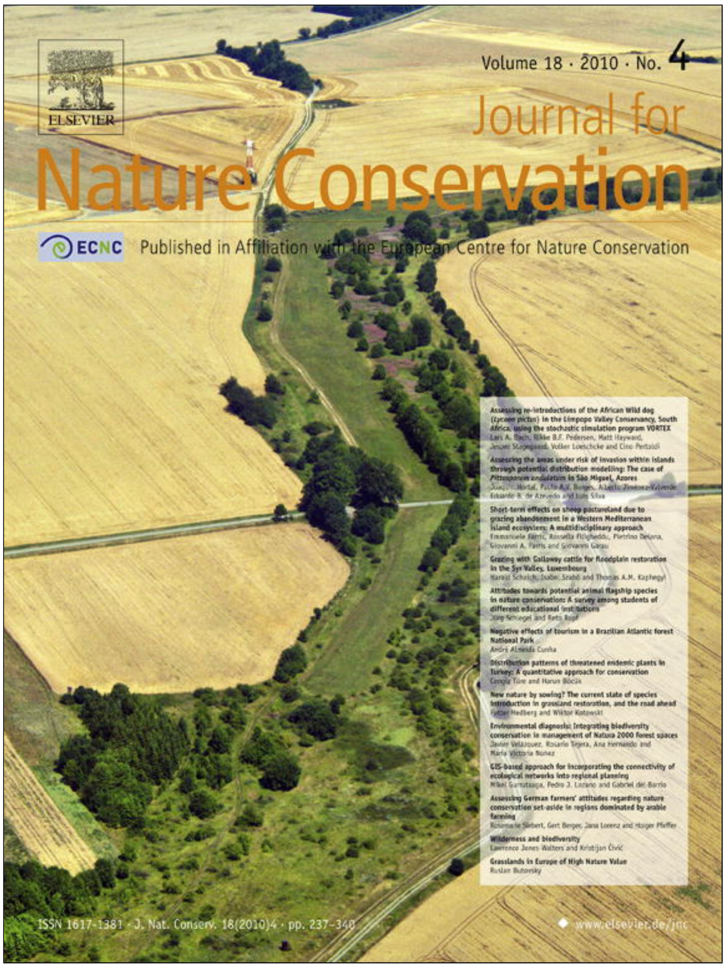
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GIS-based approach for incorporating the connectivity of ecological networks into regional planning

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ABSTRACT

Conservation networks, such as the European Natura 2000, are sets of designated reserves, the persistence of which requires the contribution of the non-protected territory in terms of connectivity. For that reason, the European Union's Habitats Directive urges the improvement of its ecological coherence. This work reports a spatial modelling methodology to complete the existing Natura 2000 network in the Basque Country with elements of ecological connectivity. It is based on cost surfaces built for a set of target species associated with the dominant habitats of the region. Least-cost paths were then used to identify zones of probable connection between reserves. The final network is made of core areas, link corridors, link areas and buffer zones, all with an explicit spatial allocation. The regional government of the Basque Country subsequently incorporated this ecological network as a reference for the evaluation of regional development plans in 2005.

Introduction

The reduction and fragmentation of natural and semi-natural habitats, as an outcome of agricultural intensification, infrastructure networks and urbanisation, have been suggested as the main reasons for the current biodiversity crisis (Fahrig, 2003; Foley et al., 2005). During the past few decades, the general scientific consensus has been that conservation strategies based on the protection of natural areas conceived as self-contained and independent spatial units do not necessarily address ecological processes that take place in the entire territory (Burkey, 1989; Carroll et al., 2004; IUCN, 2005; Kupfer, 1995; Noss, 2000).

Eco-regional planning is playing an increasingly important role in natural conservation policies and strategies, recognising that it is necessary to integrate the protected areas of an entire territory ecologically and socio-economically (Bennett, 2004; IUCN, 1994; Múgica et al., 2002; Smith & Maltby, 2003). The application of the eco-regional approach entails developing coherent and functional conservation networks, known as ecological networks. The ecological networks are identified, from a structural point of view, by the location of ecological corridors linking protected natural areas and by the location of buffer zones between the above elements and the landscape matrix (Bennett, 1991; Bennett & Mulongoy, 2006). The design of ecological networks in an explicitly spatial manner allows for their implementation in landscape planning (Bennett, 1999; Huber et al., 2007; Jongman, 2002; Jongman et al., 2004; Opdam et al., 2006; Vuilleumier & Prelaz–Droux, 2002) and in turn has an effect on land use policy and the evaluation processes for environmental impact of plans and projects.

Globally, numerous ecological networks are being developed that focus on the landscape or regional scale (Bennett, 2004; Bennett & Mulongoy, 2006; Jongman et al., 2004). This process is however still incipient, given that most of the initiatives to develop ecological networks in the world are at the planning stage and have not been completely implemented (Bennett & Wit, 2001).

While scientific competence increases in relation to the effectiveness of ecological networks in conservation (Davies & Pullin, 2007; Debinski & Holt, 2000), the precautionary principle (Cooney, 2004) demands the development of suitable instruments in order to prevent fragmentation and loss of landscape connectivity within the territories (Jongman, 2002; Jongman & Pungetti, 2004).

In the framework of the European Union, the European Community Directive 92/43/EEC, or Habitats Directive, which regulates the development of the European ecological network Natura 2000, urges, in Article 10, the improvement of European ecological coherence through the management of landscape elements that are fundamental in guaranteeing the migration, geographical distribution and genetic interchange of wild species.

Ecological networks are characterised by their emphasis on biodiversity conservation at the level of the ecosystem, landscape

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or region. The focus is on maintaining or strengthening ecological coherence and in ensuring the protection of critical areas against effects of possibly harmful external activities, while at the same time taking into consideration the restoration of degraded ecosystems (Bennett & Wit, 2001). One of the main contributions derived from this delimitation of coherent ecological networks is the definition of critical interaction areas between the protected natural territory network and its surrounding matrix of artificial urban land and communication infrastructures. Adequate management of these critical areas is decisive for conservation policies to be effective (Bruinderink et al., 2003; Díaz Pineda et al., 2006; Trocmé, 2006). Finally, ecological networks typically promote opportunities for sustainable use of natural resources, encouraging complementary facets between land use objectives and those of biodiversity conservation (Opdam et al., 2006).

The flow of genes and individuals between populations is considered essential for the survival of those species that are sensitive to the fragmentation of their habitats (Fahrig & Merriam, 1994). Therefore, the loss of ecological connectivity, or capacity of the territory to allow for the movement of organisms between resource patches (Taylor et al., 1993), poses a challenge for biodiversity conservation (Bennett, 1999).

An organism's response to landscape structure varies depending on the scale of its perception of the landscape's heterogeneity, its mobility and ecological profile. In consequence, landscape functional connectivity is species-specific (With & Crist, 1995; Tischendorf & Fahrig, 2000). Hence, the assumption is that there are no "universal corridors" to support the movement of taxa that are sensitive to the fragmentation of habitats, neither are there unique and valid scales to study the ecologic connectivity of the different taxa (Beier & Noss, 1998; Forman, 1995).

Thus, the design of ecological corridors created for integration in eco-regional planning often evaluates the territory by the mobility requirements of certain target species with rather wide mobility ranges and that act as umbrella species (Bani et al., 2002; Beier & Loe, 1992; Bruinderink et al., 2003; Carroll, 2006; Noss & Daly, 2006). Geographic information systems (GIS) based models are widely used tools for the design of ecological corridors, and least-cost modelling stands out, because of the explicit results it yields and because it allows for parameterisation and testing through empirical studies (Broquet et al., 2006; Noss & Daly, 2006; Theobald, 2006).

Empirical studies carried out with the purpose of validation require time in order to obtain results (Bennett, 1999). Meanwhile, within the framework of landscape planning, the precautionary principle (Cooney, 2004) requires the implementation of preventive measures and priority management in the corridors designed.

Therefore, the objective of this work was to design an ecological network of corridors in the Basque Country at a regional level, meeting the following requirements: i) to optimise the stability of the natural reserves that are scattered in this territory; and ii) to make the most of the Basque Country's geographical conditions, which are representative of many European territories, in order to develop a methodological prototype to be applied in other domains of the EU.

Study area and data

The Basque Country comprises an area of 7,224 km^2 and has a population density of 302 inhabitants per square kilometre. There are three NUTS-3 provinces: Alava; Biscay; and Guipuzcoa. Located to the north of the Iberian Peninsula (Fig. 1), it borders the Cantabrian Sea and sits between the mountain ranges of the Pyrenees and the Cantabrian Range. It belongs to the Atlantic biogeographic region. The area is still covered by significant zones of natural and semi-natural vegetation made of deciduous oak and beech forests, partly resulting from the migration of people from rural areas to industrial centres during the past century. However, the growth of economic activity has involved an expansion of urban and artificial areas, as well as an increased density of communication infrastructures. Approximately, natural forest covers 25% of its area, forestry plantations 29%, non-wooded mountains 13%, cultivated land 25%, and urban land and infrastructures 5.7%.

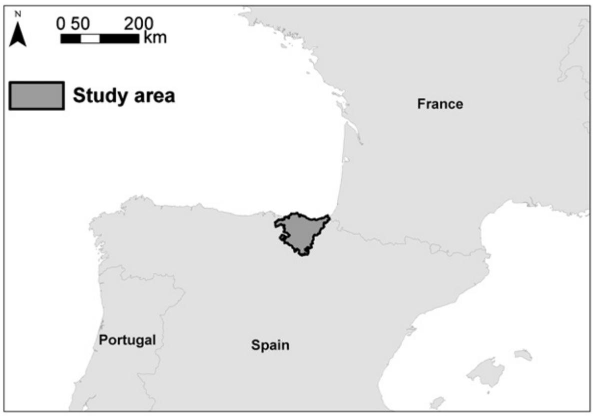

Fig. 1. General location map of study area: Basque Country (N Iberian peninsula).

The following data sets provided by the regional government of the Basque Country were used in this work: Natura 2000 areas; land use from the Third Forestry Inventory of Spain; residential and industrial land from municipal planning; rail and road networks; average daily traffic intensity; and viaducts and tunnels in highways. The working scale was 1:25,000, and the raster cell resolution was set to 20 m.

Within the south-western quadrant of Europe, the study area is configured as an area of strategic significance for the conservation of the connectivity of woodland habitat, given the location of the Basque Country between the Pyrenees and the Cantabrian Range, as can be appreciated in the indicative map of the Pan-European Ecological Network in Western Europe (Jongman et al., 2006). Both mountain ranges comprise very important biodiversity reservoirs. As a result, the study area has a role of vital importance in the regulation of relevant biotic flows beyond its intrinsic internal relevance.

Methods

Connectivity is a species-dependent property that cannot be addressed solely on the basis of a generic landscape mosaic. One approach therefore is to select target species that will be used as the basis for the design of ecological corridors between protected areas. Ecological connectivity depends on landscape structure as well as on the mobility and ecological requirements of the species in question (With & Crist, 1995); the scale of a corridor is linked to the scale of the species' perceived landscape structure (Foppen et al., 2000; Van Der Sluis et al., 2004). In general terms, during the past few decades in the Basque Country, changes in landscape pattern have caused a loss of ecological connectivity at the regional level. These structural changes are the fragmentation of natural forests, the loss of heterogeneity in agro-landscapes due to intensification of agriculture, and the fragmentation caused by transport infrastructure networks and urbanisation (Gurrutxaga, 2007).

Several large and medium-sized mammals that prefer to move in woodland habitats were selected as a functional group in order to prepare a landscape connectivity model between core areas. The group comprises wild ungulates such as *Capreolus capreolus*, *Sus scrofa and Cervus elaphus*, and also medium-sized carnivores such as *Martes martes*, *Felis silvestris*, *Genetta genetta*, *Meles meles* and *Martes foina*. The study is based on the assumption that the proposed landscape connectivity model used in the design of ecological corridors responds adequately to the degree in which the landscape matrix enables or impedes the mobility of the target species.

Special Protection Areas (SPA) of the Natura 2000 network that contain forests and/or agroforest mosaics were selected as core areas to be connected through ecological corridors at a regional scale in the Basque Country. Therefore, SPAs with non-zonal or extra-zonal environments, such as coastal habitats and wetlands, were not included in this study. The potential distribution of the different target species in the study area goes beyond core areas because there are adequate habitats in several sectors of the landscape matrix, but in creating the ecological network model, only the core areas are used as points of origin.

The distribution of the SPAs that act as core areas in the study area could prove to be insufficiently coherent, especially if they are concentrated in some areas but not in others. Thus, core areas that do not belong to the Natura 2000 network may be selected if necessary, so as to provide sufficient spatial coherence to the group of core areas to be connected. The group of selected core areas in the Basque Country is shown in Fig. 2.

Once the core areas and the functional group of target species were defined, the GIS method of least-cost modelling was applied to estimate the connectivity of the landscape matrix (Adriaensen et al., 2003; Clevenger & Wierzchowski, 2006; Larkin et al., 2004; Ray et al., 2002; Singleton et al., 2002; Theobald, 2006; Walker & Craighead, 1997). This type of modelling, which is based on the configuration of resistance or friction maps in raster format, is generically named cost surfaces in the GIS literature (Berry, 1993).

Two layers of information are required: a map of source places (in this case, the core areas); and a map of the resistance of the landscape matrix to the mobility of the selected species. To avoid the bias that would result from selecting a study area with merely administrative delimitations, the resistance map was extended 20 km into the peripheral regions surrounding the study area (Autonomous Communities of Navarre, Cantabria, Castilla and Leon, and Rioja). Data for southwest France, adjacent to the study area, could not be used and this led to its exclusion from the analysis. However, this area is small and marginally located, so it should not impact the results. The resistance map, with a 20 m cell resolution, was built using maps at a scale of 1:25,000, land use from the Third Forestry Inventory of Spain, residential and industrial land from municipal planning, rail and road networks, average daily traffic intensity and viaducts and tunnels in highways.

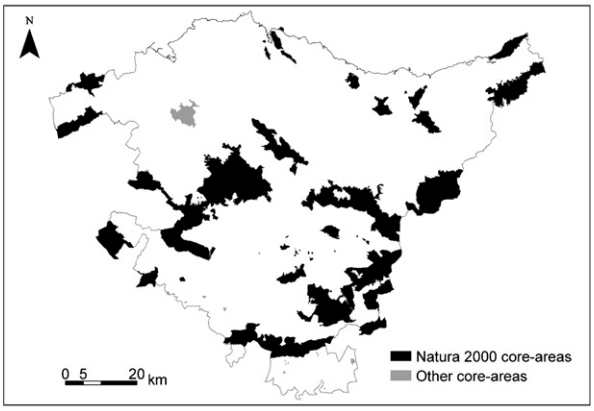

Fig. 2. General location map of core-areas.

One of the main difficulties in least-cost modelling is deciding how to assign resistances (Ferreras, 2001; Ricketts, 2001). We coded the different land uses in consultation with experts on the concerned species, and the values were set to a range between 1 and 1000. Follow-up experimental studies looked at the mobility patterns of different species across the landscape (Ferreras, 2001; Graham, 2001; Palomares et al., 2000).

When use refers to wood or forests, a minimum friction is assigned (value 1) to native forests. The value is higher when assigned to plantations of medium-term felling time for non-native species, for example *Picea abies* (value 10), and higher again when assigned to short-term ones, for example *Pinus radiata* (value 20) (Table 1). Wherever the patches registered contain more than one forestry species, an overall resistance value was computed through weight averaging using the cover percentages.

The resistance values of roads were assigned depending on their traffic and whether they were fenced (Table 2). Viaducts and tunnels of highways are areas with a large relative permeability, and therefore were assigned resistance values depending on their land use.

The 20 m resolution does not guarantee an accurate representation of linear elements of the landscape in the resistance map; therefore, special attention was paid to the incorporation of complete road routes so that the impedance value of the roads along all their lengths would be included. This is important if we wish to avoid disruptions in the representation of such elements in the resistance map (Rothley, 2005). The resistance map of the study area and its surrounding zones is shown in Fig. 3.

The function *CostDistance* of ArcGIS 9.2 was applied on the described maps of core areas and resistances to compute the cumulative resistance, or cost, of radial displacement from each of the core areas. This is called the cost surface and is, in fact, a continuous map of connectivity. The gradient of cost values refers to the degree of difficulty for the target species to access each point of the territory from these core areas.

Table 1
Resistance values of land uses.

Land use	Resistance
Water	100
Urban	1 000
Rock	40
Quarries	90
Meadows	40
Pastures	30
Bushes	5
Wood forests	Min. 1, Max. 20
Crops	60

Table 2
Resistance values of roads and railways.

ADT (Average Daily Traffic) on the roads	Resistance
< 1 000	80
1 000-5 000	100
5 000-10 000	300
10 000-20 000	Not fenced: 700 Fenced: 900
> 20 000	Not fenced: 800 Fenced: 1 000

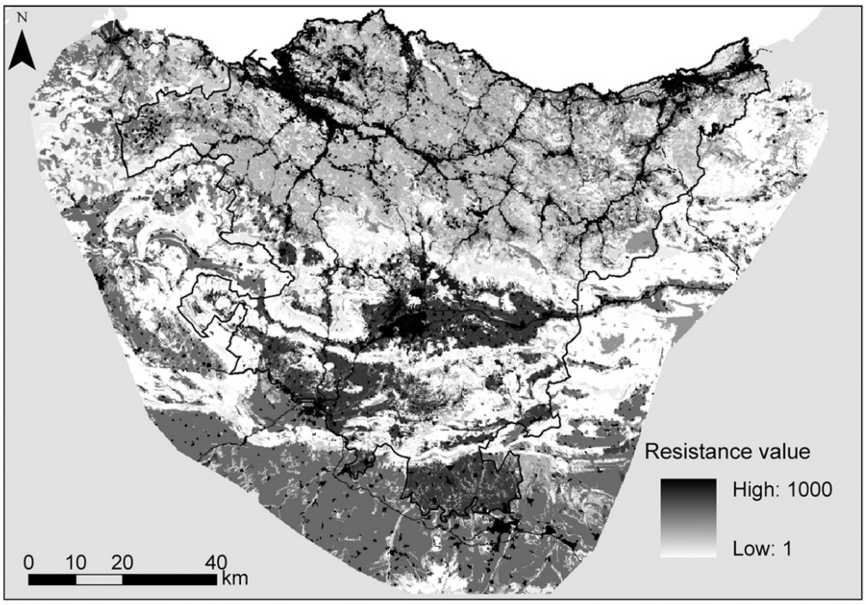

Fig. 3. Resistance map of study area and surrounding zones.

The cost surface is also used by *CostPath* to compute the least-cost paths linking pairs of core areas. By definition, such paths can be taken as corridors with the largest landscape permeability for every particular pair. The least-cost paths should be interpreted as potential paths that minimise the cost of mobility, rather than functional expressions of the dispersal process (Theobald, 2006; Walker & Craighead, 1997). The latter also depends on the dynamics of the populations of origin, such as the sufficient production of individuals with mobility capabilities (Carroll, 2006). The ecological corridors, or linkages, were delimited around *least-cost paths* even when the width remained to be determined (Theobald, 2006).

The resulting corridors are strips of variable width connecting core areas. This approximation underestimates connectivity to a certain extent, as in most cases there may be additional corridors between core areas with accumulated resistances that are also quite low. However, the delimitation of corridors around least-cost areas was guided by the criterion of selecting those sectors within the territorial matrix that showed the largest ability to maintain connectivity between core areas, so as to detect priority locations to guarantee the incorporation of criteria for landscape planning and management.

The corridors are defined around the least-cost paths following consistent criteria as far as possible. Changes in land use were used (from native vegetation to cultivated land or forestry plantations, or from cultivated land or forestry plantations to peri-urban areas), as well as physiographical criteria such as hydrographical basin divisions and contour lines, where no significant changes in land use were evident. The delimitation was based on expert judgement. The aim was to bring together the maximum extension of natural and semi-natural vegetation patches around a strip of variable width of about 2 km. The width varied in each sector, narrowing and broadening depending on the connectivity interest of the surrounding landscape mosaic.

The least-cost paths were initially calculated taking into account land bordering the study area. However, this meant that some paths might end up outside the study area, where the regional administration of the Basque Country has no jurisdiction in regional planning. Therefore, least-cost paths were also calculated by excluding those zones outside the Basque Country. Thus, the optimum existing corridors were identified, with a view to guaranteeing that they could be incorporated into Basque Country planning processes.

Results

Ecological corridors and buffer zones

The cost surface covering the entire study area, together with the least-cost paths between pairs of core areas, is shown in Fig. 4. Some primary links between peripheral core areas were outside the Basque Country, and a further calculation was made excluding those zones.

The resulting corridors are strips of variable width connecting core areas. Because of such variable width, areas of special natural interest can be identified where the corridors broaden quite noticeably. Thus, the ecological corridors can be divided into two structural types: linkage corridors; and linkage areas (Fig. 5). The linkage areas correspond to areas of important natural interest and are labelled as such (Gobierno Vasco, 1996).

Buffer zones were then defined around the core areas and ecological corridors with a view towards mitigating edge effects coming from the anthropic activities that take place in the matrix (Fig. 5). These buffer zones are drawn over rural areas of variable extension and the aim was to include that act as transitional landscapes between the network of core areas and linkages and the territorial matrix surrounding them.

The set of core areas, linkage corridors and areas, and buffer zones, makes up the ecological network of the Basque Country according to the objectives of this work.

As a whole, linkage areas cover 3.8% of the study area, linkage corridors make up 10.4% and buffer zones account for 31%. Up to 84% of the area of natural forest contained within the study area is included in the coherent network designed, 37% being within Natura 2000, 11% within linkage areas, 16% in linkage corridors and 20% in buffer zones.

When analysing land use within such an ecological network, a clear dominance of forestry land, including natural forests and plantations, is observed in linkage areas (86.1%). This decreases

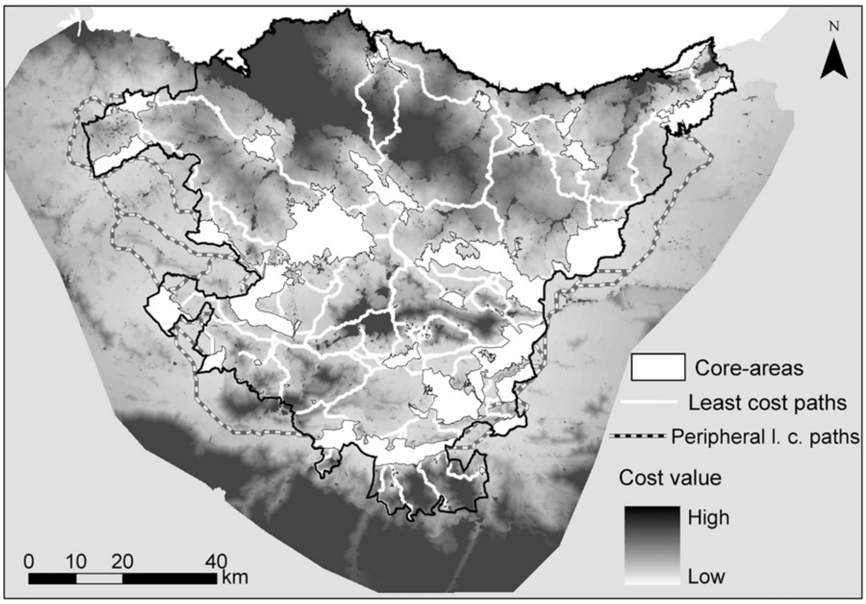

Fig. 4. Map of cost surface and location of least cost paths between core-areas.

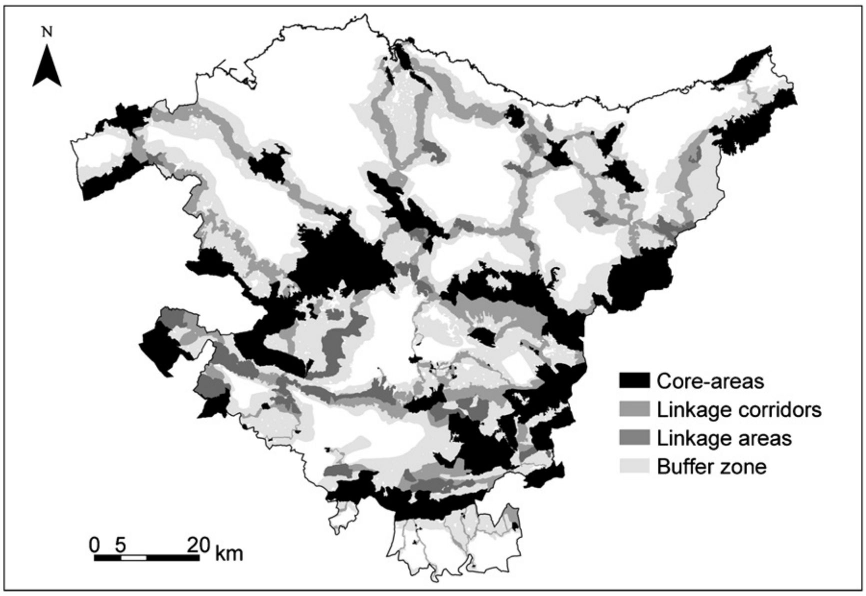

Fig. 5. Map of ecological network's structural elements.

somewhat in linkage corridors (68.7%) and further still in the buffer zones (47.4%). Agricultural land, by contrast, is dominant in buffer zones (40.4%) in comparison with linkage corridors (14.8%) and linkage areas (3.9%).

With regard to the ownership of the land, it is interesting to note that 72.3% of the linkage area is public land. This decreases to 41.5% in linkage corridors and to 18.3% in buffer zones.

Identification of critical areas

Once the ecological corridors had been defined, it was an easy task to identify interaction areas between them and urban land and the highways network, thus building a basis for suggesting preventive and corrective priority measures. This was accomplished through three additional operations performed on the results.

First, main areas where narrowing of ecological corridors occurs, due to the presence of urban areas on both sides, were identified (Fig. 6). Second, interaction areas between ecological corridors and highway networks were identified. These highways have an important effect on corridors because they may act as barriers that impede the displacement of medium and large mammals (Forman et al. 2003). Critical interaction stretches were selected by overlaying the highways network over the cost surface between core areas. Those critical stretches comprised highways that cover zones with a high permeability gradient between core areas. Each critical path was terminated where the cost gradient decreased significantly with respect to surrounding larger values (Fig. 7).

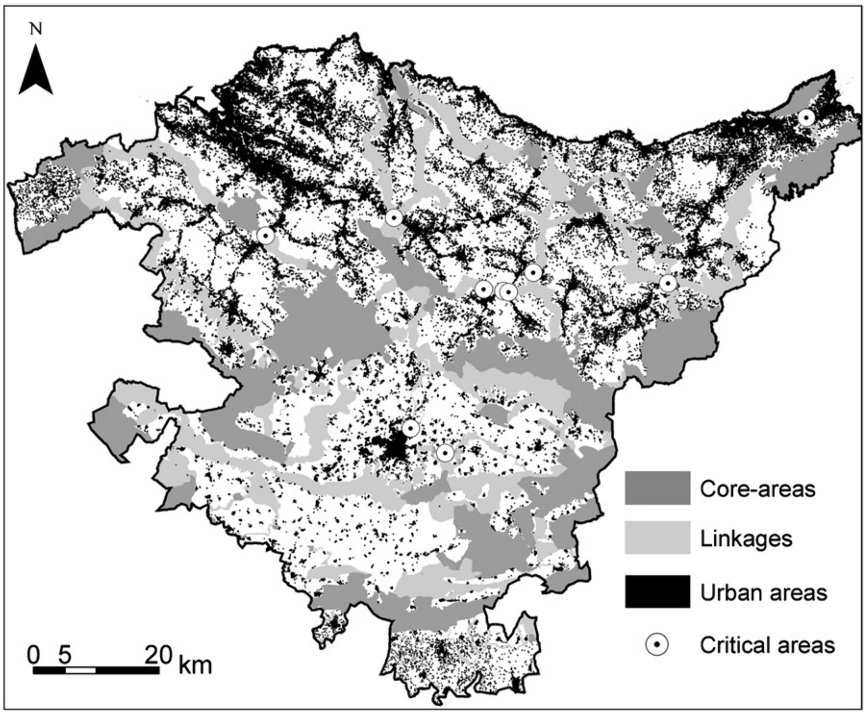

Fig. 6. Location map of critical areas of corridors due to urban land.

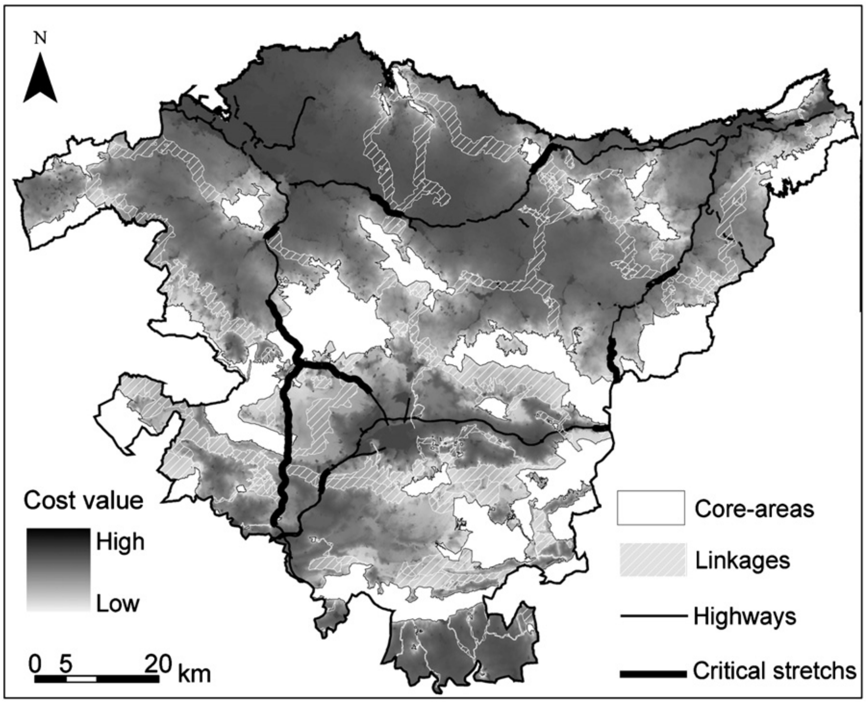

Fig. 7. Location map of critical highway stretchs.

Discussion

We believe that the definition of an ecological network as described provides an explicit spatial framework that allows the incorporation of the connectivity and coherence criteria of the Natura 2000 network in the decision-making process. Thus, priority can be given to the prevention and correction of activities that have an impact on connectivity through the sectoral agents and policies that play a role in land-use planning. In fact, the corridors, buffer zones and delimited critical areas presented in this work have been adopted as reference information in environmental evaluations of plans and projects in the Basque Country since 2005.

At a regional scale, urbanisation is particularly important and should be considered as a critical threat to the designated linkages, especially to the identified critical areas. The vulnerability of corridors that are faced with development projects is evident considering that there was an increase of 20%

in urban areas registered in the Basque Country between 1994 and 2004 (Gobierno Vasco, 2005).

Residential and industrial development plans, and infrastructure projects that have an effect on linkages and critical areas that were identified in the study area, have become the main focus in environmental evaluations. Certain urban developments that were planned locally and subregionally were rejected (Gurrutxaga, 2007).

However, there is no way to completely guarantee the conservation of the rural land where corridors are located until a legally binding regulation is established. Currently, the Basque Government is considering the integration of the corridor network reported here into territorial planning at a statutory level within the next revision of the Territorial Planning Directives (Decree 28/1997). The Territorial Planning Directives of the Basque Country establish the framework of reference for the formulation of the remaining regional and urban planning directives.

The design of this corridor network has promoted relevant advances in the study area since 2005, especially in the field of prevention, though its incidence in active management of the landscape is still at the early stages. Active management with respect to landscape connectivity criteria in the detected linkages and buffer zones will have to be achieved by creating positive synergies between instruments for nature conservation and sectoral policies.

Appropriate management of agricultural and forestry holdings within the ecological network is fundamental, given that they cover a large part of the linkages and buffer zones. This is connected to the fact that, in common with other regions of the European Union, intensification of agriculture and forestry has effectively decreased the heterogeneity of the rural landscape and has damaged the habitat of a rich biological community and the permeability of the landscape matrix (Burel & Baudry, 2005; Burel et al., 2004; Dover & Sparks, 2000; Gonseth, 2000; Hinsley & Bellamy, 2000). The importance of the agricultural layout has also been indicated because it can act as a structural support for future changes in the distribution of different organisms due to climate change (Araújo et al., 2004; Del Barrio et al., 2006; Hannah et al., 2002).

At the transportation policy level, it is particularly important to guarantee the permeability of highways for fauna, given that roads with perimeter fencing and a high volume of traffic generally have an important barrier effect (Clevenger & Wierzchowski, 2006). Thus, in the critical interaction stretches of highways with the defined ecological corridors, it is necessary to pay special attention to the creation of enough suitable crossing points to allow the spread of medium-sized to large mammals (Iuell et al., 2003).

Further support for the urgent need to analyse critical path areas with more detail comes from the fact that the majority of the highways in the Basque Country, in common with most of Western Europe, were built before environmental impact assessments began to demand that highways provide permeability for fauna. Appropriate defragmentation measures (ecoducts, oversized drainages, etc.), following the example of various countries and regions (Trocmé, 2006) can now be suggested (Gurrutxaga, 2007).

Conclusions

The network reported in this work supplements the existing Natura 2000 series of natural reserves with elements of ecological connectivity. The final network is made of core areas, linkage corridors, linkage areas and buffer zones. Their identification has been optimised so as to minimise the incorporation of new territory into conservation schemes, while maintaining a structure that can act as a support for the flow of specimens and populations between core areas. The interaction of such a network with particular landscape elements or in given locations can be further examined because all elements have an explicit spatial allocation. The definition of landscape connectivity using only a limited set of target species is a limitation of the approach, but at the same time provides a pragmatic solution to the designation of connectivity networks for management purposes.

We believe that this complete ecological network improves the coherence of the existing Natura 2000 network, which might previously be better described as a patchwork. The results reported here better meet the demands of the European Habitat Directive and for that reason were adopted by the regional government of the Basque Country.

The methodology used in this work has some interesting aspects. It is objective and repeatable. It involves some steps where an expert should provide external inputs, but this is done at concrete points and with explicit rules. In addition, the input data are readily available for many other regions, and the functions used are implemented in most GIS software packages. For these reasons, we think that these methods, or an evolution of them, could be easily replicated in other European areas to provide Natura 2000 with a practical management framework.

This kind of connectivity analysis is however really a starting point rather than a final solution. Complex landscape mosaics such as the Basque Country present opposing forces of economic development and nature conservation, with a background of agro-ecosystems under variable degrees of intensification. The real role of a methodology such as that presented here is the stratification of such challenges.

Given that the corridors were designed in response to an analysis at a regional level, they should be complemented with corridors that are created at a supraregional, subregional and local scales, thus configuring a multiple scale network of effective linkages. What makes this necessary is that landscape connectivity manifests itself in a multiple scale format depending on what species or functional groups are sensitive to the fragmentation of the habitats selected (Noss 1991, Bennett 1999, Foppen et al. 2000). This multiple scale network should provide support for the movement of species that are sensitive to the fragmentation of grasslands, montane pastures, and aquatic and rocky habitats.

The prediction in an international context for the next few years is that there will be a great amount of activity at the scientific level in the fields of planning and management in relation to connectivity, conservation and restoration. In fact, globally, most of the initiatives to develop ecological networks are at the planning stage and practically none have been completely implemented (Bennett & Wit 2001). At the decision-making level, the full implementation of connectivity criteria between natural spaces will have to be developed by explicitly integrating binding regulations into the renovation processes of regulation frameworks and into administrative instruments for regional and sectorial planning. Globally, there are very few ecological networks that can rely on legal support to provide complete protection in regions and countries (Bennett and Mulongoy, 2006; Bennett & Wit, 2001). Therefore, it is necessary to design and execute programmes for intervention, with their corresponding budgetary assignations, so as to restore connectivity in priority areas.

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