A GIS Methodology for Assessing Ecological Connectivity: Application to the Barcelona Metropolitan Area

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Joan Marull
Autonomous University of Barcelona

Josep-Maria Mallarach
Universitat de Girona

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A GIS methodology for assessing ecological connectivity: application to the Barcelona Metropolitan Area

Joan Marulli[a], Josep M. Mallarach[b,*]

[a] *Barcelona Regional, Zona Franca, Edifici Z, Carrer 60, 25-27 08040 Barcelona, Spain*
[b] *Departament de Geografia, Plaça de Sant Domènec, Universitat de Girona, 17000 Girona, Spain*

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Abstract

We developed a new methodology for the assessment of landscape and ecological connectivity at regional scale. This method has been entirely formalized using mathematical language, is supported by a topological analysis of a 1:25,000 scale land use map, and has been developed using Geographic Information Systems (GIS). The method allows the elaboration of a diagnose of the connectivity of terrestrial landscape ecosystems, on the basis of a previously defined set of ecological functional areas, and a computational cost-distance model which includes the barrier effect. This last component takes into consideration the type of barrier, the distance impact, and the adjacent land use and vegetation type. We defined two new compound indices: one for ecological connectivity and another for the barrier effect. The practical interest of our model is that it not only allows a cost-effective assessment of the current situation, but it has predictive capabilities, allowing the quantitative assessment and comparison of the impacts resulting from different planning scenarios or different infrastructure alternatives on the landscape and ecological connectivity.

The application of this model to the Barcelona Metropolitan Area (BMA), 16% of which is currently classified as urban, showed that 65% of the BMA area is currently occupied by functional ecological areas, and that 18% is covered by artificial barriers, although they have a direct negative impact on 56.5% of the area. The model also allowed the identification of vulnerable spots, including 1.7% of the BMA that has a critical importance for ecological connectivity, as well as the network of landscape linkages and ecological corridors that offer a high restoration potential. Further applications of this methodology assessing the impacts of regional and urban plans on ecological connectivity, suggest than it could easily be extrapolated to other regions.

Keywords: Barcelona; GIS; Metropolitan area; Ecological connectivity; Regional planning

1. Introduction

Since the 1990s, scientific concerns for habitat and ecosystem fragmentation and landscape and ecological connectivity has entered the political arena, as can bee seen the Global Strategy for Biodiversity (1992), the Habitat Directive (1992), the Paneuropean Strategy of Biological and Landscape Diversity (1995) or the Biodiversity Strategy of the European Community (1998). The EECONET (European Ecological Network) declaration, endorsed by the European Union Treaty (1991) has fostered a gradual development of ecological networks in many European countries (Jongman, 1995; Kubes, 1996). The principles

* Corresponding author. Tel.: +34-972-267140.
E-mail addresses: jmarull@bcnregional.com (J. Marulli), jmallarach@natura.ictnet.es (J.M. Mallarach).

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suggested by the EECONET framework include that the network: (1) must encompass the places of greatest importance for the conservation of the biological and landscape related diversity, (2) must guarantee the keeping of the ecological processes and the connectivity of the territory, (3) must be incorporated into the planning of the territory, and (4) must promote sustainable development (Bennet, 1991).

The analysis and modeling of ecological permeability or connectivity has been the goal of several methodological developments in different countries, usually based on landscape ecology principles (Beier and Noss, 1998; Gustafson and Gardner, 1996; With and Crist, 1995; Forman, 1990; Schreiber, 1987) such as in the Netherlands or Denmark (Brandt, 1995), although in some cases, such as the Estonia ecological network (Sepp et al., 1999) or the Territorial System of Ecological Stability developed in Slovakia and the Czech Republics (Kubes, 1996) combine these principles with planning pragmatic approaches.

However, there is a lack of quantitative methods of landscape ecology to cost effectively assess ecological connectivity or ecological fragmentation at regional scale, in a way that can be easily incorporated into the planning processes and the strategic environmental assessment. A difficulty that most existing methodologies have for assessing ecological connectivity is that they are very data demanding, including distribution of linear features and movement requirements for key species (Múgica et al., 2002). As suggested by Gardner and O'Neill (1990) the simplest model that can adequately explain the observed phenomena is the most useful.

This paper has a double purpose; first, to present a new Geographic Information Systems (GIS) quantitative methodology, based on landscape ecology principles, for assessing several aspects related with landscape and ecological connectivity, that could be applied either to regional planning or to strategic environmental impact assessment. And second, to show the performance of this methodology in a case study, the Barcelona Metropolitan Area (BMA), in Catalonia, Northeastern Spain, displaying some preliminary results, and discussing its implications. Since our methodology was developed in the BMA, we first present some key characteristics of this area.

2. The Metropolitan Area of Barcelona

The Barcelona Metropolitan Area is one of the most densely populated areas of Europe. With a surface of 3200 km^2 and 4.2 million people, it currently has a density of 1300 inhabitants/km^2. However, BMA also maintains natural areas of great value, with a high landscape and biological diversity, from Mediterranean sierras and cliffs, extensive agrosystems, to sandy, rocky coastal areas and deltas, totaling over 40 habitats of European significance, to be included within the Nature 2000 network. No wonder, therefore, that the BMA has been identified as one of the European regions with the highest concentration of pressures and impacts on the environment (European Environmental Agency, 1999).

Since the establishment of the first Natural Park of Spain in Sant Llorenç del Munt (1972), local and regional governments have been working to provide legal protection to the most significant natural sites, creating a system that, nowadays, almost covers 20% of the BMA (Fig. 1). Most of this system is located on mountain forested areas, which are becoming increasingly isolated by the expansion of urban areas and traffic infrastructures spreading over the valleys and plains. Traffic and energy infrastructures combined cover some 20,000 ha (6% of the BMA).

Typically, municipal land use and urban plans do not take into consideration functional ecological processes, and, as a result, most protected areas located on littoral sierras, such as the Parks of Collserola and Serres de Montnegre-El Corredor, had already become biological islands, surrounded by a sprawl of urban, industrial, commercial areas, and highways.

It is well known that a set of natural areas, even when they are properly designed and managed—which is uncommon—are not sufficient to provide for long term protection of biodiversity, not to mention to perform many other important ecological functions (Forman and Godron, 1986; Noss and Coperrider, 1994). Moreover, recent studies in the BMA have revealed that some components of biodiversity, such as a large number of endangered o threatened bird species, are concentrated outside protected natural areas, specially in agricultural mosaic landscapes, such as the Vallès plains (Pino et al., 2000).

The main cause of habitat and landscape fragmentation in the BMA has been rapid urban and industrial

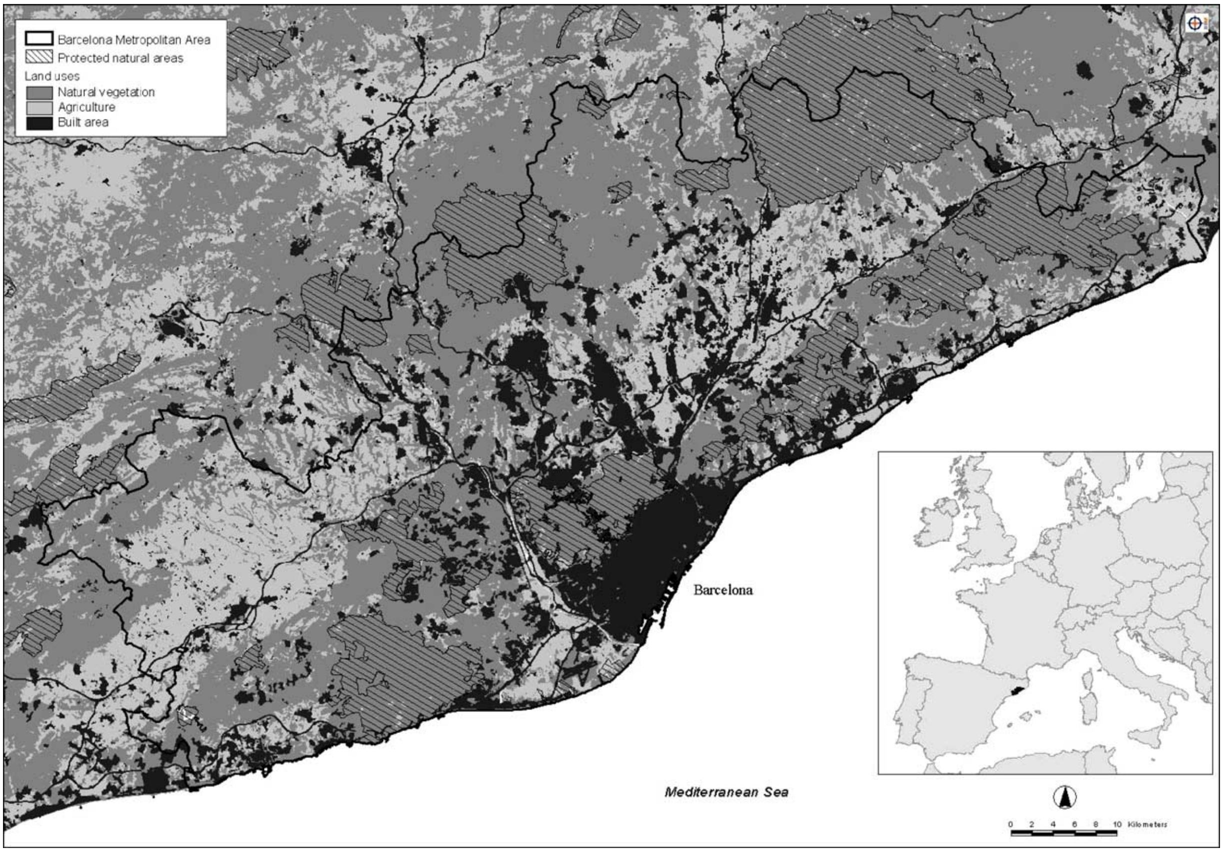

Fig. 1. Simplified land cover map of the Barcelona Metropolitan Area, showing the distribution of main urban areas and the system of protected natural areas.

sprawl. Indeed, from 1972 to 1992 urban land use steadily increased from 22,000 to 46,000 ha, whilst population only increased a 7%, in the same period, with a tendency to stability during the last two decades (Beltran, 2000)—see Fig. 2.

According to the last land use map produced by Barcelona Regional and Institut Cartogràfic de Catalunya (2001), urban land uses and infrastructures covered around 58,000 ha in 1997, from which 22,000 ha were recent low density residential areas. Natural and seminatural habitat transformation rate has been around 1000 ha per year, an unsustainable trend that poses increased impacts and pressures from new urban developments. Most municipal urban plans in the BMA do not adequately integrate environmental concerns, and a large portion of urban growth has evolved on the margins of municipal planning (Mallarach, 2000). The Barcelona Metropolitan Plan of 1976, amended more than 2000 times, is nowadays completely obsolete. The addition of 164 current municipal urban plans gives for the BMA a potential of new 1500 ha for urban areas. Therefore, if all current plans were to be executed, urban area would cover 22% of BMA, creating significative direct impacts over an area almost twice as large.

Thus, from a landscape ecological point of view, one of the main trends in the BMA during the last thirty years has been the rapid fragmentation and transformation of the natural landscape, creating thousands of patches of habitat, increasingly smaller and disconnected. While some patches can have significant social value, such as green buffers or small urban parks, the majority of them have lost many of its ecological functions. On the other hand, the impacts produced by the combined effect of the sprawl of urban, industrial and transports systems, i.e. air or light pollution and noise,

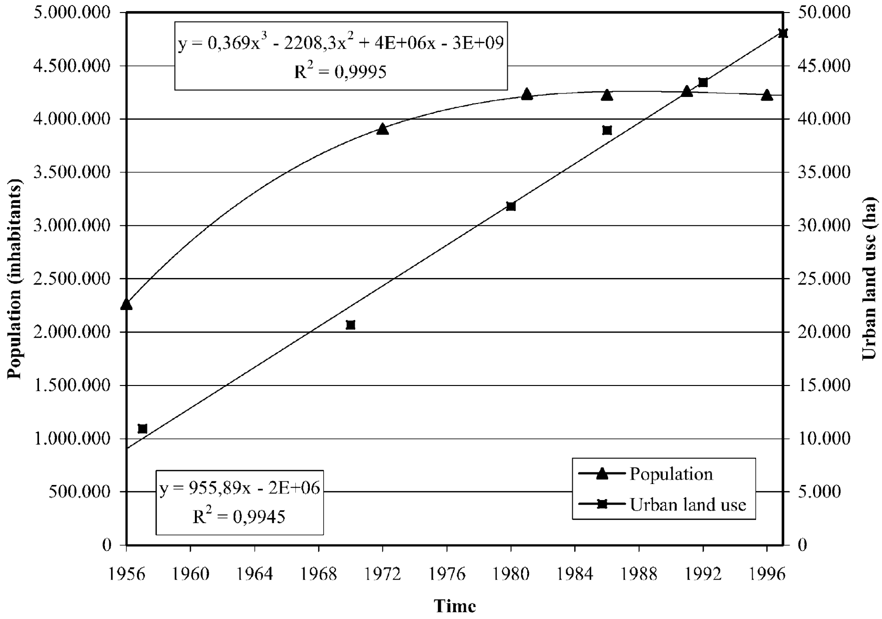

Fig. 2. Evolution of urban land use area and total permanent population from 1957 to 1997 in the Barcelona Metropolitan Area.

are such that they are negatively impacting almost all naturals systems of the BMA (Mallarach, 2000).

3. Methodology

Our method relies on a series of topological analysis of land use and infrastructures maps, it has entirely been formalized using mathematical language, and it has been developed and implemented using Geographic Information Systems. Depending on the objectives of each analysis, we choose raster or vector formats from ArcInfo program (ESRI, 2000), in all the stages of the project.

The land use map had been produced by Barcelona Regional and Institut Cartogràfic de Catalunya (2001), combining color and infrared orthophotography 1997–1998 interpretation, field work, and existing urban and infrastructure maps at 1:5000. Map scale is 1:25,000, it includes 41 classes, 23 non urban and 19 urban, with minimum mapping area of 1 ha for urban classes and 2 ha for non urban classes, and a pixel size of 25 m^2. General accuracy for the entire land use map is over 85%.

The following sections present the three key components of this methodology: the ecological functional areas, the Barrier Effect Index (BEI), and the Ecological Connectivity Index (ECI), including three variations of this last index that can be used for different applications.

3.1. Ecological functional areas

Our method begins with the identification of what we define as “ecological functional areas”. When assessing ecological connectivity we need, first, to make a decision about the natural areas that need to be connected, which cannot be restricted to the existing system of protected natural areas. Next, we need to decide what kind of connectivity network would be required to allow the flux of energy, matter, genetic information, and so on, that is necessary to sustain the ecological processes, allowing the long term conservation of biodiversity. However, in a highly populated and fragmented landscapes, such as those of the Barcelona Metropolitan Area, ecological functional areas do have an intrinsic value, independently of the level of connectivity that they may have.

For the identification and mapping of these ecological functional areas we used the following protocol:

(1) Based on the 1:25,000 land use map, we performed a first topological analysis grouping the original 41 land use classes, depending on its affinity, in eight "simple ecological functional areas". We defined these simple ecological functional areas by applying two quantitative criteria: a minimum surface (S_r = 50–200 ha), depending of each land use type, based on a review of existing literature (Andrén, 1994; Bender et al., 1998; Fahring and Merriam, 1994; Virgós et al., 2002), and the inclusion of at least 30% of its polygons, based on the results of the analysis of the statistical distribution of polygon sizes.
(2) The areas that could not be considered simple ecological functional areas, were used to perform a second topological analysis, grouping them in "forest mosaics" or "agricultural mosaics". In both cases we applied the same criteria of minimum surface (150 and 50 ha, respectively), based on existing literature (Forman, 1990; Virgós et al., 2002), and statistic distribution (including at least 30% of its polygons) than we did in the previous analysis.
(3) The areas that were not included in the two previous categories were used to perform a third topological analysis to identify "agroforest mosaics", again applying the same criteria of surface (over 50 ha of size) and statistic distribution.
(4) These previous steps allowed us to obtain eleven types of "ecological functional areas", including eight simple classes and three mosaic classes. All remaining areas were considered "fragmented areas".

We decided that our "ecological functional areas" should include mosaics, because it has been proven the existence of a strong correlation between diversity of habitats (i.e. mosaic landscape) and biodiversity, specifically vertebrate diversity. In our study area, extensive agroforest mosaics are the second habitat in terms of vertebrate diversity, after wetlands (Institució Catalana d'Història Natural, 1999) and many endangered bird species are concentrated on agroforest mosaic landscapes (Pino et al., 2001).

Results of the analysis performed at the BMA are displayed in Fig. 3. As expected, the combined surface of the ecologically functional areas C'_r (65.25% of the BMA) is lower than the land use surface of natural and semi natural habitats to be connected C_r (78.53% of the BMA). It is worthwhile recalling that, according to the percolation theories (O'Neil et al., 1992; With and Crist, 1995), when the proportion of natural habitats becomes less than 60% in a given region, problems for biodiversity conservation begin to appear. A considerable proportion (24.75%) of the BMA is covered either by urban areas or by natural

Code	Type	S_r (ha)
C'1	Wetf orestlands	≥ 100
C'2	Wetlands	≥ 50
C'3	Dryf orestlands	≥ 200
C'4	Shrubs and prairies	≥ 200
C'5	Irrigatedg roves>	_ 50
C'6	Irrigatedc roplands	≥ 50
C'7	Dryg roves>	_ 100
C'8	Dryc roplands	≥ 50
C'9	Forest mosaic	≥ 150
C'10	Agricultural mosaic	≥ 50
C'11	Agroforest mosaic	≥ 50

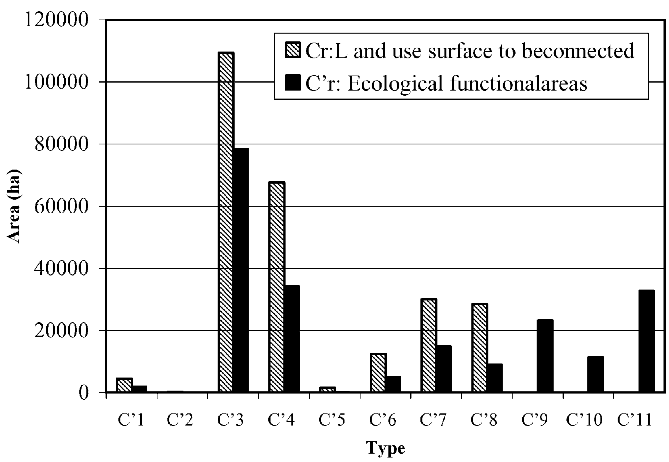

Fig. 3. Results of the topological analysis at the BMA showing the existing relationship between land use types to be connected and ecological functional areas.

areas that are too small to be considered functional, from an ecological point of view. The largest ecologically functional areas are Mediterranean forestlands (mainly evergreen forest and pine forests) covering 24.16% of the BMA, followed by forest and agroforest mosaics, which cover 20% of the study area. On the other end, wetlands and irrigated groves cover less than 0.1% of the BMA. In particular, small wetlands, which hold the highest vertebrate biodiversity (0.03% of the BMA) are the rarest habitat type, and therefore the most vulnerable. Fig. 4 shows the distribution of the main ecological functional areas in the BMA such as forestlands in mountain ranges and agrarian systems that still occupy some portions of the low valleys and plains.

What follows next is a presentation and discussion of two indices we defined to deal with ecological and landscape connectivity: the Barrier Effect Index and the Ecological Connectivity Index.

3.2. Barrier Effect Index

Barriers include all artificial land uses that create obstacles to the flow of energy, information, or matter across the matrix, in other words, the landscape resistance (Forman, 1995). To calculate the effects of artificial barriers on ecological and landscape connectivity we defined a Barrier Effect Index (BEI) as follows:

$$\mathrm{BEI} = \frac{Y_{\mathrm{i}}}{Y_{\max}}$$

were Y_{i} is the value of the barrier effect in a pixel and $Y_{\max}$ is the maximum value of the barrier effect calculated on a given area.

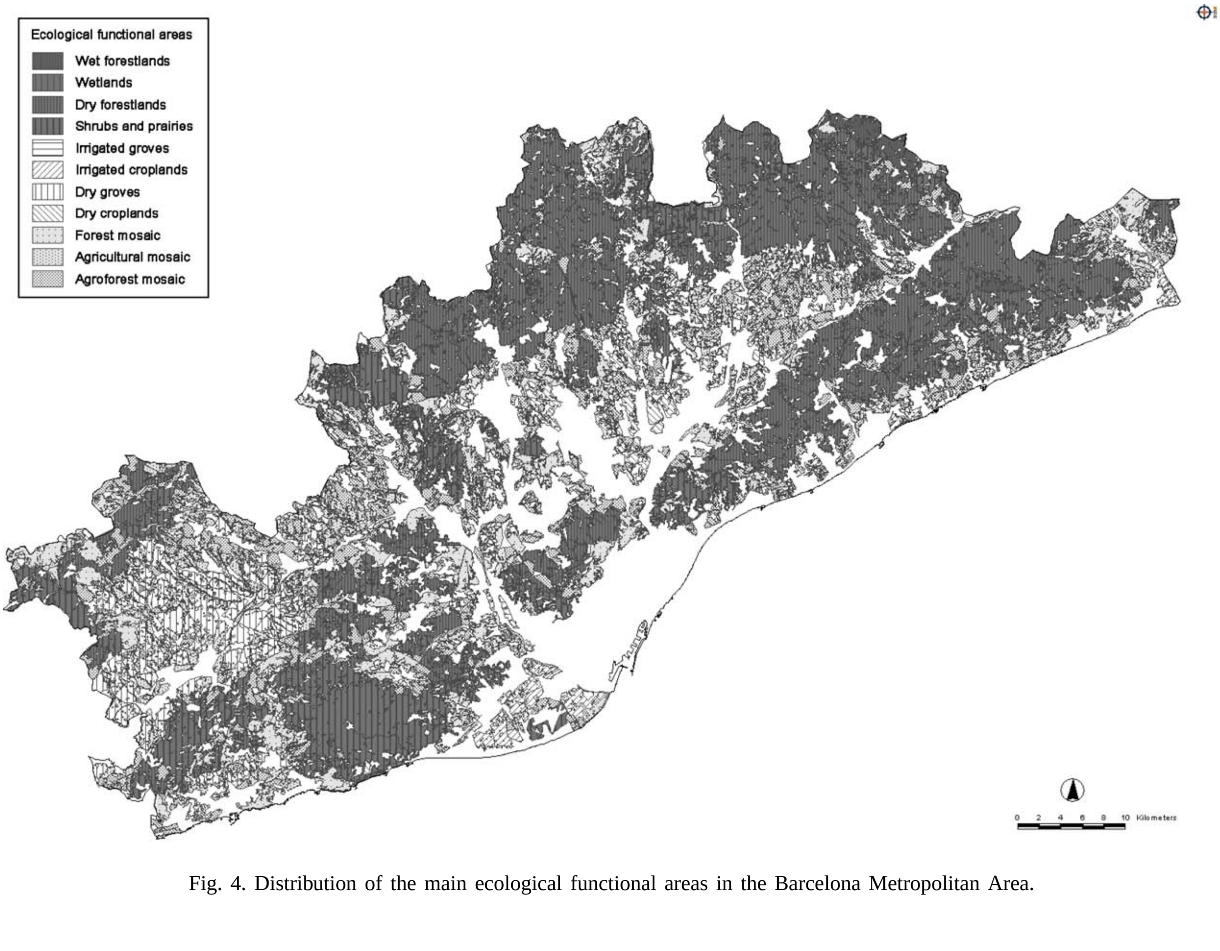

Fig. 4. Distribution of the main ecological functional areas in the Barcelona Metropolitan Area.

Table 1
Basic barrier types (B_s) in the Barcelona Metropolitan Area

Code	Type	Weight (b_s)	ks_1 [a]	ks_2 [a]
B_1	Low density urban areas and parks	$b_1 = 20$	$k1_1 = 11.100$	$k1_2 = 0.253$
B_2	Secondary communications	$b_2 = 40$	$k2_1 = 22.210$	$k2_2 = 0.123$
B_3	Water	$b_3 = 60$	– [b]	– [b]
B_4	Main communications	$b_4 = 80$	$k4_1 = 44.420$	$k4_2 = 0.063$
B_5	Urban areas	$b_5 = 100$	$k5_1 = 55.520$	$k5_2 = 0.051$
			$\alpha = Y_s(b_s/2)/b_s$	
			$Y_3 = b_3$	

[a] Constants for a logarithmic fall of 30% ($\alpha = 0.3$).
[b] For $s = 3$ there is not surrounding spatial affectation.

The BEI is based on the weight that we assigned to each barrier type (Table 1), the affected land use class, and the distance from the barrier, according to a potential impact matrix and a logarithmic relationship of distance, as shown in Table 2. Thus, it reflects an impedance surface, were a_i corresponds to the maximum significantly affected distance for each type of barriers, and A_i corresponds to the potential impact value for each type.

This model applies the CostDistance function using the Grid module of the ArcInfo program (ESRI, 2000) and uses two databases: one "origin surface" (X_{B_s}; $s =$ 1–5) for each barrier type (B_s) (and one "impedance surface" (X_A) from the potential impact matrix (M_A). From this process, an adapted cost distance is obtained ($d'_s = b_s - d_s$; where $b_s - d_s > 0$; being $d_s =$ cost distance). In this way, our model individually calculates the barrier effect Y_s for each subclass type. Based on Kaule (1997) and Hooftman and Kuijfhout (1997), we assumed that the effect of a single barrier from a given point is logarithmic and decreasing as distance increases, according to the following expression.

$$Y_s = b_s - ks_1 \ln(ks_2(b_s - d'_s) + 1)$$

where b_s is the weight of each barrier type, ks_1 and ks_2 are constants for logarithmic decreasing function, and d'_s is the adapted cost distance per barrier type. Constants ks_1 and ks_2 are needed for adjusting the shape of the function to a logarithmic fall of 30%. An important procedural GIS aspect needs tot be pointed out here. Since the barrier effect must have decreasing values, the calculated cost distance values need to be inverted, subtracting from b_s, and then one has to truncate the resulting values to 0, to avoid the appearance of negative values, which would be meaningless. Fig. 5 shows the resulting function, corresponding to a theoretical case where $s = 5$.

Thus, the entire barrier effect Y in the landscape is defined as the addition of the effects of all barrier types on a given area. The reason for this is that a combination of different barrier types, such as highways, railways and urban areas, has a potential effect much greater that the maximum impact of each individual type of barrier. In other words, it is a way of taking into consideration cumulative impacts. From this process, a "barrier effect surface" (X_Y) is obtained.

Table 2
Impact matrix (M_A) for the calculation of the Barrier Effect Index

Code	Type	Classes included [a]	Affectation coefficient (a_1) [b]	Affectation value (A_1)
V_1	Neutral	N_1, N_2	$a_1 = 1000$ m	$A_1 = 0.10$
V_2	Agriculture	C_5, C_6, C_7, C_8	$a_2 = 750$ m	$A_2 = 0.13$
V_3	"Natural"	C_1, C_2, C_3, C_4, E_2	$a_3 = 500$ m	$A_3 = 0.20$
V_4	Barrier	B_1, B_2, B_3, B_4, B_5	$a_4 = 250$ m	$A_4 = 0.40$
V_5	Corridor	E_1	$A_5 = 1$ m	$A_5 = 100$
				($A_n = b_5/a_n$)

[a] Class description is found in Table 3.
[b] A_1 defines the maximum significantly affected distance by each type.

Table 3
Ranking of the barrier effect in the landscape, according a decimal scale, with indication of some examples

Barrier Effect Index (BEI $= (Y_{\mathrm{i}}/Y_{\mathrm{max}})$	Effect	Type of barriers
0	Non existent	Lack of anthropogenic barriers Total permeability of matter, energy and information
1 2	Low impact	Small and scattered barriers, such as isolated farms High ecological permeability remains
3 4	Medium impact	Small roads or low density residential areas Medium ecological permeability remains
5 6	High impact	Main roads, scattered urban, commercial or industrial areas Low ecological permeability
7 8	Very high impact	Synergic combination of urban areas and highways or other transport corridors Very low ecological permeability
9 10	Critical impact	Synergic combination of large, high density urban areas with main transport corridors Minimum ecological permeability

$$Y = \sum_{s=1}^{s=n} Y_s$$

BEI is a relativistic index, which means that for each given area where it is applied it has been designed to give values within an ordinal scale from 1 to 10, as shown in Table 3. The reason for this is twofold. First, barrier impact cannot be easily measured in absolute terms, being always a function of the diverse natural systems or landscapes that are affected. Second, grouping the high variability of continuous BEI potential values using a conventional discrete decimal scale helps in making interpretations and comparisons easier.

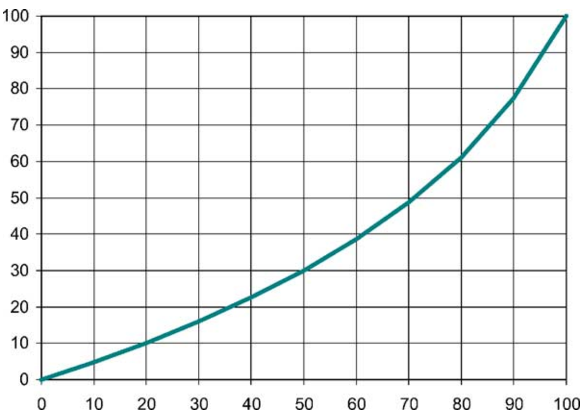

Fig. 5. The function corresponding to the theoretical case where $s = 5$ is used to illustrate how the formula $Y_s = b_s - ks_1 \ln(ks_2(b_s - d'_s) + 1)$, used in calculating the barrier effect, actually works.

The application of the BEI to the BMA showed that at least 56.5% of the BMA is under negative impact from artificial barriers (see Fig. 6) a result that is comparable with studies conducted in other regions (Forman, 2000; Trombulak and Frissell, 1999; Forman and Alexander, 1998). This figure does not take into consideration the extension of large natural protected areas, that are almost ecologically isolated already. If they were included, the proportion of the BMA under negative impact of barriers would doubtless raise to over 65%. The maps resulting from the application of the BEI (Figs. 7 and 8) show the peripheral distribution of large areas with continuous natural habitats, little affected by barriers, in contrast with the pervasive impacts spreading in the central part of the BMA, specially the Vallès plains, as well as around several protected natural areas located in coastal sierras.

3.3. Ecological Connectivity Index

Ecological connectivity refers to the functional aspects of the actual connection between the different elements of the landscape, from energy to information and matter, for instance nutrient cycles, pollen dispersion, and movements of flora or fauna populations or metapopulations. We defined an ecological

BEI	Impact level
0	No impact
1-2	Low impact
3-4	Medium impact
5-6	High impact
7-8	Very high impact
9-10	Critical impact

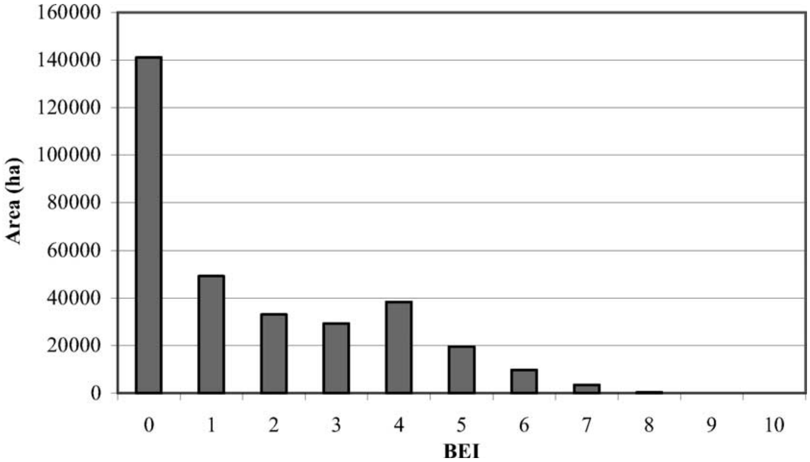

Fig. 6. Results of the application of the Barrier Effect Index (BEI) to the Metropolitan Area of Barcelona.

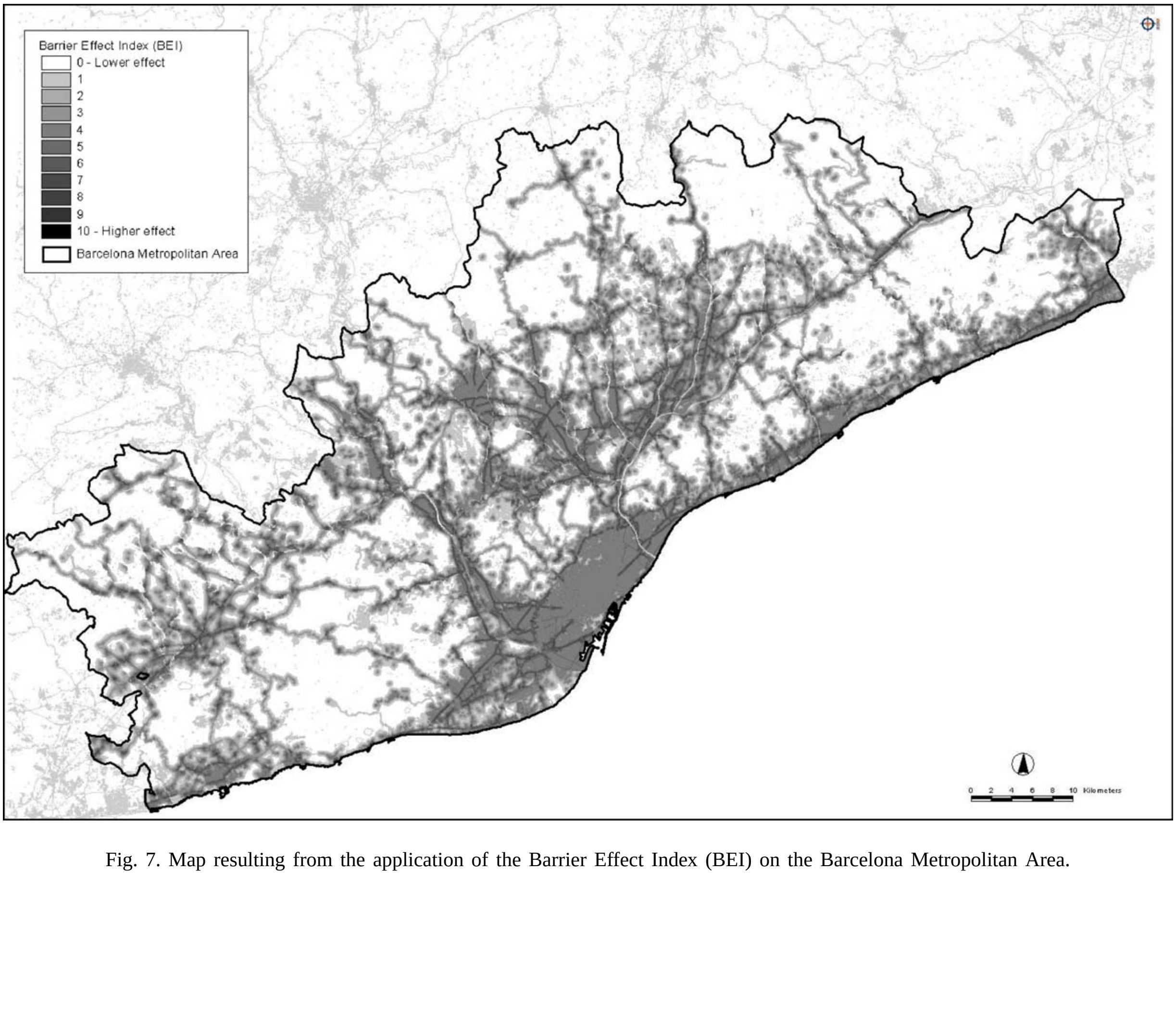

Fig. 7. Map resulting from the application of the Barrier Effect Index (BEI) on the Barcelona Metropolitan Area.

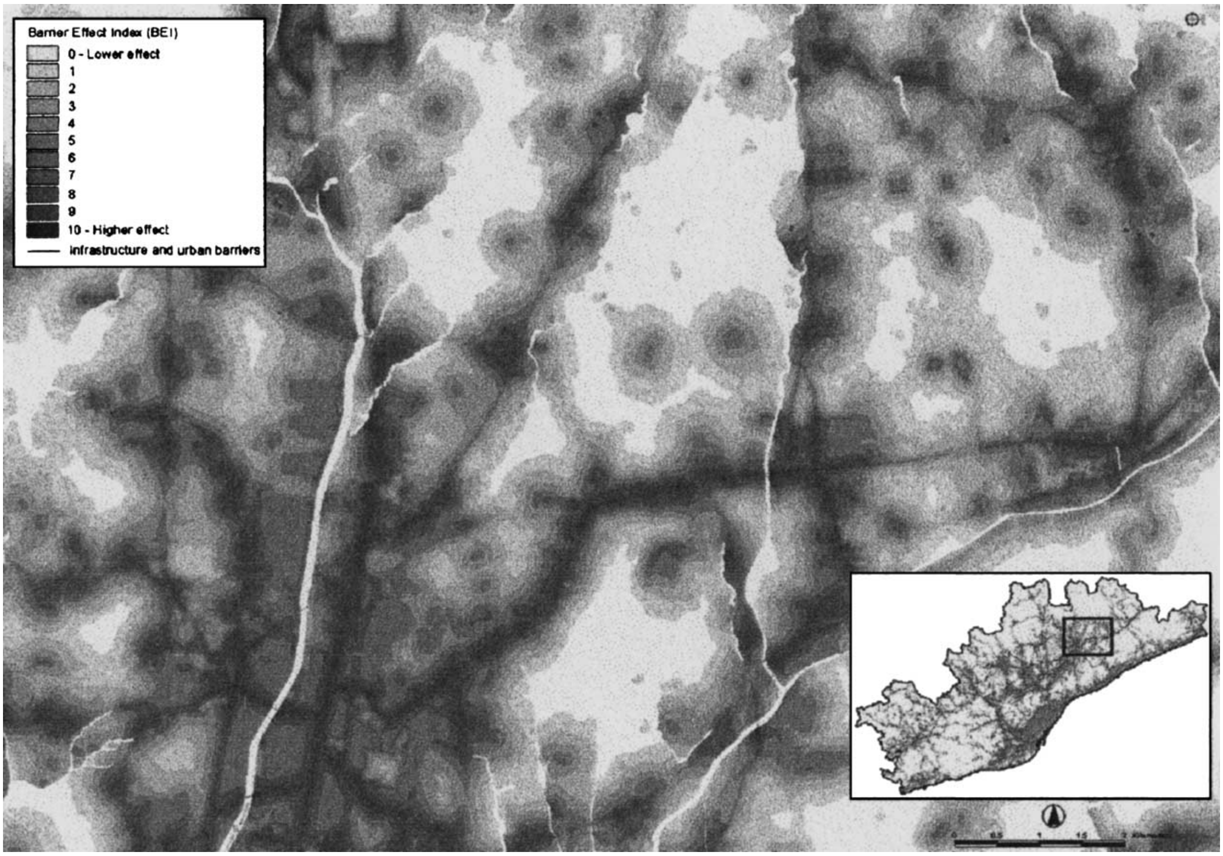

Fig. 8. Barrier Effect Index zoom map around the town of Granollers, Metropolitan Area of Barcelona.

connectivity index based on a cost-distance model that considers the different "functional ecological areas" and an "impedance surface" which incorporates the "barrier effect" Y and a "potential affinity matrix" M_C for all the land use types—see Table 4. This matrix includes the potential affinity range of values that we assumed it is reasonable to expect among the different types of ecological functional areas in our study area. Since all these weighs are expert-based, we decided to assess its significance on the results of the ECI, by performing a sensitivity analysis for a chance variation of all M_C weights of ± 0.3, resulting that the impact on the new ECI was negligible. In the calculation of ECI the barriers effect surface X_Y is very significant. However, among the areas where the barrier effect is minor, the surface of the affinity matrix X_C reveals interesting nuances that fully justify their elaboration.

The model applies the CostDistance function of the ArcInfo program (ESRI, 2000), using two databases: one "origin surface" for each type of ecological functional area ($X_{C'_r}$; $r = 1$–11) and one "impedance surface" resulting from the application the effect of the barriers and the potential affinity matrix ($X_I = X_C + X_Y$). In this way, we obtain an adapted cost distance by each type of ecological functional area ($d'_r \leq 20,000$ in order to avoid distorted results when several classes get combined). Finally, we calculate the total adapted cost distance value x for all the ecological functional area types, according to the following expression:

$$x = \sum_{r=1}^{r=n} d'_r$$

To facilitate interpretation and comparisons, we decided to transform the continuous values of the cost

Table 4
Affinity matrix (M_C) for the Metropolitan Area of Barcelona

Code	Type	C'_1	C'_2	C'_3	C'_4	C'_5	C'_6	C'_7	C'_8	C'_9	C'_{10}	C'_{11}
C_1	Wet forestlands	0	0.1	0.2	0.3	0.4	0.6	0.5	0.7	0.3	0.1	0.5
C_2	Wetlands	0.1	0	0.3	0.4	0.5	0.6	0.7	0.8	0.2	0.4	0.6
C_3	Dry forestlands	0.2	0.3	0	0.1	0.5	0.7	0.4	0.6	0.3	0.1	0.5
C_4	Shrubs and meadows	0.3	0.4	0.1	0	0.6	0.7	0.2	0.5	0.2	0.1	0.3
C_5	Irrigated groves	0.4	0.5	0.5	0.6	0	0.1	0.2	0.3	0.2	0.3	0.1
C_6	Irrigated croplands	0.6	0.6	0.7	0.7	0.1	0	0.3	0.2	0.2	0.3	0.1
C_7	Dry groves	0.5	0.7	0.4	0.2	0.2	0.3	0	0.1	0.2	0.3	0.1
C_8	Dry croplands	0.7	0.8	0.6	0.5	0.3	0.2	0.1	0	0.2	0.3	0.1
B_1	Low density urban areas and parks	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
B_2	Secondary roads and railways	1	1	1	1	1	1	1	1	1	1	1
B_3	Water	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
B_4	Main highways and railways	1	1	1	1	1	1	1	1	1	1	1
B_5	Urban areas	1	1	1	1	1	1	1	1	1	1	1
E_1	Riparian corridors	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
E_2	Transitional areas	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_1	Severely altered areas	1	1	1	1	1	1	1	1	1	1	1
N_2	Denude areas	1	1	1	1	1	1	1	1	1	1	1

distance to discrete values based on a decimal scale. Also, we decided to use a neperian logarithm to emphasize high values, because low values are associated with more artificialized areas, having less interest from the point of view of this index. Thus, we define the Ecological Connectivity Index as follows:

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

were x_i is the adapted cost-distance value in a pixel, x_max are the maximum and x_min are the minimum adapted cost-distance values on a given area.

We consider that this index reflects a kind of "general ecological connectivity", since its computation includes all the ecological functional areas C'. Thus, it is a generic approach which is not tied to specific indicator species. An interesting propriety of the ECI is that it has a relativistic distribution of values, always giving values between 0 and 10. This feature is useful to compare different alternatives. However, by the same reason, the General Ecological Connectivity Index cannot be used for comparing different geographical areas or different time periods in the same area.

Ranking distribution of ECI overestimates areas with high ecological fragmentation, which are common in many metropolitan areas, allowing the identification of areas of low absolute value as the only viable way of connecting existing ecological functional areas.

However, in a particular case, when $x_\mathrm{min} = 0$, $x_\mathrm{max} = x_\mathrm{t}$, we obtain a variation of the ECI, that we named Basic Ecological Connectivity Index ($\mathrm{ECI_b}$). Therefore, we can define:

$$\mathrm{ECI_b} = 10 - 9\frac{\ln(1 + x_\mathrm{i})}{\ln(1 + x_\mathrm{t})^3}$$

were x_t is the maximum possible adapted cost-distance value. $\mathrm{ECI_b}$ is useful for calculating the ecological connectivity of different geographical areas or distinct ecological functional areas C'_r. Values of $\mathrm{ECI_b}$ are comprised between 1 and 10.

Finally, from this Basic Ecological Connectivity Index ($\mathrm{ECI_b}$) we can derive another particular application, that we named the Absolute Ecological Connectivity Index ($\mathrm{ECI_a}$), which implies the addition of all $\mathrm{ECI_b}$ that had been calculated for the study area, according to the following expression:

$$\mathrm{ECI_a} = \sum_{m=1}^{m=n} \frac{\mathrm{ECI_b}}{m}$$

where m is the number of ecological functional areas C'_r considered. Values for $\mathrm{ECI_a}$ are more objective, so to speak, giving, in general, values lower than 10, and being very useful for comparing different territories or different temporal series, as well as for providing directions for regional and land use planning.

ECI	Category
1	No connectivity
2	Low connectivity
3	
4	Medium connectivity
5	
6	High connectivity
7	
8	Very high connectivity
9	
10	

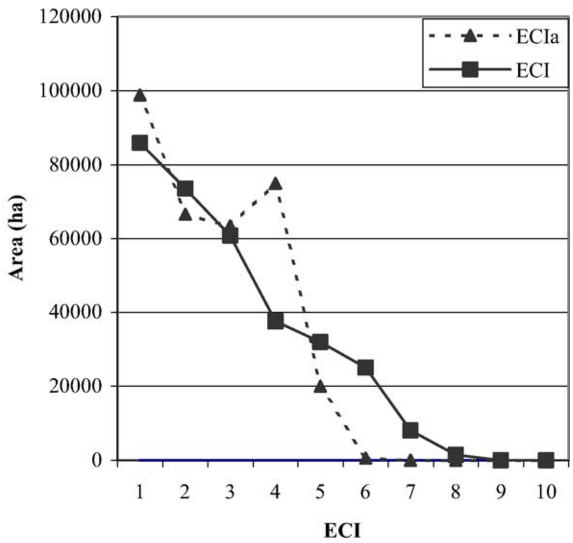

Fig. 9. Application of ECI and ECI_a to the Metropolitan Area of Barcelona.

Fig. 9 compares the results of applying both ECI and ECI_a to the BMA. It is not surprising that areas with very high ecological connectivity are absent, or that the areas having high ecological connectivity are scarce. Comparing how ECI and ECI_a work, we found out some significant lessons: ECI uses relative values which cover all possible ranks (0–10), resulting in a linear descendent function. Thus, ECI gives a significant proportion of high to medium values (ECI = 4–7) and a small proportion of very high values (ECI = 8–10). It could be said that it is either an “optimistic” or a “possibilistic” index, in the sense that it is useful for evaluating the relative worth of the existing ecological connections between natural ecosystems, such as fauna corridors, even when their value is quite low.

On the other hand, ECI_a uses absolute values and attains a maximum that depends on the “objective” ecological connectivity of the study area, which in the BMA is only 5, resulting in a descendent exponential function. Thus, ECI_a gives a significant proportion of medium to low values (ECI_a = 2–5) and almost none with high or very high values (ECI_a = 6–10). It, therefore, provides a more “realistic” assessment of the current status of ecological connectivity of our study area.

ECI_a maps (Figs. 10 and 11) show different scale images of the ecological and landscape connectivity for the terrestrial ecosystems of the BMA. One can discern the incidence of the ecological barriers (lower values), the relevance of topography (higher values), the problem of the ecological isolation (mosaic distribution of medium and high values) and, finally, the importance of the riparian corridor system that provide ecological connectivity among the largest remaining natural areas.

4. Diagnose for landscape and ecological connectivity

Once all the previous analysis were completed, we undertook an expert-based identification of landscape linkages and ecological corridors for the entire BMA. Following an iterative process, we decided to make the assumption that all areas having an ECI > 1 have a sufficient level of ecological connectivity. We believe that this decision is justified in our case study given the above mentioned high level of fragmentation already existing in the BMA. Then, we designed an ecological network to connect all areas with ECI > 1 using five categories: functional ecological corridors (ECI > 1), potential ecological corridors (ECI = 1), functional landscape linkages (ECI > 1), potential landscape linkages (ECI > 1), and stepping stone

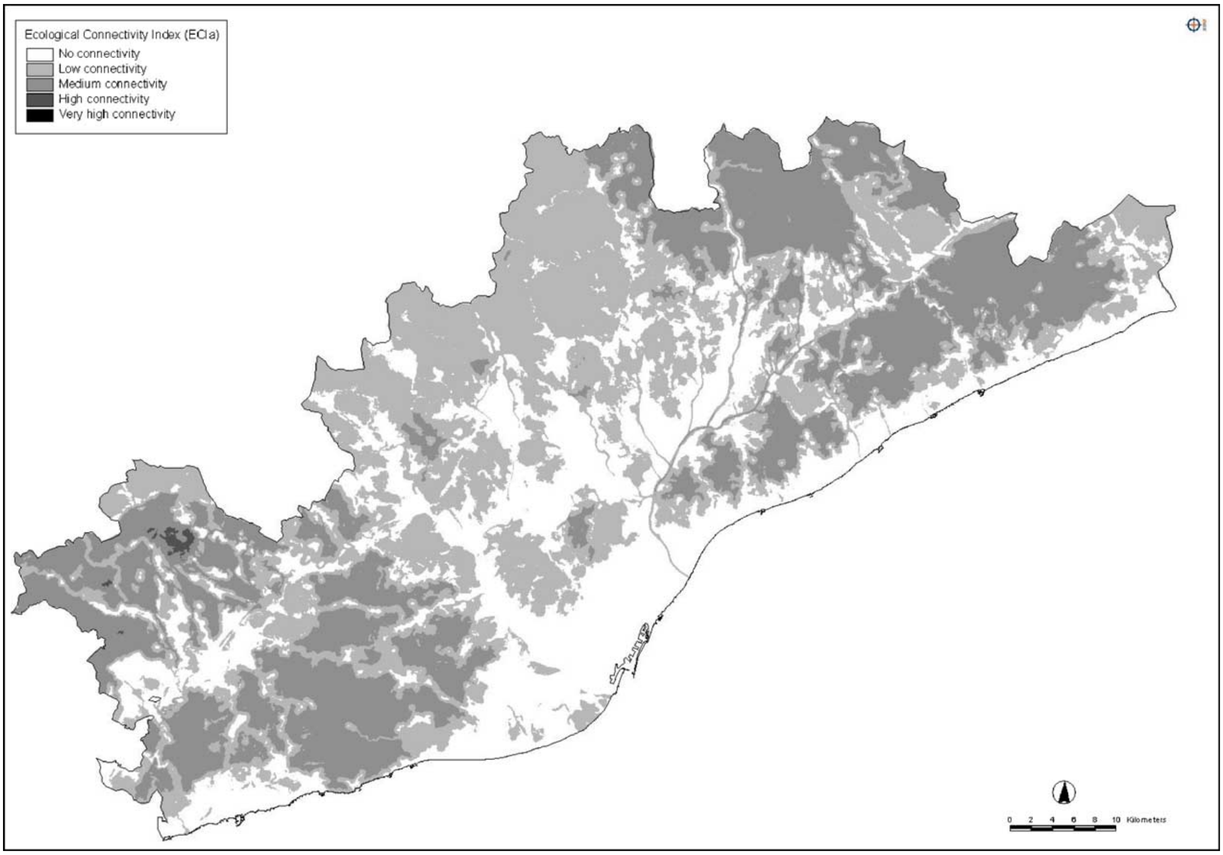

Fig. 10. Map resulting from the application of the Ecological Connectivity Index (ECI_a) to the Barcelona Metropolitan Area.

habitats. This last category was included to contribute to the ecological permeability and resilience of spaces already suffering from high fragmentation rates, reinforcing weak functional ecological corridors.

We decided to provide for redundancy as a means to compensate the vulnerability resulting from the intense pressures that are affecting many of the components of this ecological network. Also, we decided to include potential ecological corridors and landscape linkages, which require a variable level of ecological restoration, since there is an increasing social interest and political will in the BMA to restore them, as can bee seen in several undergoing restoration projects in the low Besòs and low Llobregat valleys.

As shown in Fig. 12, regional ecological corridors typically are linear continuous strips of land, several kilometers long, and a few hundred meters wide, with frequent stream or gully corridors connecting them to nearby stepping stone habitats or ecological functional areas. Given the current relationship between topography and land-uses in the BMA, most ecological corridors are found along river or stream corridors, although we could not include aquatic ecosystems due to the current lack of quality data for the entire BMA. Stepping stones habitats, on the other hand, tend to have low surface/perimeter ratio to reduce external disturbances, with a size which can attain a few hundred hectares, being distributed next to key ecological corridors. Finally, landscape linkages are designed to provide regional ecological connectivity among the largest protected natural areas. They often include ecological corridors and typically are 2–6 km wide.

All combined, these five categories include 30,989 ha, that is 9.5% of the BMA—see Fig. 13. Functional categories encompass 81% of the total area of this network, whilst the remaining 19% corre-

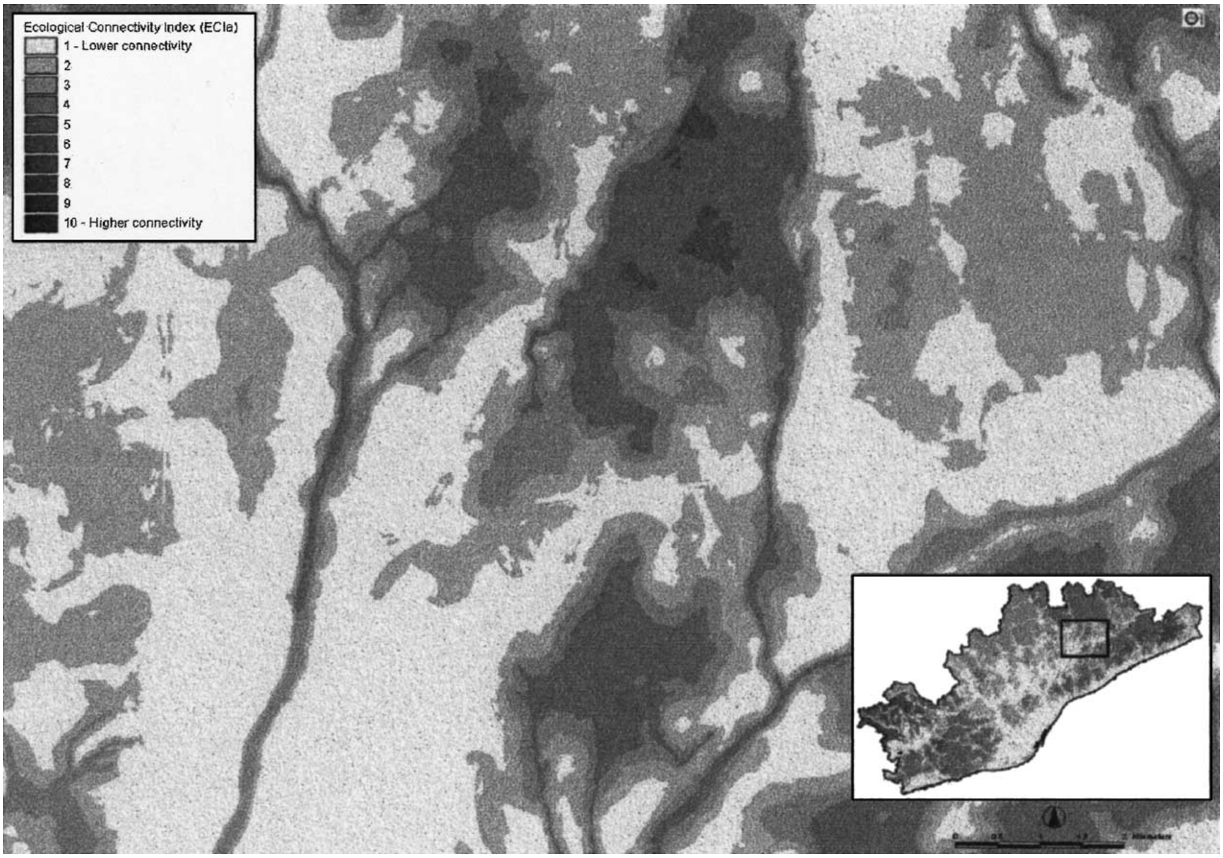

Fig. 11. Ecological Connetivity Index (ECI_a) zoom map around the town of Granollers, Metropolitan Area of Barcelona.

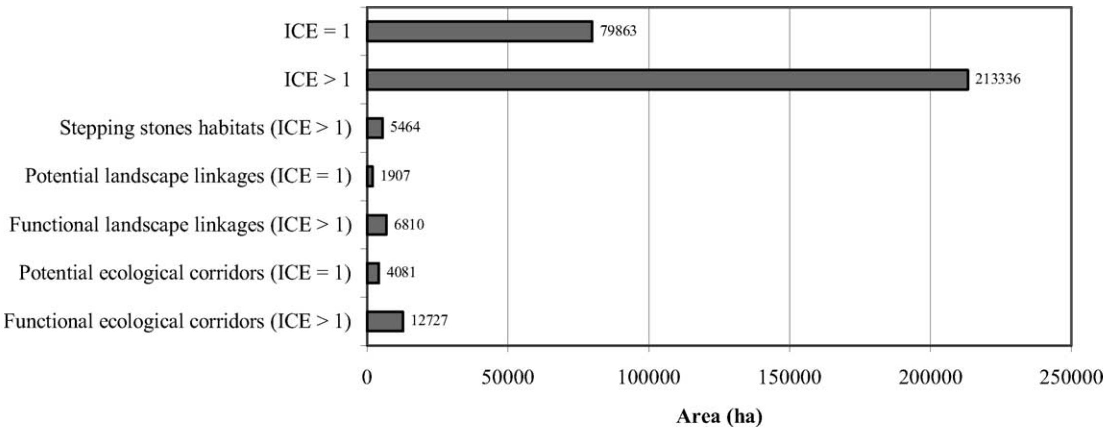

Fig. 12. Simplified diagnose of the landscape and ecological connectivity in the Barcelona Metropolitan Area.

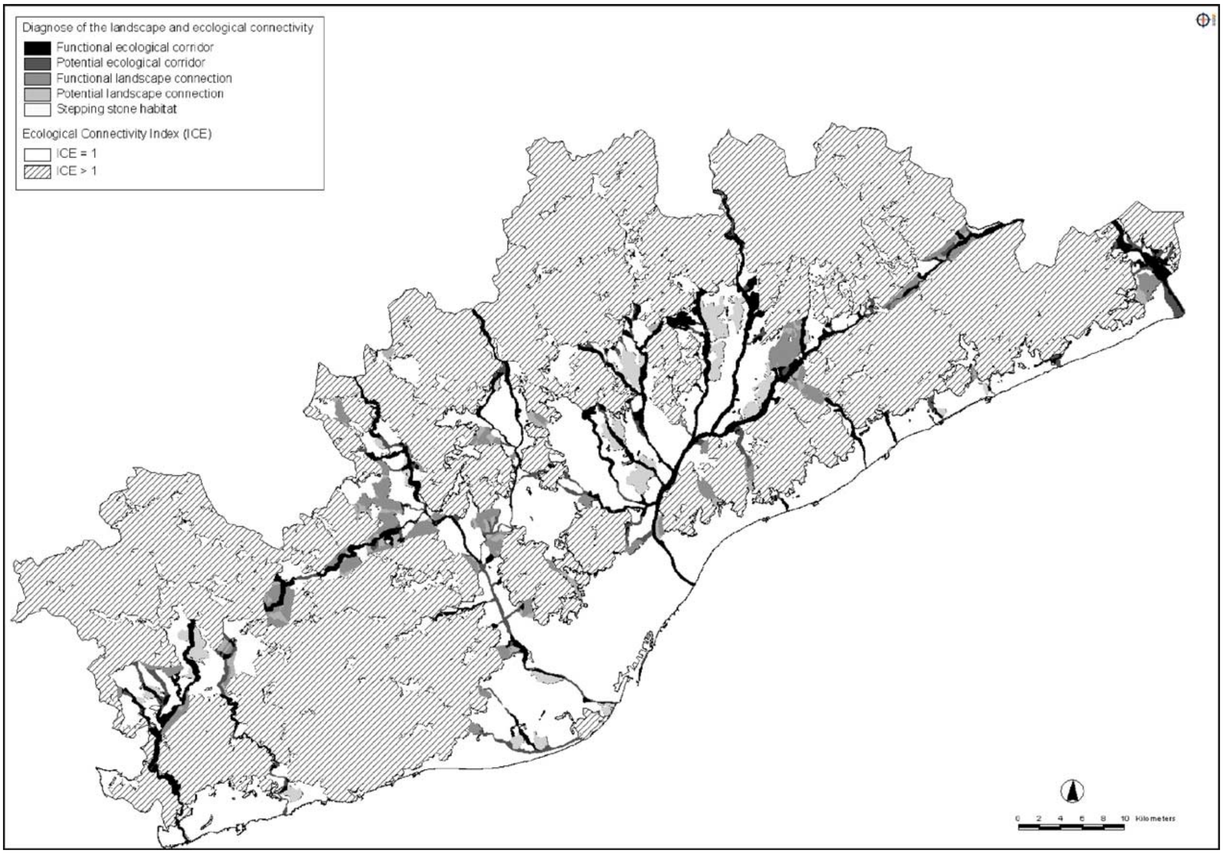

Fig. 13. Area distribution of categories that make up the landscape and ecological network of the Metropolitan Area of Barcelona.

spond to those categories requiring some ecological restoration to become functional again.

5. Impact of current land use and urban municipal plans on landscape and ecological connectivity

As an example of the potential applications of this new methodology, we assessed the impact on landscape and ecological connectivity of the 164 municipal urban and land use plans that encompass the entire BMA. To this purpose, we first elaborated a unified classification for all zoning types included in these plans and then we aggregated them at 1:5000 scale to produce a 1:50,000 unified map for the entire BMA. Assuming that current trends prevail, Fig. 14 shows the future scenario of urban growth in 15 years, totaling 18,828 ha of new developed areas. Next, we applied the ECI_a to the urban growth future scenario and we overlaid the resulting map with another map that is the result of applying the ECI_a index to the current situation. Impact on the Ecological Connectivity Index (ECI_a) by current land use urban and municipal plans in the BMA is shown in Fig. 15.

This analysis allowed the identification of other important features for ecological connectivity such as vulnerable spots, riparian areas that offer a high restoration potential, as well as areas with little value for ecological connectivity. As shown in Table 5, we identified a large number of areas, encompassing over 6818 ha, most of them adjacent to existing urban areas, that could be developed with minimum environmental impact. On the other hand, we also identified some 2728 ha of proposed urban areas (14.49%) that have a critical impact on ecological connectivity, sug-

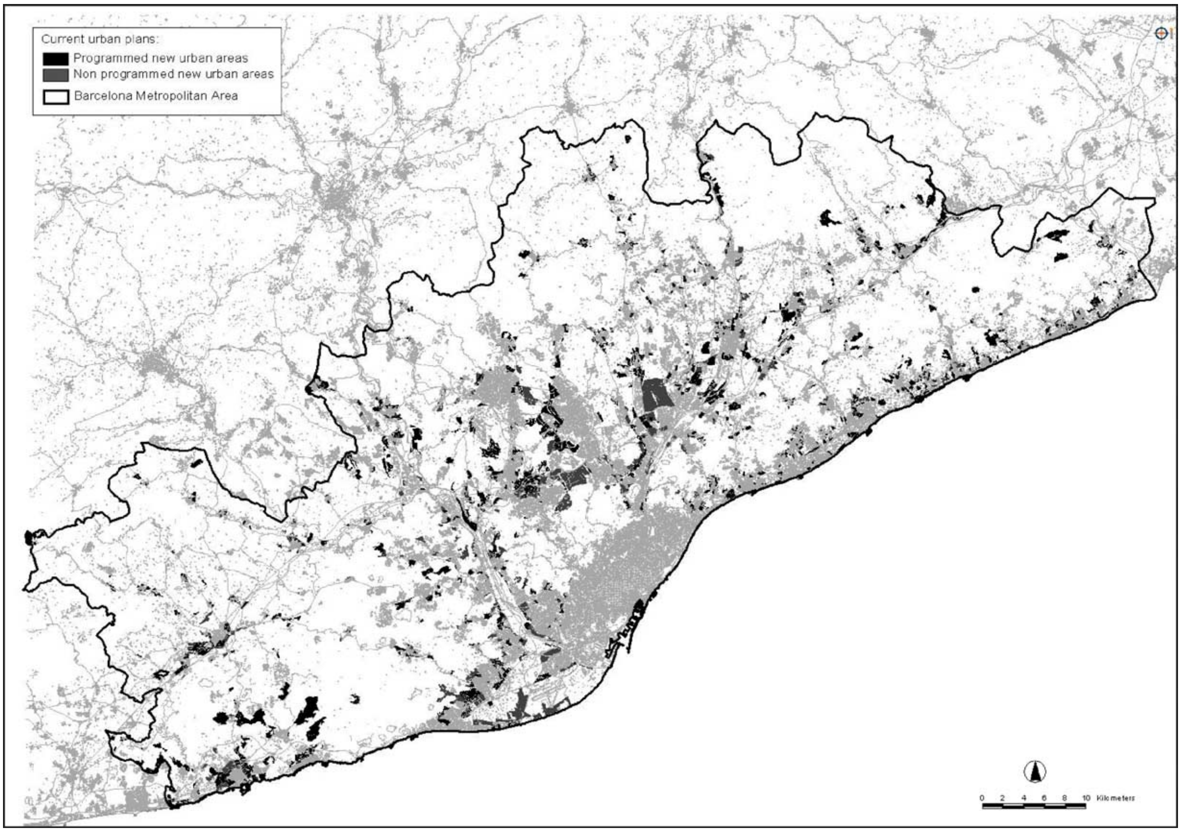

Fig. 14. Future scenario according current urban municipal plans in the Barcelona Metropolitan Area: distribution of new urban areas.

Table 5
Impact of current urban municipal plans on landscape and ecological connectivity in the Barcelona Metropolitan Area, measured in rounded hectares

Land uses	Current urban municipal plans	Landscape and ecological connectivity strategic evaluation							Other affected areas	
		Functional ecological corridors (ICE > 1)	Potential ecological corridors (ICE = 1)	Functional landscape connections (ICE > 1)	Potential landscape connections (ICE = 1)	Stepping stone habitat (ICE >1)	Strategic affected areas (ha)	Strategic affected areas (%)	ICE > 1	ICE = 1
Residential	8909	312	66	162	43	200	783	4.24	3349	4777
Industrial	2462	276	109	114	69	53	621	3.36	1416	424
Facility	605	118	142	95	115	43	513	2.77	83	8
Railway	2256	11	6	1	2	3	23	0.12	1933	300
Tertiary	3050	22	23	50	1	56	152	0.82	1671	1227
Parks	1202	257	66	165	28	119	635	3.44	485	81
Total	18484	996	412	587	258	474	2727	14.76	8937	6818

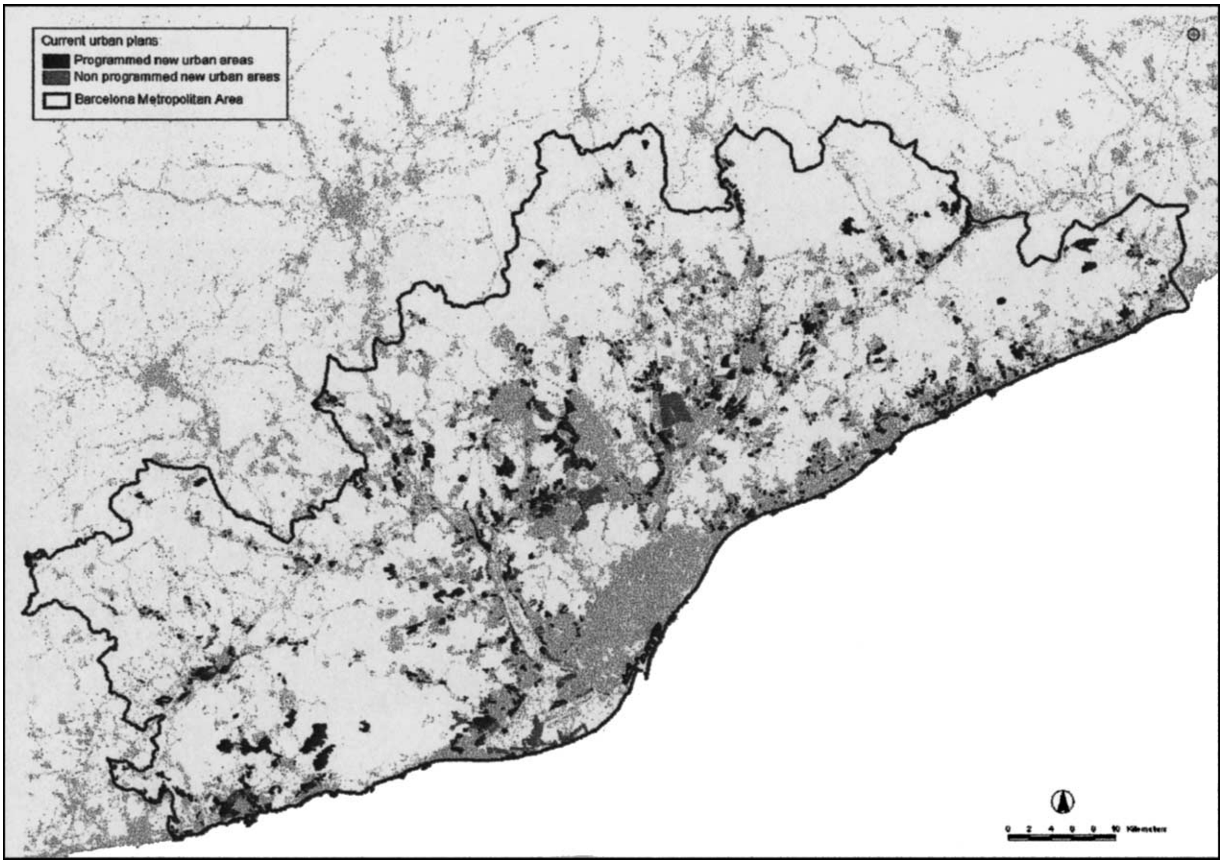

Fig. 15. Impact on the Ecological Connectivity Index (ICE_a) by current urban plans in the Metropolitan Area of Barcelona.

gesting that they should be reclassified for ecological restoration.

Our analysis suggest that integration of landscape and ecological connectivity is quite weak in the design of most municipal urban and land use plans of the BMA. We identified 11,665 ha of proposed urban areas that would create impacts of different severity to landscape and ecological connectivity, although 1121 ha (9.6%) do correspond to urban parks which could adopt some measures to make compatible its existence with conservation of ecological connectivity.

6. Discussion

The method we propose for assessing landscape and ecological connectivity at the regional level allows quick assessments and applications, which can be very effective for regional and metropolitan land use planning, strategic impact assessments, and sectoral planning. One advantage of this methodology is that it does not require extensive databases, but only a good quality digital land use map, at a scale near to 1:25,000, and reliable information of infrastructures, including its permeable components, such as bridges and tunnels. Another significant advantage is that it is a transparent method, where all its key components (functions, constants and variables) are visible, and can be adjusted to local conditions, using empirical data if available, and allowing further refinements when new relevant information appears.

This method has been mainly designed for applications on regional planning and strategic environmental assessments. Since it is based on quantitative landscape ecology, and these type of indices are crude simplifications of a an extremely complex reality, relative rankings and quantities only have relative significance; that is they are very useful for comparing different alternatives in a quantitative way, as a support for the decision making process.

Although there had been over a dozen previous studies on biological or ecological connectivity in this metropolitan area (Mallarach, 2000), this is the first comprehensive study of the terrestrial ecological connectivity and landscape fragmentation that has been produced for the entire BMA at a scale useful for metropolitan and regional planning. Therefore, we hope that it can make a contribution to the future Metropolitan Plan of Barcelona to reverse detrimental trends, creating a more sustainable scenario, through the establishment of a functional ecological network of natural areas and ecological corridors, according to the EECONET concept.

The focus of these models is terrestrial ecosystems, and they do not include river ecosystem connectivity. The reason for that is two-folded. First, data on biological quality of river waters and forest riparian areas is lacking for the entire study area at the same level of resolution than land use, vegetation, urban areas or infrastructures. On the other hand, it is well known that analysis, planning, management, and restoration of river ecosystems requires another approach, namely a watershed scope. However, we believe that the increasing application of analytic indices such as BILL (Prat et al., 1983), QBR (Munné et al., 1998) or IVF (Agència Catalana de l'Aigua, 2001) at the watershed level, will soon make possible to include river ecosystem connectivity in our methodology. Thus, we believe that, with a some minor adjustments, this methodology could be valid for these same uses in other metropolitan regions. However, for more detailed scales, such us municipal planning or natural area design, it would need to be complemented with empirical or expert-based methods, using empirical data of local ecological dynamics and key species habitats, corridors and barriers (Clevenger et al., 2002).

The long awaited European directive on strategic environmental assessment (2011/42/EC) has the potential to foster the incorporation of sound environmental principles and criteria, such as ecological connectivity, at strategic level, for many types of plans and programs, including regional, urban, land use, and infrastructure plans. In this respect, since it will be necessary to compare different alternatives, we believe that the methodology we presented can be cost-efficient when evaluating its potential impacts for landscape and ecological connectivity.

Finally, this is the first of three interrelated approaches that we are currently developing for regional planning and strategic environmental assessment. The other two approaches include a set of compound indices for measuring land vulnerability and constrains, and another set for measuring natural heritage values (Marull, 2003). We believe that, combining these three approaches with multi-criteria optimization using GIS-based functional assessments (Grabaum and Meyer, 1998) will provide some new useful tools for helping to make sounder decisions and hopefully to reverse some of the most unsustainable trends in the complex and stressed scenarios that offer most metropolitan areas.

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Josep Maria Mallarach Carrera (Olot, Catalonia, Spain, 1955) is teaching environmental policy evaluation in the doctoral program on the environment at the University of Girona, Catalonia, Spain. For over 20 years he has been working in planning, management and evaluation of natural protected areas, both in Spain and the USA, where he was member of the Indiana Biodiversity Initiative Steering Committee (1994–1997). His interest on ecological connectivity arose during the late eighties, when he was the management director of la Garrotxa Volcanic Zone Nature Park, which includes 10 urban areas, 26 nature preserves, and complex fragmentation processes. Since then, he has been involved in several projects related to ecological connectivity, from local to regional levels, both in Spain and the US. He is currently coordinating the first comprehensive evaluation of a large system of protected areas in Spain. He is member of the IUCN Working Group on Effectiveness Evaluation of the World Commission on Protected Areas, and member of the International Association of Impact Assessment. His background is in environmental geology and environmental sciences.

Joan Marull López (Camallera, Catalonia, Spain, 1964) is currently working at Barcelona Regional, a public agency involved in the development of urban studies and projects within the Metropolitan Area of Barcelona, where he is coordinating the corporative GIS. He is leading several projects of applied research on methodologies for strategic impact assessment of territorial and urban planning. He holds a PhD on biology for the University of Barcelona (1992) and has authored over 30 scientific papers in subjects such as evolutionary genetics and landscape ecology.

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Erratum

Erratum to "A GIS methodology for assessing ecological connectivity: Application to the Barcelona Metropolitan Area" [Landscape Urban Plan 71(2–4):243–262]

Joan Marull [a], Josep M. Mallarach [b,*]

[a] *Barcelona Regional, Zona Franca, Edifici Z, Carrer 60, 25-27 08040 Barcelona, Spain*
[b] *Departament de Geografia, Plaça de Sant Domènec, Universitat de Girona, 17000 Girona, Spain*

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The publisher regrets a number of errors in the original printed article. The correct first authors' author name and contact details, Figs. 3 and 15 and Table 2 are now shown below.

Code	Type	S_r (ha)
C'_1	Wet forestlands	≥ 100
C'_2	Wetlands	≥ 50
C'_3	Dry forestlands	≥ 200
C'_4	Shrubs and prairies	≥ 200
C'_5	Irrigated groves	≥ 50
C'_6	Irrigated croplands	≥ 50
C'_7	Dry groves	≥ 100
C'_8	Dry croplands	≥ 50
C'_9	Forest mosaic	≥ 150
C'_{10}	Agricultural mosaic	≥ 50
C'_{11}	Agroforest mosaic	≥ 50

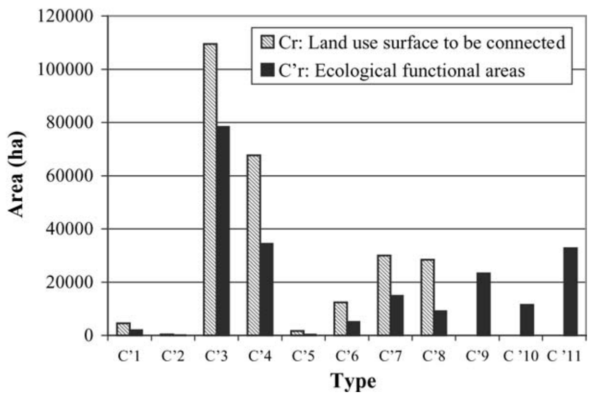

Fig. 3. Results of the topological analysis at the BMA showing the existing relationship between land use types to be connected and ecological functional areas.

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* Corresponding author. Present address: Apartat de correus 148, 17800 Olot, Catalonia, Spain. Tel.: +34 972 290129.
E-mail addresses: jmarull@bcnregional.com (J. Marull), mallarach@natura.ictnet.es (J.M. Mallarach).

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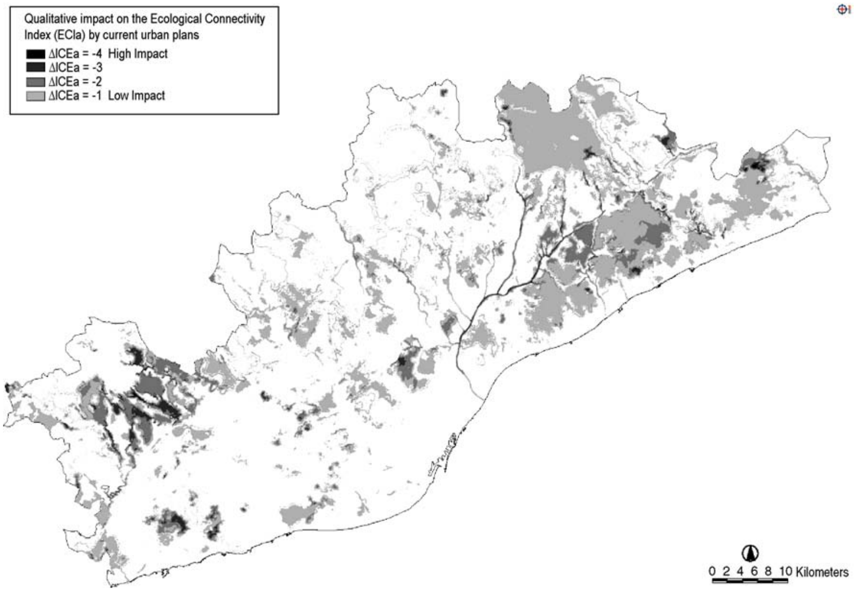

Fig. 15. Impact on the Ecological Connectivity Index (ICEa) by current urban plans in the Metropolitan Area of Barcelona.

Table 2
Impact matrix (M_A) for the calculation of the Barrier Effect Index

Code	Type	Classes included[a]	Affectation coefficient (a_n)[b]	Affectation value (A_n)
V_1	Neutral	N_1, N_2	$a_1 = 1000$ m	$A_1 = 0.10$
V_2	Agriculture	C_5, C_6, C_7, C_8	$a_2 = 750$ m	$A_2 = 0.13$
V_3	"Natural"	C_1, C_2, C_3, C_4, E_2	$a_3 = 500$ m	$A_3 = 0.20$
V_4	Barrier	B_1, B_2, B_3, B_4, B_5	$a_4 = 250$ m	$A_4 = 0.40$
V_5	Corridor	E_1	$a_5 = 1$ m	$A_5 = 100$ ($A_n = b_5/a_n$)

[a] Class description is found in Table 3.
[b] a_n defines the maximum significantly affected distance by each type.