on the region's capacity (as affected by human activities) to support organisms and ecological processes. This is calculated on the basis of four indicators basically obtained from GIS calculation: I_{11}, capacity of relation between habitat patches; I_{12}, ecotonic contrast between adjacent habitats; I_{13}, human impact on habitats; and I_{14}, vertical complexity.

$$\mathrm{LMI} = 1 + 9\left(\frac{\gamma_{\mathrm{i}} - \gamma_{\min}}{\gamma_{\max} - \gamma_{\min}}\right)$$

where γ_{i} is the sum of the indicators for each point in the region, while $\gamma_{\min}$ and $\gamma_{\max}$ are the minimum and maximum values, respectively, in the study area under consideration

(iv) The Eco-systemic Service Index (ESI) assesses habitats in relation to the goods and services obtained from them (based on Constanza et al., 1997). We modeled four indicators from among those found in the literature using basic data on forestry inventories, GIS procedures, and expert knowledge: I_{15}, carbon fixing; I_{16}, water regulation; I_{17}, control of erosion; and I_{18}, leisure use.

$$\mathrm{ESI} = 1 + 9\left(\frac{\delta_{\mathrm{i}} - \delta_{\min}}{\delta_{\max} - \delta_{\min}}\right)$$

where δ_{i} is the sum of the indicators for each point in the region, while $\delta_{\min}$ and $\delta_{\max}$ are the minimum and maximum values, respectively.

2.4. The Ecological connectivity Index

Ecological connectivity is a highly significant landscape attribute for sustainable land planning, since it has been shown that isolated protected areas, independently of how well they are designed and managed, are unable to conserve biodiversity and to meet other ecological and social functions (Forman and Godron, 1986). There are many methodological approaches for assessing ecological connectivity in regional land use planning in various countries (Brandt, 1995; Kubes, 1996; Beier and Noss, 1998; Sepp et al., 1999). These approaches always combine principles of ecology and biology with planning and political considerations. Most of the existing methods require large amounts of data, including the distribution of key species (Múgica et al., 2002). However, a simplified holistic model can sufficiently explain the observed phenomena and may be of greater use at the regional scale (Gardner and O'Neill, 1990; Mallarach, 2003). This hypothesis was explored by developing a model incorporating a topological analysis of land uses. The model was conceived to do a general assessment of ecological connectivity, but it also permits evaluation of the impacts of each human-made barrier on the ecological connectivity and landscape fragmentation of its surrounding area.

The methodology of the ECI has been described in detail in Marull and Mallarach (2005). Essentially, it takes into account the distance between different functional ecological areas, the affinity of their habitats and the impact of human-made barriers.

$$\mathrm{ECI} = 10 - 9\left[\frac{\ln(1 + (x_{\mathrm{i}} - x_{\min}))}{\ln(1 + (x_{\max} - x_{\min}))}\right]^3$$

where x_{i} is the cost distance by pixel, and $x_{\min}$ and $x_{\max}$ are the minimum and maximum values of the cost distance in the study under consideration, respectively. The cost distance was calculated using an impedance matrix which is a function of two factors: (i) ecological affinity (assessed from expert knowledge) of a set of Functional Ecological Areas (FEA) and (ii) barrier effects of urban and infrastructure areas. The FEA determine the natural areas to be linked up, in accordance with two basic criteria: minimum area (Andrén, 1994; Virgós et al., 2002) and topology (i.e. compactness). Land use mosaics are included, given the existing correlation between habitat heterogeneity and biodiversity (Pino et al., 2000). The FEA definition is of intrinsic value given that in accordance with the trickle-down theory (With and Crist, 1995), serious problems in conserving biodiversity tend to arise when functional ecological areas fall below a certain threshold. The Barrier Effect Index (BEI) measures the impact that urban and infrastructure areas may have on the study area based on residential and traffic density. According to several studies (Kaule, 1997), we assumed that the effect of a human-made barrier Y_{S} on a surrounding area decreases logarithmically as distance to it increases.

Once the modelling of the ECI is completed, the databases have to be examined to identify strategic ecological connectivity areas (E_{n}) in the study area, drawing upon expert judgment for this purpose. Following an iterative process, we tested the hypothesis that all the areas with an ECI > 1 possess sufficient ecological permeability. This level was chosen given the considerable ecological fragmentation that metropolitan areas usually undergo (ECI = 1: potential areas; ECI > 1: functional areas). A set of strategic ecological areas was then drawn up to link all areas with an ECI > 1, employing the following five categories: E_1, functional ecological areas; E_2, functional ecological network; E_3, stepping stone habitats; E_4, landscape linkages; E_5, ecological corridors.

3. Application to the Barcelona Metropolitan Region (BMR)

3.1. The BMR

The BMR is one of the most heavily built-up regions in Europe (Fig. 3). It covers 3200 km^2 and has a population of 4.2 million, which results in an average density of 1300 people per square kilometer. However, it still has a number of impor-

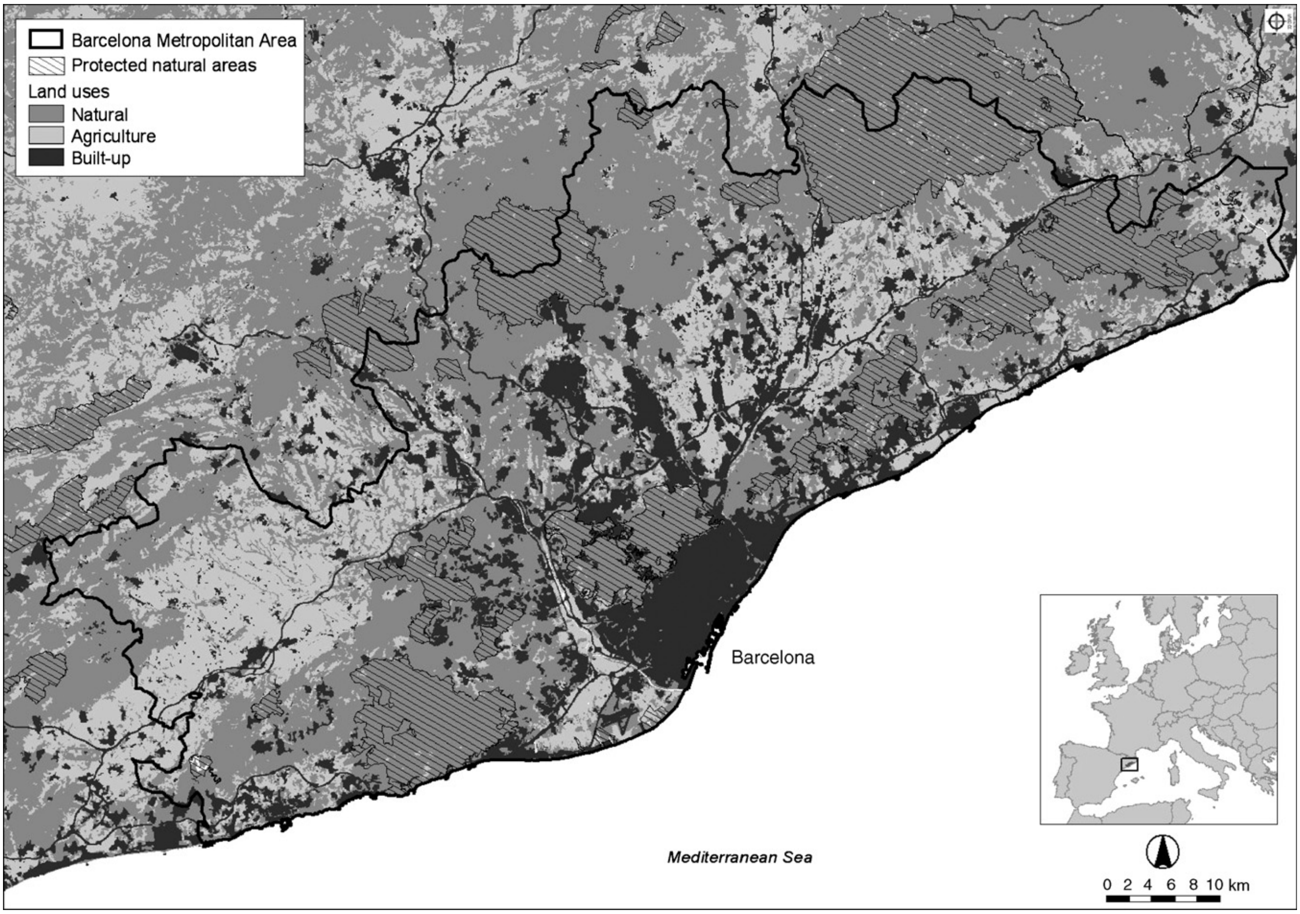


Fig. 3. Simplified land cover map of the BMR, showing the distribution of main urban areas and the system of protected natural areas.

tant natural areas featuring considerable ecological diversity. It accounts for more than 40 habitats of European significance, including many species of fauna and flora that are either on the endangered list or are threatened with extinction. It has been identified as one of the areas facing the most serious environmental pressures and impacts in the European Union (European Environmental Agency, 1999). According to the most recent land use map (Barcelona Regional and Institut Cartogràfic de Catalunya, 2001), urban nd infrastructural uses take up more than 58,000 ha (18% of the BMR), of which 22,000 ha are occupied by housing estates. Rural and forest areas have been converted to urban related uses at a rate of roughly 1000 ha a year in the last 5 decades, which means that the environmental pressures and impacts arising from the implementation of current land use planning are increasingly unsustainable (Marull, 2003; Marull and Mallarach, 2005).

Much of the BMR's urban growth has been based on environmentally unsound urban and land use plans in which ecological considerations are largely absent (Paül and Tonts, 2005). The 1976 General Metropolitan Plan has been amended so many times that it is now completely outdated. In addition, the 164 municipal plans of the BMR designate 22,382 ha of land as suitable for development, of which approximately 43% are earmarked for low-density housing. If all these plans were carried out, the built-up area would cover 22% of the BMR, directly affecting an area almost twice as large. Urban and semi-urban areas and their infrastructures are splitting up the natural and semi-natural habitats of the metropolitan area in ever smaller and more isolated patches, creating a host of residual spaces that have lost most of their ecological functions (Marull et al., 2005). Basic infrastructure networks providing transport and energy (roads, railways, high voltage power lines, gas pipelines, services, and water treatment) now occupy almost 20,000 ha (6% of the BMR). In addition, industry and transport produce a number of impacts, such as air pollution, noise, sewage and other liquid and solid wastes that adversely affect all the BMR's natural systems in a myriad of ways.

3.2. Application of the method

As an example of the potential applications of this methodology, we have evaluated the ecological consequences of the 164 municipal urban plans that make up the BMR on the basis of the LSI (see LSI map in Fig. 4). With this aim, a unified classification of all these plans was first set up, from which a cartographic base unified to 1:5000 scale was prepared in order to finally produce a map at 1:50,000 scale of the whole BMR (Departament de Política Territorial i Obres Públiques and Institut Cartogràfic de Catalunya, 2000). The databases of the current plans later were updated by Institut d'Estudis Territorials (2003).

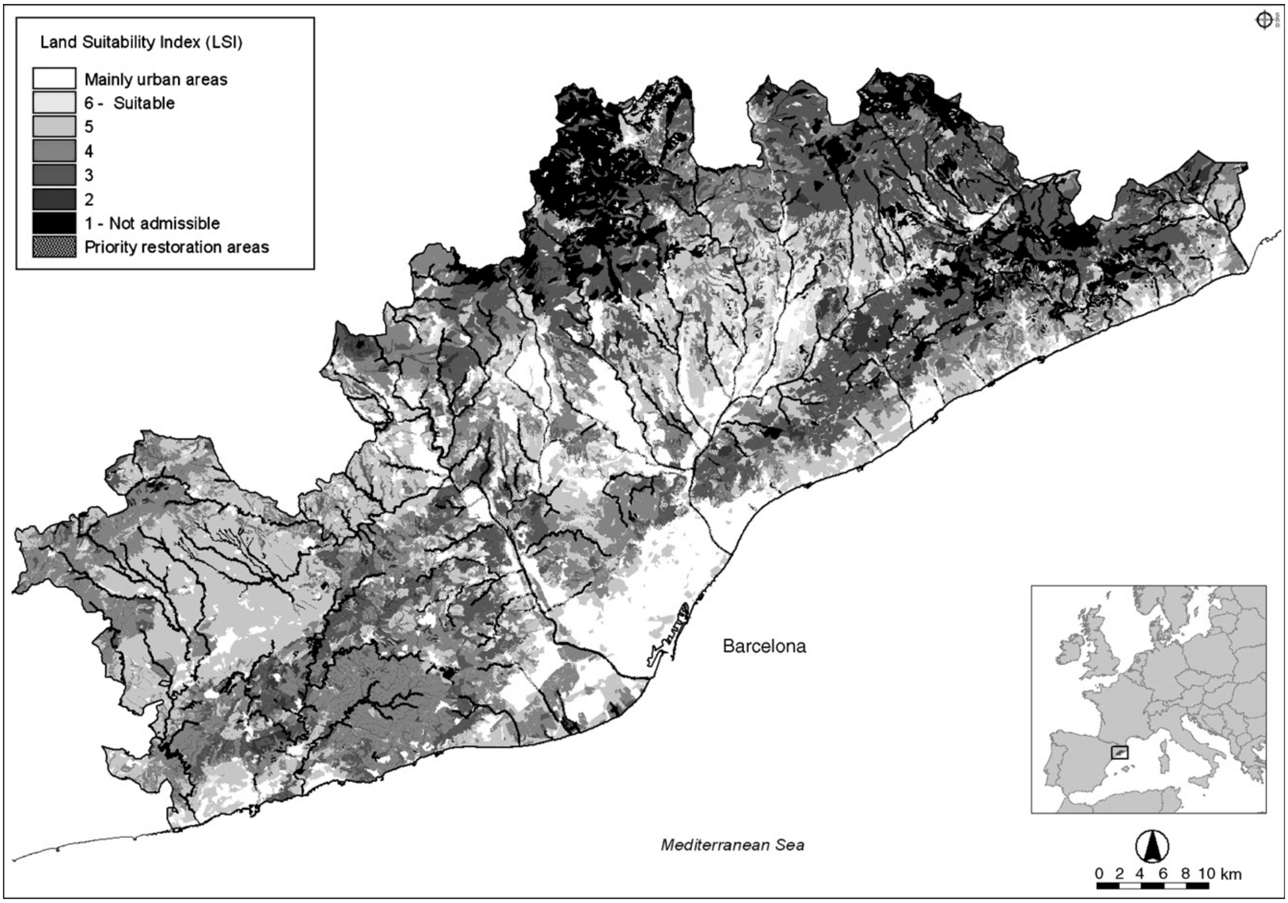


Fig. 4. Map resulting from the application of the Land Suitability Index to the Barcelona Metropolitan Region.

The distribution of development plans on the LSI showed that the surface still suitable for development (LSI = 5–6; 91,223 ha) occupies 28.18% of the BMR, which amounts to more than four-times the surface considered in the planning (Fig. 5, Table 1). Also, 13.60% of the potential development land (3045 ha; 1809 ha of which are residential) corresponds to very little or non-suitable areas (LSI = 1–3), where any type of city-planning interventions should be advised against. On the other hand, a significant 13.51% of the land destined to be developed (3024 ha, 1890 ha of which are residential) corresponds to lands with little suitability (LSI = 4) that would require including significant corrective measures in the development plans (or alternatively, not to build). Also, 909 ha affected by current plans in the BMR had been identified as areas that will require measures of ecological restoration, to improve the functioning of the territory. Only 68.82% of the land zoned for urban uses corresponds to suitable areas according to the criteria defined by the index (LSI = 5–6; and mainly urban areas) and, therefore, requiring low to mod-

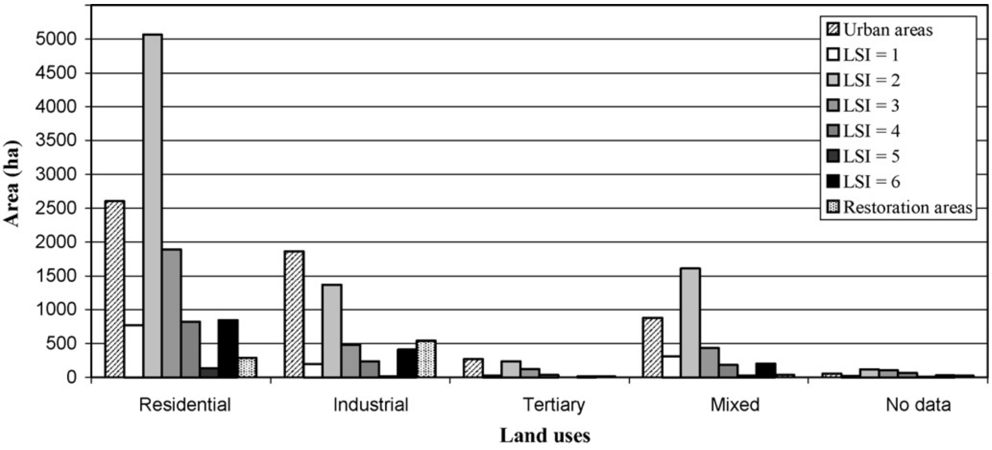


Fig. 5. Frequency distribution of land suitability categories of current urban municipal plans in the Barcelona Metropolitan Region.

Table 1
Area (ha) and percentage of total area included in each category of the Land Suitability Index, in all the Barcelona Metropolitan Region and in the current urban municipal plans in this region

LSI	Suitability level	BMR		Current plans in the BMR					
		ha	%	Pending		Final		Total	
				ha	%	ha	%	ha	%
–	Mainly urban areas	41,756	12.90	2119	19.23	3550	31.24	5669	25.33
6	Suitable	10,168	3.14	638	5.79	698	6.15	1336	5.97
5	Moderately suitable	81,055	25.04	4660	42.29	3738	32.90	8399	37.52
4	Low suitability	67,930	20.99	1531	13.90	1493	13.14	3024	13.51
3	Very low suitability	62,104	19.19	733	6.65	618	5.44	1350	6.03
2	Unsuitable	7631	2.36	94	0.85	91	0.80	185	0.83
1	Not admissible	48,348	14.94	890	8.08	619	5.45	1510	6.74
–	Priority restoration areas	4672	1.44	354	3.21	555	4.88	909	4.06
Total		323,664	100.00	11,020	100.00	11,363	100.00	22,382	100.00

erate corrective measures. Obviously, in such a mountainous metropolitan area, the remaining surface available is a very limited and increasingly valuable resource, so it is necessary to manage it using the precautionary principle.

Results from the application of the partial suitability variables (Δ) for environmental strategic assessment of current urban municipal plans in the BMR are given below so that the reader can fully understand how the proposed methodology works:

(i) Application of Δ_{TVI} reveals that 19.32% of the land considered for urban plans in the BMR (4326 ha, of which 2411 are earmarked for housing) include areas that are highly or extremely environmentally vulnerable ($\Delta_{\mathrm{TVI}} = 1–3$), and in which it would be advisable to avoid any kind of urban development (Fig. 6, Table 2). In addition, a significant portion of "development land" (41.03%, 9184 ha, of which 5891 ha are earmarked for housing) is located in areas whose environmental vulnerability is rated medium ($\Delta_{\mathrm{TVI}} = 4$), thus requiring precautions to be taken in building schemes, or refraining from building altogether in some cases. Only 10.24% of land zoned as future urban lands is located in areas of low environmental vulnerability (i.e. low geotechnical risk or low probability of affecting highly vulnerable groundwater reserves or plant communities) as defined by the indicator ($\Delta_{\mathrm{TVI}} = 5–6$).

(ii) Application of Δ_{NHI} to assess the potential impact on the natural heritage may well lead to a re-appraisal of some urban plans in the BMR. While the project is currently at the initial development stage, the analyses done have shown the index to be useful in revealing areas of natural and ecological interest not included in the protected nature areas system of the BMR (Fig. 1) and which, because of their location, may be adversely affected by urban development. A total of 93,846 ha with a high or very high NHI value ($\Delta_{\mathrm{NHI}} = 1–3$) are not included in the existing protected areas system. The analysis of the potential impact of urban planning (Fig. 6) shows that 14.06% of land proposed for urban development in the BMR (3148 ha, of which 2333 ha are earmarked for housing in the residential category) pertain to these high value natural heritage areas ($\Delta_{\mathrm{NHI}} = 1–3$).

(iii) Analysis of the results of applying Δ_{ECI} revealed that the criteria adopted by most urban plans in the BMR were not adequate to maintain ecological and landscape connectivity (Fig. 6). Some of the 4489 ha considered for urban development (20.06% of the BMR) are located in areas of key value for ecological connectivity ($\Delta_{\mathrm{ECI}} = 1–3$). However, approximately 24% of these new urban lands have been zoned as parks or green areas for which corrective measures could easily be adopted to ensure they provide enough permeability to ecosystems in adjoining areas. In addition, a large number of sites (102,427 ha in the BMR)

Table 2
Area (ha) and percentage of total area included in each category of Δ_{TVI}, Δ_{NHI} and Δ_{ECI} in all the BMR and in the current urban municipal plans in this region

	BMR		Current plans in the BMR	
	ha	%	ha	%
Δ_{TVI}				
–	46,428	14.34	6579	29.39
6	1982	0.61	298	1.33
5	17,656	5.45	1995	8.91
4	118,578	36.64	9184	41.03
3	124,776	38.55	3951	17.65
2	13,783	4.26	365	1.63
1	462	0.14	10	0.04
Δ_{NHI}				
–	46,428	14.34	6579	29.39
6	53,743	16.60	8969	40.07
5	56,100	17.33	2877	12.85
4	19,592	6.05	809	3.61
3	51,868	16.03	1674	7.48
2	70,138	21.67	1366	6.10
1	25,795	7.97	108	0.48
Δ_{ECI}				
–	46,428	14.34	6579	29.39
6	57,083	17.64	5942	26.55
5	45,344	14.01	2749	12.28
4	117,969	36.45	2624	11.72
3	14,373	4.44	1881	8.41
2	17,843	5.51	1202	5.37
1	24,623	7.61	1406	6.28

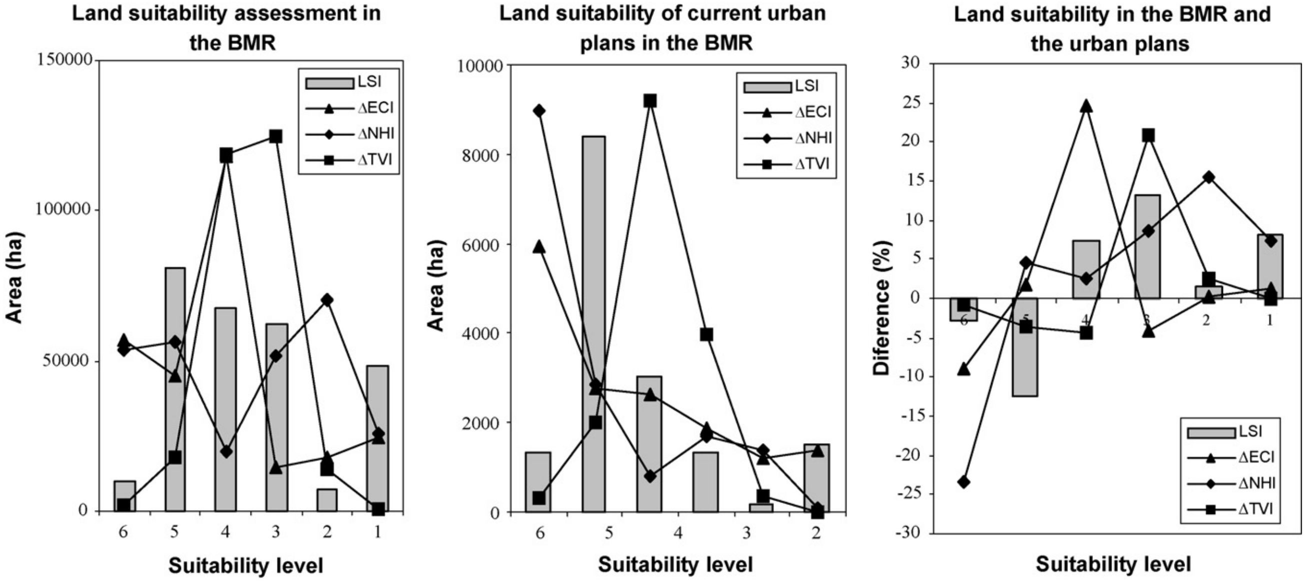


Fig. 6. Suitability assessment of current urban municipal plans in the Barcelona Metropolitan Region based on the Land Suitability Index and its physical (Δ_{TVI}), biological (Δ_{NHI}), and functional (Δ_{ECI}) components.

bordering existing urban areas were identified where plans would have minimal impact on ecological connectivity. If environmental sustainability is to be a presiding principle of land use planning, urban plans should be reviewed and alternatives sought or corrective action taken, at least in areas where critical impacts have been identified.

3.3. Redundancy, sensitivity and validation analyses

Investigations to eliminate redundancy and to select landscape indices that provide unique information about a common landscape are ongoing (O'Neill et al., 1999). An analysis of the internal redundancy of LSI has been performed by testing the degree of association among (i) the three main indices of LSI (NHI, TVI, and ECI); (ii) the partial indices of NHI; and (iii) those of TVI (ECI was conceived differently and it has no partial indices). We generated a coverage with 80,000 points randomly distributed through the BMR and, using the crossing layer applications of ArcInfo, we assigned to each point its value for each main and partial index included in NHI, TVI, and ECI. For each possible pair of variables (main and partial indices) we performed a cross-classification table using 40,000 points randomly selected from the point coverage. For each table we calculated the Kendall's tau-b, which ranges from −1 to 1 and is considered an adequate measure of association for ordinal variables (Agresti, 1984).

The comparison of the three main indices revealed significant ($P < 0.001$) and moderate to low values of the Kendall's tau-b. The highest association corresponded to the NHI–TVI comparison (tau = 0.39), whereas ECI was much less associated with the other indices (tau = 0.13 and 0.11 with NHI and TVI, respectively). We also obtained low values of the Kendall's tau-b when comparing the TVI partial indices (0.37 for VVI–SVI; 0.21 for VVI–HVI, and 0.24 for SVI–HVI). In the case of NHI (Table 3), values ranged from 0.55 for the IHI–CII comparison to 0.09 for the ESI–CII case. Comparisons between IHI, CII and LMI gave values around 0.5, whereas those involving ESI showed much less degree of association. These results indicate several redundancy concerns, albeit moderate, of classical criteria for assessing natural heritage, but also that ecological services introduce new dimensions to this assessment, which are relatively uncorrelated with any other factor.

When an index has the same numerical value for dramatically different landscapes (Tischendorf, 2001), or displays erratic behaviour under certain landscape conditions (Schumaker, 1996), its diagnostic value is limited. A preliminary sensitivity analysis of LSI has been performed considering separately the three main indices (NHI, TVI, and ECI). Because of their different nature, approaches to sensitivity analysis were quite different: in the case of indices based on categorical variables (NHI and TVI) sensitivity was measured as the probability that the index values of cases do not change when varying three factors: the intensity of change (as the increase by 1 or 2 values in the scale of the indicators), the number of indicators changed per partial index (1–4 for NHI, 1–2 for TVI), and the proportion of changed cases (10–60%). We selected 20,000 points from the point coverage previously described. We then randomly modified their values following the abovementioned rules of intensity

Table 3
Values of Kendall's tau-b obtained in the pair wise comparisons of the NHI partial indices using cross-tabulation tables

	IHI	CII	LMI
CII	0.525		
LMI	0.548	0.493	
ESI	0.172	0.092	0.359

All comparisons gave a significant association between indicators for the χ^2 test at $P < 0.001$ (acronyms: IHI, Intrinsic Habitat Index; CII, Chorologic Interest Index; LMI, Landscape Metrics Index; ESI, Ecological Service Index).

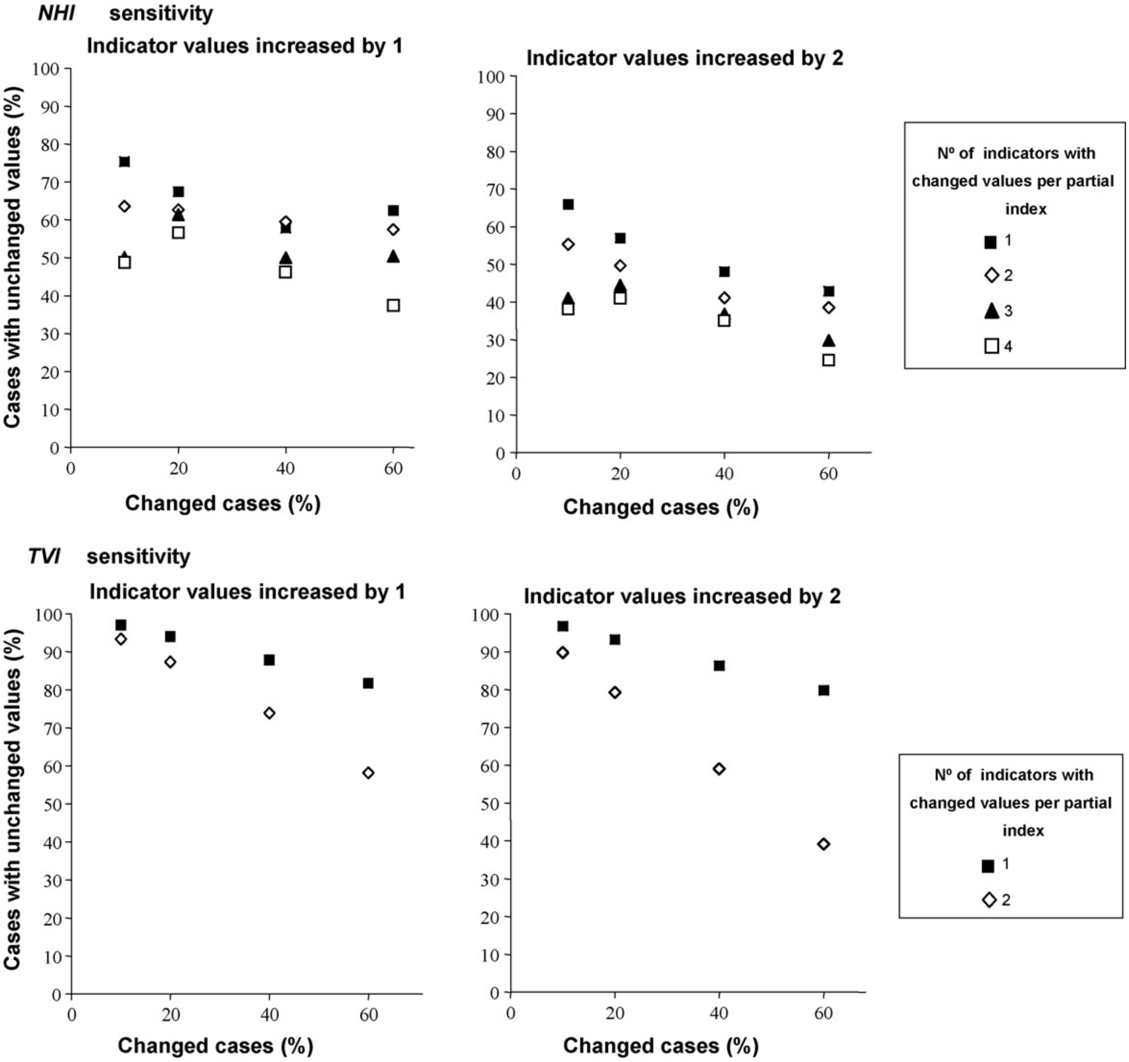


Fig. 7. Sensitivity analyses for the NHI and TVI indices, measuring the percentage of cases with unchanged values in relation to changes in three factors: (1) the percentage of changed cases (*X*-axes), (2) the number of indicators with changed values per partial index (symbols), and (3) the increase in the indicator values (1 or 2).

of change, number of indicators changed, and proportion of cases changed. Both main indices showed considerable sensitivity to changes in input variables (Fig. 7). However, TVI showed higher sensitivity to changes than NHI, as deduced from the higher slope of the variation in the index values. This is probably because the former is calculated as the maximum of the partial indices, whereas the later is an unweighted sum of them. In contrast, if we decrease the value of the indicators (data not shown) changes in TVI are small (less than 5% of its original value), whereas NHI shows a similar behaviour as seen in Fig. 7.

We have performed some preliminary validations of the methodology. For example, ECI values have been compared with those obtained using different approaches to the ecological connectivity of the BMR (Mallarach and Marull, 2006; Rueda, 2002; Forman, 2004). During the last decade there have been a number of studies on the ecological connectivity of different portions of the BMR, ranging from one municipality, a biological corridor between protected areas, a watershed, to the entire BMR. These works were developed using different methodologies, which always included field work. An acceptable way to validate our method would be to compare its results with the results from the most complete and reliable studies which have been performed to date. After the compilation and subsequent analysis of the available works, two studies analysing the ecological connectivity for the entire BMR using distinct methodologies were selected (Rueda, 2002; Forman, 2004). These studies showed an overall coincidence of over 80% with the ECI results.

These analyses show that the hierarchic and complex structure of the proposed methodology has a certain homeostatic effect in the final expression of the index in the case of redundancy. Indeed, values are sufficiently low to ensure that partial and main indices do not explain the same information. However, sensitivity to changes of indicator values are quite remarkable in the case of categorical indices (NHI and TVI), which are highly dependent on expert knowledge. This is an interesting result warning us of the risk of building assessment tools exclusively based on expert knowledge.

4. Discussion

While landscape ecology emerged in the 80s in Europe (Naveh and Lieberman, 1984; Burel and Baudry, 2000), it has been undergoing unprecedented developments in theory and practice in other continents, as major advances in ecological research have been made through spatial analysis and modelling (Wu and Hobbs, 2002). However, the high expectations of landscape indices to improve our understanding and prediction of ecological processes have not always been satisfied, thus making their application to land planning difficult (Corry and Nassauer, 2005). Li and Wu (2004) identified three kinds of critical issues: conceptual flaws in landscape pattern analysis, inherent limitations of landscape algorithms and the improper use of pattern indices. Generally speaking, research related to planning and designing alternative landscape scenarios requires much more information about the relationship between patterns and processes (Opdam et al., 2001). On the other hand, there is still a great deal to be done in the process of integrating ecological and landscape considerations in most regional, urban, and sectorial planning to attaining an acceptable standard of sustainable development. The Index of Sustainability (Esty and Cornelius, 2002) and the Ecological Footprint (Rees and Wackernagel, 1996), which is available for most European countries, provide eloquent measures of the degree of unsustainability of dominant trends.

Applying SEA to planning at the regional, county and municipal levels in metropolitan areas is a complex challenge because of (i) the complexity of planning procedures; (ii) the difficulties of incorporating environmental assessment in plans and programs; and (iii) the lack of intelligible assessments that make public participation possible (Mallarach and Marull, 2006). However, in practice, one of the biggest hurdles is the lack of methodologies for establishing socio-environmental parameters. The decision to incorporate our proposal of LSI to the existing methodologies was precisely justified as it provides a quantitative approach for SEA of land use plans and programs (Botequilha and Ahen, 2002), aimed at helping to reduce the negative impact of the proposed interventions.

The LSI is a quantitative cartographic index that incorporates, via expert knowledge and GIS calculation, various factors which are considered relevant and combines them in a way that is useful for making environmental management decisions. It is necessary to emphasize that the index does not disqualify or accredit projects, but it simply alerts of their environmental consequences. Its automatic application is not desirable, but the information that it provides during or after the plan elaboration process can be very important. In certain cases (LSI = 1–3), the index clearly shows the inconvenience of executing a plan, but this is not the usual scenario. LSI is most useful is during the evaluation of different plan alternatives. When the alternative of lower impact is not selected, it is very helpful for designing measures of correction and/or compensation. On the basis of the type of plan analyzed (regional planning, road, railway, etc.) and to the variable that weighs the most in the final value of the index (Δ_{TVI}, Δ_{NHI}, Δ_{ECI}), it will be possible to decide which is the most adequate plan.

To be useful to planners, indices must be reliable at the scale required for decision making (Thompson and McGarigal, 2002). The aim of LSI is not so much to achieve a precise algorithm, which may prove to be unattainable, but rather as an operational tool. The map scale employed (≥1:25,000) permits environmental impact evaluations at the regional, county, and sub-county levels. By contrast, this methodology constitutes a benchmark framework at the municipal urban planning level, and requires smaller map scale impact assessments, similar to those used in drawing public work projects (<1:5000), which normally require additional empirical data collected from the field.

If it is used selectively, the LSI should prove useful in deciding how suitable a given infrastructure or urban development plan or program is for a given location. It should be stressed that the main worth of the numerical values provided by the LSI and its sub-indices is that they allow quantitative, quick map-based comparisons. One of the principal advantages of the method described here is that it requires a fairly modest volume of data. A further advantage is its clarity, given that the formulae are based on explicit models and all of the constants and variables can be easily modified to take local conditions into account, when complementary empirical data is available. It is therefore possible to successively refine such models as the basic parameters of their key components become better understood and known.

However, the reliability of the indices also depends on both the algorithm used and the parameters included. The models weigh up a set of composite indices, which are mere simplifications of an extremely complex reality. The expert selection (which is necessarily subjective) of the parameters is of vital importance if the algorithm is to provide a reasonable approximation to the phenomenon being studied. It should also be borne in mind that the indices help place phenomena in a hierarchy and monitor their behaviour, but such behaviour is neither isomorphic nor (in most cases) does it capture the whole range for which parameters are sought. In consequence, security devices are needed to ensure the robustness of the approach. This was the reason to assess, for the LSI, the redundancy of the information provided by the main indices, the sensitivity to changes in parameters, and the goodness-of-fit to independent field data.

The BMR is one of the most dynamic metropolitan areas, with one of the highest coincidences of environmental pressures and impacts in the European Union. If current plans and trends are not checked, urban and infrastructure development will exert even greater pressure on natural systems in the future (Paül and Tonts, 2005), particularly along plains and valley bottoms, creating severe impacts on critical environmental resources, functions and values. Accordingly, new tools and criteria are needed to ensure that the region's development is compatible with the maintenance of social, ecological, and economic goods and services. In addition, public pressure for high environmental standards respecting the region's ecology and landscapes will increasingly make itself felt on both public and corporate decision-making. In this context, the application of the LSI on the BMR plan and its environmental evaluation would be an excellent opportunity to re-orient current metropolitan planning towards a more sustainable development. Our initial findings also suggest that this methodology could, with suitable modifications, be employed in other regions.

5. Conclusions

The LSI constitutes a holistic index for SEA that makes an assessment of the suitability for land development for a given area. It is formally integrated in mathematical language, developed through GIS, and based on a hierarchical, modular structure incorporating the impacts of plans on biological, geological and hydric resilience (TVI), natural heritage (NHI), and ecological connectivity (ECI). The applications of the method to date have shown it to be highly effective and – more importantly – demonstrated the ease with which its underlying concepts and application can be grasped by planners, who are its main end-users (Marull, 2005).

The quantitative and cartographic language, developed through GIS, employed by the LSI, facilitates conveying results to planners and policy makers. A further advantage is that it is straightforward to carry out the successive iterations needed to assess the environmental impacts of different alternatives of planning and corrective measures.

Planners and designers should be cautious in making ecological inferences from land index values applied to alternative plans. In this context, our methodology is open for debate. The precautionary principle indicates that a lack of precise scientific data on some key features of the biosphere, lithosphere and hydrosphere cannot prevent the adoption of planning measures to counteract unsustainable development. One can envisage more environmentally appropriate planning in the future as new, more comprehensive and reliable data become available to the public and policymakers to increase general awareness and, thus, a more informed and conscious public participation.

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