Sustaining forest landscape connectivity under different land cover change scenarios

L. Rubio[1, *], M. Rodríguez-Freire[2], M. C. Mateo-Sánchez[3], C. Estreguil[2], S. Saura[4]

[1] *Departament d'Enginyeria Agroforestal. Universitat de Lleida.*
Av. Alcalde Rovira Roure, 191. ES-25198. Lleida, Spain
[2] *European Commission-DG Joint Research Centre, Institute for Environment and Sustainability,*
Land Management and Natural Hazards Unit, T.P. 261, Via E. Fermi 1, 21027. Ispra (VA), Italy
[3] *Departamento de Proyectos y Planificación Rural. E.U.I.T. Forestales. Universidad Politécnica de Madrid.*
Ciudad Universitaria s/n. ES-28040. Madrid, Spain
[4] *Departamento de Economía y Gestión Forestal. E.T.S.I. Montes. Universidad Politécnica de Madrid.*
Ciudad Universitaria s/n. ES-28040. Madrid, Spain

Abstract

Managing forest landscapes to sustain functional connectivity is considered one of the key strategies to counteract the negative effects of climate and human-induced changes in forest species pools. With this objective, we evaluated whether a robust network of forest connecting elements can be identified so that it remains efficient when facing different types of potential land cover changes that may affect forest habitat networks and ecological fluxes. For this purpose we considered changes both in the forested areas and in the non-forest intervening landscape matrix. We combined some of the most recent developments in graph theory with models of land cover permeability and least-cost analysis through the forest landscape. We focused on a case of study covering the habitat of a forest-dwelling bird (nuthatch, *Sitta europaea*) in the region of Galicia (NW Spain). Seven land-use change scenarios were analysed for their effects on connecting forest elements (patches and links): one was the simplest case in which the landscape is represented as a binary forest/non-forest pattern (and where matrix heterogeneity is disregarded), four scenarios in which forest lands were converted to other cover types (to scrubland due to wildfires, to extensive and intensive agriculture, and to urban areas), and two scenarios that only involved changes in the non-forested matrix (renaturalization and intensification). Our results show that while the network of connecting elements for the species was very robust to the conversion of the forest habitat patches to different cover types, the different change scenarios in the landscape matrix could more significantly weaken its long-term validity and effectiveness. This is particularly the case when most of the key connectivity providers for the nuthatch are located outside the protected areas or public forests in Galicia, where biodiversity-friendly measures might be more easily implemented. We discuss how the methodology can be applied to a wide range of forest landscape management situations, where both the conservation of the forest critical areas and an adequate management of the landscape matrix between them are of concern to achieve the sustainability of the ecological flows and ecosystem services at the wider forest landscape scale.

Key words: Forest habitat networks; Forest landscape planning; Least-cost modelling; Spatial graphs; Habitat availability metrics; Landscape matrix; *Sitta europaea*.

Resumen

Conservación de la conectividad del paisaje forestal bajo diferentes escenarios de cambio en las cubiertas del suelo

La gestión de los bosques para mantener la conectividad ecológica se considera una de las estrategias clave para contrarrestar los efectos negativos provocados por el cambio climático y de los usos del suelo sobre las especies forestales. Con este objetivo, en este estudio evaluamos la posibilidad de identificar una red de elementos conectores forestales que sea robusta y eficiente ante cambios potenciales en las cubiertas del suelo que puedan afectar a las redes

de hábitats forestales y a los flujos ecológicos entre ellos. Para ello, consideramos cambios tanto en las áreas de bosque como en la matriz no arbolada del paisaje. Combinamos algunos desarrollos recientes en teoría de grafos con modelos de permeabilidad del paisaje forestal y análisis de mínimo coste. Centramos nuestro caso de estudio en el hábitat de un ave forestal (trepador azul, *Sitta europaea*) en Galicia (NO España). Analizamos siete escenarios de cambios de uso del suelo según sus efectos en los elementos conectores (teselas y enlaces): uno (el caso más simple) en el que el paisaje se representó como un patrón binario de bosque/no bosque (sin considerar la heterogeneidad de la matriz), cuatro escenarios en los que las teselas de bosque se transformaron en otros tipos de cubierta del suelo (matorral debido a incendios, agricultura extensiva e intensiva y zonas urbanas), y dos escenarios en los que los cambios se produjeron tan solo en la matriz no arbolada (renaturalización e intensificación). Nuestros resultados muestran que a pesar de que la red de elementos conectores para esta especie fue eficiente frente a la conversión de las teselas de hábitat forestal en diferentes tipos de cubierta, los cambios en la matriz del paisaje podrían debilitar considerablemente su validez y eficacia a largo plazo. Este es especialmente el caso dado que la mayor parte de los elementos conectores clave para el trepador azul están localizados fuera de las zonas protegidas o de los montes de utilidad pública en Galicia, donde las medidas para la conservación de la biodiversidad forestal podrían implementarse con mayor facilidad. Discutimos cómo esta metodología puede aplicarse en un amplio rango de escenarios de gestión del paisaje forestal, en los que tanto la conservación de las teselas de hábitat forestal críticas como un manejo adecuado de la matriz situada entre las mismas son de interés para conseguir la sostenibilidad de los flujos ecológicos y de los servicios de los ecosistemas en las escalas amplias en las que operan dichos procesos.

Palabras clave: Red de hábitats forestales; Planificación del paisaje forestal; Modelos de mínimo coste; Grafos espaciales; Índices de disponibilidad de hábitat; Matriz del paisaje; *Sitta europaea*.

Introduction

Biodiversity is a multi-scale concept, which implies that the conservation of forest biodiversity should be carried out from the level of a single stand and species to regional and landscape levels comprising complex species pools and the relationships between them (Lindenmayer *et al*., 2006). In this context, a landscape-level approach that promotes forest landscape heterogeneity and connectivity could be one of the best strategies to (1) ensure the sustainability and multi-functionality of forest management, (2) counteract the possible negative effects of climatic and socioeconomic changes on the goods and services provided by woodland habitats, and to (3) increase the ability of the forest-dwelling species to adapt to the changes and dynamics that act at a variety of scales (Saura, 2010).

Specifically, connectivity is defined as the degree to which the landscape facilitates or impedes movement of species and other ecological flows across the resources existing in the landscape (modified from Taylor *et al*., 1993). The assessment of landscape connectivity requires a functional approach that not only demands information about the spatial structure and heterogeneity of the forest landscape but that also needs to take into account the organism's movements and responses to that structure (Taylor *et al*., 2006). When assessing functional forest connectivity, one of the most important factors to account for is the landscape matrix (the non-habitat areas of the landscape that surround forest habitat patches). The permeability of the matrix is determined by the combination of different land covers that make up heterogeneous mosaics that facilitate or impede species dispersal to different degrees. Management of the matrix could be itself one important contribution for restoring and preserving landscape connectivity between forest habitat areas (Taylor *et al*., 2006). Moreover, connectivity is a dynamic property as the landscape itself, and therefore it must be assessed in a context of local and global changes, especially human-induced ones (Kettunen *et al*., 2007). Climate and land use changes are two of the major factors that have modified forest systems (Hansen *et al*., 2001). When referring to land use or land cover changes, we can find key processes such as rural abandonment, agricultural intensification (De Aranzabal *et al*., 2008) or urban development (Mitsova *et al*., 2011), among others. These processes can affect both the forest habitat patches and the landscape matrix, determining the effective levels of connectivity between distant populations. Forest management and conservation efforts should therefore take into account the current and foreseen patterns of change in the landscape and forest habitat configuration. This could assure the long-term success and effectiveness of forest conservation planning and related management measures.

At present, there is a wide range of metrics and approaches to characterize landscape configuration and connectivity (Baskent and Jordan, 1995; Calabrese and Fagan, 2004; Galpern *et al.*, 2011) that help to incorporate the concerns for ecological flows into forest landscape management and conservation planning. In particular, there are two complementary approaches that have significantly contributed to an improved and operational forest landscape connectivity analysis: (1) graph theory, where habitat patches are represented as nodes and the connections between them as links (Urban and Keitt, 2001; Galpern *et al.*, 2011); and (2) habitat availability (reachability) metrics, which consider a patch itself as a space where connectivity exists, integrating the habitat area that is available within each habitat patch (intrapatch connectivity) with the area that can be reached through the connections between different patches (interpatch connectivity) (Pascual-Hortal and Saura, 2006; Saura and Pascual-Hortal, 2007; Saura and Rubio, 2010). Connectivity is then considered as a property of the landscape that allows species to reach (to have available) a larger amount of the habitat resources existing in the landscape, no matter if such reachable habitat comes from a big or high quality patch itself (intrapatch connectivity), from the strong connections between different patches (interpatch connectivity) or, more frequently, from a combination of both. Saura and Rubio (2010) described how the habitat availability metrics can be partitioned in three fractions (*intra*, *flux* and *connector*) that are measured in the same units within a unifying analytical framework. Each of these fractions quantifies the distinctive ways in which a landscape element (patch or link) can contribute to overall habitat connectivity and availability (reachability) in the landscape. The *intra* fraction represents the contribution of a patch according to the amount of habitat resources available within itself (intrapatch connectivity), as determined by its area of some other local characteristic of ecological or management relevance. The *flux* fraction quantifies the dispersal flux through the connections of one patch with the rest of patches in the landscape, when that patch is either the origin or destination of those dispersal fluxes. The *connector* fraction evaluates which landscape elements contribute to the connectivity between other habitat patches, acting as an irreplaceable connecting element or stepping stone between them. This *connector* fraction (1) provides a unique information that is not redundant with other connectivity metrics (Baranyi *et al.*, 2011), (2) it is the only one that

can be measured both for habitat patches and links in a network, and (3) it is not affected by the local characteristics (e.g. habitat area or quality) of the landscape elements being evaluated (Saura and Rubio, 2010). The habitat availability metrics have been applied in many studies (Neel, 2008; Pascual-Hortal and Saura, 2008; García-Feced *et al.*, 2011; Pereira *et al.*, 2011; Awade *et al.*, 2012) (see a full list in http://www.conefor.org/applications.html). More recently, the research attention has been focused on the *connector* fraction, both in network analytical (Bodin and Saura, 2010; Baranyi *et al.*, 2011) and ecological application studies (Gurrutxaga *et al.*, 2011; Saura *et al.*, 2011; Rubio and Saura, 2012). This is because, for the reasons outlined above, this fraction is directly usable for a solid and operational design of networks of connecting elements. However, the planning guidelines derived so far from the graph theory approach and the habitat availability metrics (including the recent ones based on the *connector* fraction) are based on (1) considering that all the forest habitat patches that might be lost are converted to the same land use type (e.g. from habitat to non-habitat) without explicitly evaluating which might be the impact of the conversion to different land cover types in terms of landscape permeability, and therefore of the feasibility of movement between the rest of the remnant habitat areas in the landscape; (2) the assumption that no landscape changes would affect the permeability of the landscape matrix to ecological flows or that, if occurring, those changes would be irrelevant and have no significant effects on the effective connectivity between forest areas. These unrealistic assumptions are likely to weaken the long-term effectiveness of the proposed forest habitat networks, as long as their contingency upon a particular current (but non-permanent) landscape setting is not explicitly evaluated and considered in the related decision-support guidelines. We here propose to account for the role of landscape mosaic heterogeneity (spatial and temporal) in enhancing or reducing forest connectivity, in particular by looking at how shifts in landscape composition due to renaturalization or intensification affect the forest connecting elements. With this objective, we present a demonstrative case study for the forest habitat of the nuthatch (*Sitta europaea*) in Galicia (NW Spain), an umbrella species considerably sensitive to the effects of forest fragmentation. In particular, we focus on (1) evaluating how the connecting role of patches and links, as evaluated by the *connector* fraction of the *PC* metric, can be altered as a consequence

of land-cover changes both in the forested areas and in the intervening landscape matrix; (2) assessing the degree to which a protected habitat network constructed under this methodology can be considered as land-use change proof; (3) estimating the effectiveness of the Natura 2000 protected areas and public-managed forests for conserving the most critical connecting elements for the nuthatch's habitat. This is, to our knowledge, the first study based on a graph and habitat availability approach that (1) jointly considers the contribution of forest patches and links between them to sustain the connectivity in a landscape-scale network and (2) explicitly evaluates the robustness of such network against a variety of land cover changes that may occur in the study area.

Material and Methods

Study area and analyzed species

Galicia is a heterogeneous region located in the Northwest of Spain comprising the provinces of A Coruña, Lugo, Ourense and Pontevedra. It has an extension of about 30,000 km² and includes a long coastline along the Atlantic Ocean (Fig. 1). The climate is humid Atlantic with mild temperatures. Galicia is characterized by a complex topography, with altitudes ranging from sea level up to 2,124 m (mean altitude 508 m). According to the Third Spanish National Forest Inventory, about half of the total land area of Galicia is covered by forests (48%), with the rest corresponding to 21% shrubs and natural pastures, 28% agricultural
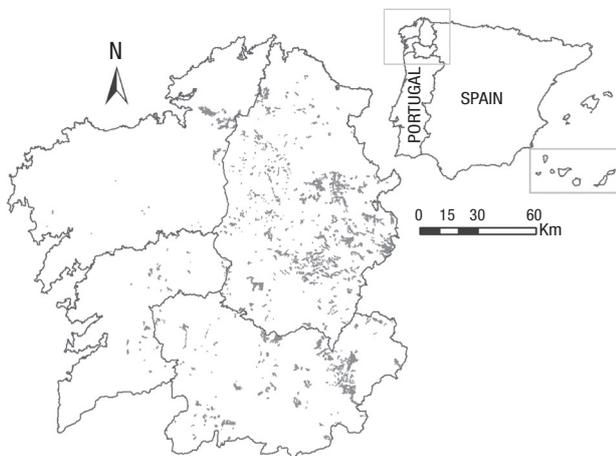

Figure 1. Location of Galicia and the forest habitat patches (grey areas) for *Sitta europaea*.

lands, 1% water bodies and wetlands and 2% urban and other human-made areas (Ministerio de Medio Ambiente, 2005). The forest landscape has been deeply modified by human action, especially during the last five centuries (Manuel and Gil, 2002). The most abundant forest tree species are *Pinus pinaster*, *Quercus robur*, *Eucalyptus globulus*, *Quercus pyrenaica*, *Pinus sylvestris*, *Pinus radiata* and *Castanea sativa*, with considerable differences among provinces.

The nuthatch (*Sitta europaea*) is a small troglodyte-nesting bird, which demands mature deciduous forests to settle (Gainzarain, 2003). Its median dispersal distance is 3 km (van Langevelde, 2000; van Langevelde *et al*., 2000). Among others, it is affected by forest fires, by intensive cuttings deriving from non-sustainable management and especially by forest fragmentation (Verboom *et al*., 1991; Enoksson *et al*., 1995; Bellamy *et al*., 1998; Santos *et al*., 2002). The nuthatch has been defined as an umbrella species (van Langevelde *et al*., 2000; 2002). By extension, therefore, we consider that this model or methodology would also be useful to evaluate the connectivity of other forest-dwelling species in the same area.

Evaluating the importance of connecting elements through the connector fraction

We used the Probability of Connectivity (*PC*), the habitat availability index presented in Saura and Pascual-Hortal (2007). *PC* is defined as the probability that two points randomly placed within the landscape fall into habitat areas that are reachable from each other (interconnected), given a set of *n* habitat patches and the links among them (Saura and Pascual-Hortal, 2007). The probability of direct dispersal (p_{ij}) between each pair of patches (required for the computation of the *PC* metric) can be estimated using a negative exponential function of the interpatch edge-to-edge Euclidean distance (Urban and Keitt, 2001; Pascual-Hortal and Saura, 2008) or of the effective distance (minimum cost) between patches (Rayfield *et al*., 2010; Gurrutxaga *et al*., 2011). The prioritisation and ranking of landscape elements by their contribution to overall connectivity can be calculated from the percentage of variation in *PC* (*dPC*) caused by the removal of each individual element (patch or link) from the landscape. After partitioning the *dPC* values into the three distinct fractions (Saura and Rubio, 2010), we focused our analysis on the *dPC-connector* both for patches and links. A certain patch or

link will contribute to the overall connectivity with *dPCconnector* values higher than zero when (1) it is part of the shortest or most feasible path (maximum product probability, p_{ij}^*) used for dispersal between other patches in the initial landscape (Saura and Pascual-Hortal, 2007) and (2) it acts as an irreplaceable connectivity provider since the alternative paths between the remnant patches that are available after losing that patch or link cannot compensate for the connecting role played by that patch or link in the intact landscape (Bodin and Saura, 2010; Saura and Rubio, 2010). The computation of this fraction only depends on the topological position of a patch or link in the landscape network. A link loss can be caused by the destruction of a corridor or by a land use change in the matrix between habitat patches that is no longer suitable for the dispersal of a particular organism. See Saura and Rubio (2010) for further details about the *connector* fraction and figure 1 in that paper for an illustrative example of its resultant values in a simple network. We used the new 2.6 version of the software Conefor Sensinode (Saura and Torné, 2009; available at www.conefor.org) in which new developments have been implemented purposefully for the objectives of this study. In particular, through this new version we could jointly assess the values of *dPCconnector* both for patches and links, and we could also evaluate the importance of individual links as connectivity providers when there are changes in the landscape matrix that either weaken or strengthen their previous ability to conduct ecological fluxes, rather than impeding it completely.

Spatial data

To identify the forest habitat patches (Fig. 1) for the species we used the Spanish Forest Map at a scale 1:50,000, developed within the Third Spanish National Forest Inventory (Ministerio de Medio Ambiente, 2005). From this map at 25 m of spatial resolution, and considering the ecological requirements of the nuthatch, we extracted the native broadleaf deciduous forest with a canopy cover of at least 70% (as given by the Spanish Forest Map) and a core area of at least 3 ha (van Langevelde, 2000) for an edge width of 25 m (Rodríguez-Freire, 2006). From these patches we selected the ones falling within the nuthatch distribution range provided by the Spanish Breeding Bird Atlas (Gainzarain, 2003), which gives information on the presence of the nuthatch in 10×10 km UTM grid squares over

the region. We considered all nuthatch forest habitat areas within a distance smaller than 100 m as a single patch (so nodes in the graph are represented as a cluster of habitat areas distant less than 100 m), given that the dispersal abilities of the species are well beyond that distance (see section 2.4). We obtained a final total number of 553 patches (n) and 152,628 links ((n^2-n)/2) to model our study area as a graph. The average area of the 553 patches was 0.81 km^2 (the maximum area being 16.72 km^2 and the minimum 0.03 km^2) distributed as shown in Figure 1. The Natura Network 2000 layer (available at http://inspire.xunta.es/website/red_natura/viewer.htm) and a layer with the distribution of public-managed forests in the region (Ministerio de Medio Ambiente, 2005) were used to determine which percentage of the key connecting elements for the nuthatch habitat was covered by each of these two figures.

Least cost modelling

The movement of the nuthatch was modelled using the least-cost algorithm (Adriaensen *et al.*, 2003) and the effective distances between each pair of patches were calculated with Pathmatrix 1.1 (Ray, 2005). Two input sources were used at a resolution of 50 m: (1) the resistance or friction to the nuthatch's movement presented by the different land cover types; and (2) the forest habitat source patches as the origin (and potential destination) of the species movements. To account for landscape resistance, two criteria were considered: the intrinsic friction to species movement of different land cover types, and the spatial context in which the land cover in each pixel was embedded. The land cover friction values were quantified on the basis of the published literature indicating that the nuthatch prefers to use wooded areas and hedges for its movements (Verboom *et al.*, 1991), and avoids open areas even if it has to make significant detours to do so (Bélisle *et al.*, 2001). With this information, Rodríguez-Freire (2006) and Rodríguez-Freire and Crecente (2006) assessed the naturalness and favourable cover for dispersal for this species based on the information provided by the Spanish Forest Map at a scale 1:50,000. The friction values were set by the degree of naturalness and canopy cover offered for dispersal. These values increased when the degree of naturalness and canopy cover decreased. Friction values range from one unit (for the native forests with a canopy cover higher or equal to 70%) to a maximum of 100 units for the artificial/anthropo-

genic classes. The friction value of each cell was also influenced by its spatial context (Casterline *et al.*, 2003), since dispersal movements typically require wider land strips comprising more than just a single cell. According to empirical data, the percentage of forest cover is valuable for predicting the movements of forest birds in a wider spatial context (Bélisle *et al.*, 2001). Thus, the percentage of native broadleaf species offering significant cover (canopy cover ≥ 40%) around each pixel was assessed by a moving window analysis. Patches with exotic forest species, although not suitable habitats for this particular species, can provide some cover having a positive influence on dispersal and were also considered as a factor to determine the final friction values. The three resistance factors were combined by multi-criteria evaluation techniques as described in Rodríguez-Freire and Crecente (2006).

We considered a median dispersal distance of 3 km for the *Sitta europaea*, which corresponded to 168,000 cost units (effective distance) in the resistance surface that resulted from the procedure just described (as determined by the average friction values in a buffer of 3 km around the forest habitat patches). This median dispersal distance (either Euclidean or effective) was assigned a probability $p_{ij} = 0.5$ in the negative exponential function of the distance between patches, from which the p_{ij} values for all pairs of patches were obtained.

Land cover change scenarios

The landscape connectivity analysis was performed under several land use change scenarios that considered (1) different land cover types to which the individual forest habitat patches were converted (i.e. a forest habitat patch converted into an urban area, into agriculture, etc.), with the impact of forest loss evaluated for each individual patch (one at a time) for each of those land cover types, and (2) changes in the intermediate landscape matrix that did not affect the forest habitat patches themselves but the landscape permeability and therefore the feasibility of movements between the habitat patches. These two types of scenarios were analysed separately, i.e. changes either occurred in the non-forested matrix or in the forested patches, but not in the two of them at the same time.

The set of change scenarios considered and analyzed were the following:

— (A) Four scenarios to evaluate the impact of converting forest habitat (with a friction value of 1) to

the following cover types (with their corresponding resistance surfaces): (A1) scrubland due to forest fires or other factors (friction 30), (A2) extensive agriculture (friction 50), (A3) intensive agriculture (friction 75) and (A4) urban areas (friction 100).

— (B) Two scenarios of land cover changes affecting only the landscape matrix (not the forest habitat patches): (B1) renaturalization by rural abandonment and habitat restoration, in which the scrubland friction changed from 30 to 1 (as if it was replaced by forest habitat), the extensive agriculture friction changed from 50 to 30 (as if abandoned crops were converted to scrublands), and the intensive agriculture and urban areas frictions remained the same; and (B2) intensification of the landscape matrix, in which forests were converted to scrubland changing their friction from 1 to 30, the extensive agriculture was considered as intensive (friction from 50 to 75) and the other land uses remained the same.

— (C) In order to gain further insights, we performed as well the connectivity analysis based solely on Euclidean (straight line) distances between patches (i.e. the matrix treated as homogeneous) to compare the outcomes of a binary landscape model (habitat vs. no habitat) with the results obtained when taking the matrix heterogeneity into account, as done in the rest of the scenarios.

The values of *dPCconnector* for every individual landscape element in each of the scenarios described above were used to quantify the importance of patches and links as providers of connectivity in the regional forest habitat network. To evaluate how the prioritisation of habitat patches and links differed between the various land cover scenarios (i.e. how the network of key connectors changed), we calculated Kendall's *tau_b* rank correlations (separately for patches and links) between the *dPCconnector* values obtained in each scenario.

Results

Contribution of forest patches and links as connecting elements under different scenarios of habitat and matrix cover change

We obtained Kendall's *tau_b* rank correlations higher than 0.9 between the *dPCconnector* values for the four scenarios (A) involving different land cover types to which the forest habitat patches were converted (Table 1). The results from these scenarios

Table 1. Kendall's *tau_b* rank correlations between the *dPCconnector* values obtained for the 553 forest patches of *Sitta europaea* habitat in the seven analyzed scenarios

	Euclidean (C)	Scrubland (A1)	Extensive Agriculture (A2)	Intensive Agriculture (A3)	Urban areas (A4)	Renaturalization (B1)	Intensification (B2)
Binary landscape with homogeneous matrix							
Euclidean (C)	1	0.730	0.738	0.734	0.735	0.373	0.876
Land cover type to which forest habitat is converted							
Scrubland (A1)		1	0.969	0.965	0.965	0.404	0.748
Extensive Agriculture (A2)			1	0.980	0.982	0.400	0.758
Intensive Agriculture (A3)				1	0.985	0.401	0.754
Urban areas (A4)					1	0.397	0.755
Changes in the landscape matrix							
Renaturalization (B1)						1	0.3805
Intensification (B2)							1

presented however lower correlations with those involving changes in the matrix (renaturalization (B1) and intensification (B2)) or when a binary landscape with a homogeneous matrix (C) was considered (Table 1). The renaturalization scenario (B1) presented the lowest correlation (about 0.4 or lower) with all the other scenarios (Table 1). Kendall's *tau_b* rank correlations between the *dPCconnector* and patch area (*dA*) for the seven scenarios in our analysis ranged between 0.40 and 0.43.

The seven analyzed scenarios had the same trend in the number of connecting elements that was needed to sustain a given amount of the total habitat connectivity and availability in the present landscape (Fig. 2). With approximately 15% of total forest habitat area, about 50% of the key connecting patches (according to their contribution to connectivity evaluated through *dPCconnector*) were conserved (Fig. 2). Only 26 of the 553 patches summed up the 50% of contribution in at least one of the seven scenarios. From these 26 patches, a total of 5 were found in all the scenarios within the set of top patches that contributed with 50% of the total *dPCconnector* values in all the study area. These 5 patches, that represent the 8.66% of the total habitat area and are shown in Figure 3, had a contribution of 24-30% to the total connecting role played by all the forest habitat patches in the study area.

When focusing on the importance of links, we obtained that only 0.01% of the links in the complete graph contributed to the 50% of the total *dPCconnector* values and that about 1% of the links accounted for almost 100% of the total importance as irreplaceable connecting elements (when considering only the contribution of links between patches) (Fig. 4). In fact,

only a range of 1,470 to 1,789 links from the total number of links in the complete graph (152,628), depending on the analyzed scenario, had *dPCconnector* values higher than zero and 37 of them represented up to the 50% of contribution in at least one of the seven scenarios (Fig. 3). From these 37 links, only 5 were present in all the scenarios, representing 15-25% of the total importance of the links that act as connecting elements in the study area.
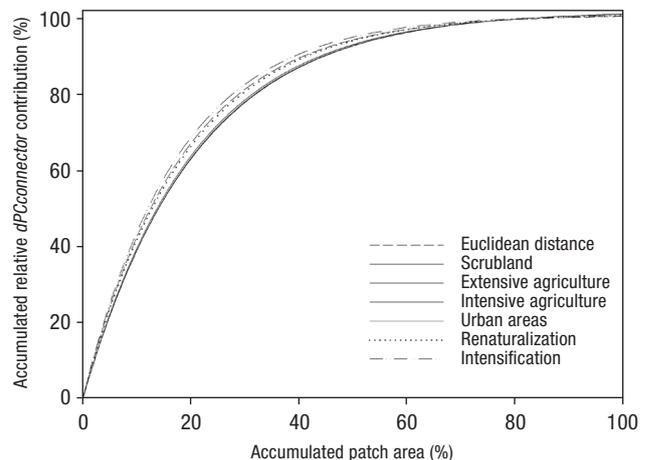

Figure 2. Relative contribution of the top connecting forest habitat patches as a function of the accumulated patch area for the seven scenarios of study. Patches were ranked according to their *dPCconnector* values (i.e. a 10% in the *x* axis corresponds to a set of patches resulting from selecting first those with the highest *dPCconnector* values until a 10% of total landscape area is attained). The relative contribution was calculated as the ratio between the sum of the *dPCconnector* values for all the patches in that set and the sum of the *dPCconnector* values for all the forest habitat patches in the study area.

How well do protected areas cover the key connecting elements for *Sitta europaea* habitat in Galicia?

We selected the Natura 2000 network and the public-managed forests in Galicia to estimate which percentage of the patches acting as connectors within the *Sitta europaea* habitat were covered by these habitat networks. In both cases the contribution was fairly low,

especially in the public-managed forests (Table 2). When referring to the Natura 2000 network, we found that some important patches of the *Sitta europaea* habitat were part of the Site of Community Importance (SIC) Fragas do Eume (Fig. 3A), while others were not partially or completely included in the network, as is the case of the habitat patches surrounding the SIC of Ancares-Courel (Fig. 3B) or the ones surrounding the SICs Macizo Central or Pena Trevinca (Fig. 3C).
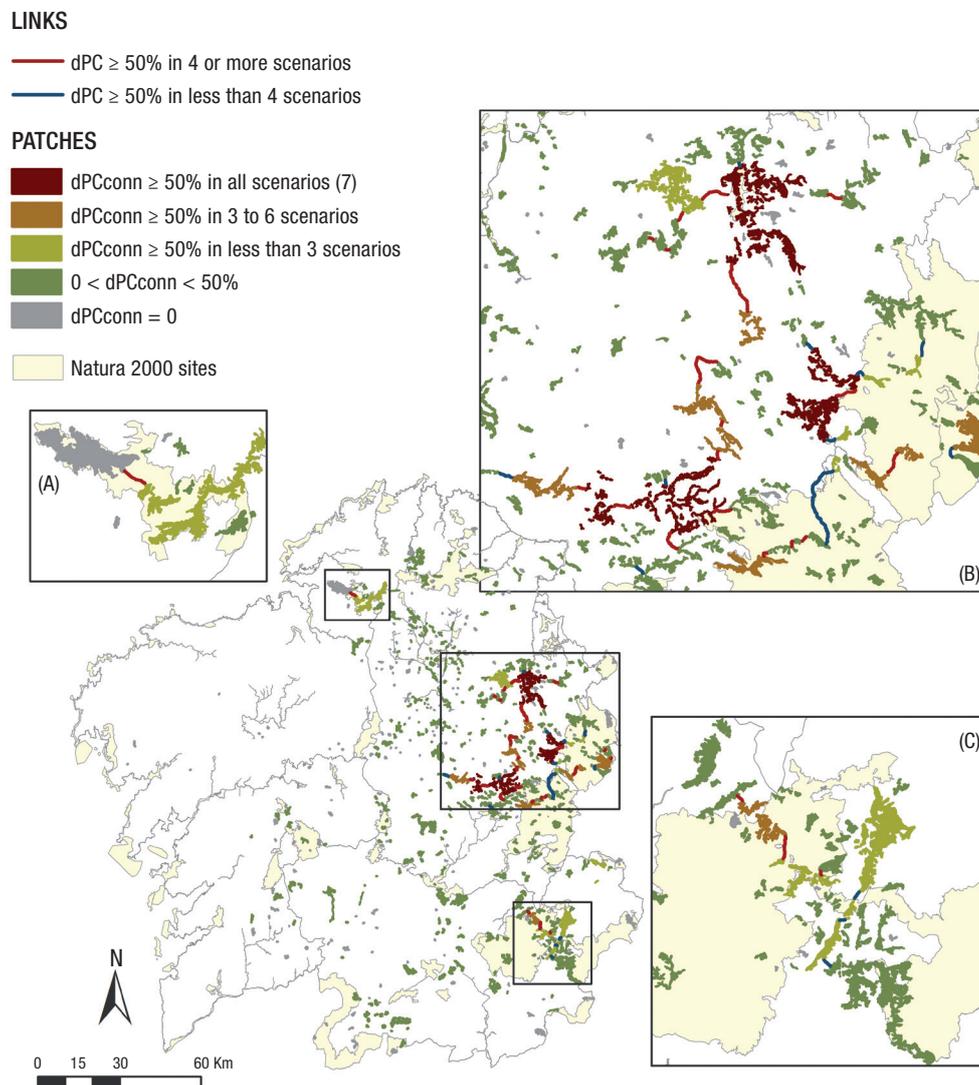

Figure 3. Patches and links that contribute to 50% of the total importance as connecting elements in at least one scenario and number of scenarios where those elements are present. The links routes correspond to the analysis of the four scenarios where forest habitat is converted to a different land cover type (A). For the other three scenarios (B1, B2 and C), the links routes would be different but still would join the same patches. The big squares correspond to a zoom of the smaller squares indicated over the map of Galicia.

Table 2. Percentage of connecting elements (patches) contribution to the overall habitat connectivity covered by the Natura 2000 network and public-managed forests for the different scenarios

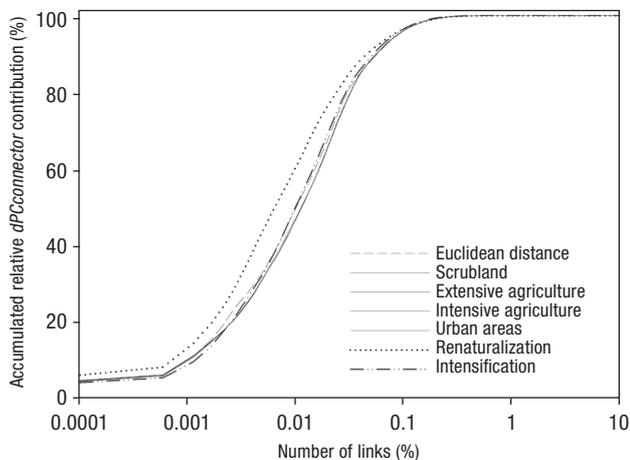|	Public forests	Nature 2000
Binary landscape with homogeneous matrix		
Euclidean (C)	6.15	31.51
Land cover type to which forest habitat is converted		
Scrubland (A1)	5.48	37.57
Extensive Agriculture (A2)	5.48	37.35
Intensive Agriculture (A3)	5.42	37.22
Urban areas (A4)	5.41	36.90
Changes in the landscape matrix		
Renaturalization (B1)	8.21	27.81
Intensification (B2)	6.48	33.28

Figure 4. Relative contribution as irreplaceable connectivity providers of the top links as a function of the proportion of the total number of links for the seven analysed scenarios. A given value in the *x* axis corresponds to the number of links with the highest *dPCconnector* values in all the forest landscape. The relative contribution was calculated as the ratio between the sum of the *dPCconnector* values for all the top links (for a given percentage threshold as indicated in *x* axis) and the sum of the *dPCconnector* values for all the forest habitat patches in the study area. Note that the *x* axis is shown in a logarithmic scale.

Discussion

Designing a habitat network requires the identification of those landscape elements that will contribute to maintain the habitat connectivity even if the matrix becomes more inhospitable to the movements of organisms between habitat patches (Beier *et al.*, 2008). Conservation planning should have as one of its main goals to design habitat networks that hold a high probability of maintaining biodiversity and natural processes over time (Noss and Daly, 2006). Vos *et al.*

(2008) identified habitats across Europe where ecosystem patterns were not adequate to accommodate species' response to climate change. Their results suggested that one of the most important strategies to prevent loss of biodiversity is to increase connectivity on a large spatial scale and to identify climate-proof ecosystems networks and priority adaptation zones. Also in a political context, in the newly adopted 2020 biodiversity strategy for the European Union (http://ec.europa.eu/environment/nature/biodiversity/comm2006/2020.htm), one of the six main targets is a better protection for ecosystems, and more use of green infrastructures, which includes habitat provision and the enhancement, conservation and restoration of biodiversity by inter alia increasing spatial and functional connectivity of natural, semi-natural and protected areas, as well as improving landscape permeability and mitigating fragmentation.

In our connectivity analysis we assessed the possibility of designing a land-use change proof habitat network through the analysis of the connecting elements under different land cover scenarios. We used the interpatch connectivity and the topology of the network by focusing on the importance of the connecting elements measured through *dPCconnector*. We decided to work with this conservation strategy because (1) we were interested in including in our analysis both habitat patches and the functional connections between them and because (2) at intermediate dispersal distances, as the case of the *Sitta europaea* (3 km) (van Langevelde, 2000; van Langevelde *et al.*, 2000), the presence of stepping stones becomes more relevant as their loss can cause a significant decrease in the species ability to reach other habitat patches (Saura and Rubio, 2010).

The rank correlation between *dPCconnector* and patch attribute, in this case area (*dA)*, was low for all

the scenarios of our analysis as this fraction measures the importance of each landscape element according to its position in the landscape independently of its area. Even so, there is some degree of correlation because the larger the patch, the more likely it is to fall between other habitat patches and act as a connecting element (Saura and Rubio, 2010).

The rank correlation between the *dPCconnector* values for the individual patches obtained for the four scenarios where forest habitat cover was converted (scenarios A) was very high (Table 1). The 553 nuthatch habitat patches represent a very low percentage of the total landscape area, compared with the matrix (Fig. 1). Adriaensen *et al*. (2003) suggested that the role of source patches when crossed by least-cost paths could be a point of debate, since it may probably be strongly dependent on the species and the study process and they are merely modelled as low resistance land cover patches. In our study, the forest habitat patches are scarce in a matrix where other cover types predominate. Therefore, the fact that we converted their habitat cover, even to surfaces with high resistance such as intensive agriculture or urban areas, had a mild impact on the overall prioritization of the patches and links with higher contribution as connecting elements. However, the rank correlations with the Euclidean analysis (scenario C) and when the cover changes affected the matrix (scenarios B, renaturalization and intensification) were much lower (Table 1). This points out the importance of including the effect of the matrix in landscape connectivity analysis (Janin *et al*., 2009; Rayfield *et al*., 2010), particularly when facing different types of land cover and land use change. When speaking of habitat loss, most of the studies consider the binary scenario, habitat being replaced by no habitat, without evaluating the specifics of such land cover change. The species response (mobility and ability to access other habitat areas at large spatial and temporal scales) would be different depending on the land cover types that expand by replacing part of the habitat patches. Consequently these factors should be included in conservation studies as done here or for example in Rouget *et al*. (2006). They designed large-scale conservation corridors to preserve pattern and process in the subtropical Thicket Bioma of South Africa. In order to quantify them, they used as criteria habitat transformation and degradation and future land-use pressures in order to avoid threatened areas to be transformed.

We obtained that with the 20% of the accumulated area, more than 60% of the connecting elements were covered in all the scenarios (Fig. 2) and only 26 of the 553 patches summed up the 50% of contribution to the overall habitat connectivity. Thus protecting a relatively small proportion of habitat area we could sustain a considerable proportion of the nuthatch dispersal events through the use of stepping stones, even in situations where the matrix exerted a high resistance to movement, such as in the intensification scenario. When referring to the links, only 0.01% of them added up the 50% of contribution to the overall habitat connectivity (Fig. 4). So the identified key links should be maintained or restored to assure that they can play their key role for sustaining the ecological fluxes at wide spatial scales (which includes avoiding their disruption by transport infrastructures or other types of spatial change).

We are aware that the results and insights gained by our case study would benefit from further empirical validation. Specifically, when referring to the cost surface for all the land-use change scenarios, cost values should be quantified through empirical data (e.g. radiotracking, landscape genetics, etc.) which most of the times are difficult and time consuming to collect. Such data are sparse or non-existent for most of the species and locations which leads to use expert opinion and literature to assign costs associated with landscape features (Rayfield *et al*., 2010; Sawyer *et al*., 2011), as done in this study.

The low percentage of habitat patches covered both by the Natura 2000 network and public-managed forests (Table 2, Fig. 3) suggests that these habitat networks may not be able to protect the most critical habitat areas for the *Sitta europaea*. Given the marked forest preference of this bird species, the low percentage of its habitat covered by public forests could have implications related to the greater difficulty of implementing in private forests management measures that are more directly targeted to favour this species. Although enlarging the protected network to cover all the connecting elements from the nuthatch habitat might not be possible, a significant improvement could be obtained by just increasing a small percentage of the total protected habitat area. According to the results shown above, adding into these two habitat networks some of the critical connecting elements that summed up the 50% of contribution to the overall habitat connectivity (Fig. 2-3) could significantly improve their effectiveness. Similar analyses were done for endangered forest bird species in Saura and Pascual-Hortal (2007) and Pascual-Hortal and Saura (2008), both indicating areas where some of the critical elements as connectivity providers for the

focal species were not included in the protected network. In Jantke *et al.* (2011) the suitability of the Natura 2000 network to cover endangered wetland vertebrate species was tested and they found out that five area-demanding vertebrates were not covered by the current reserve system. Considering that (1) most of the land cover changes will occur in the landscape matrix and not in the protected network and that (2) there are studies that point out that many of the key connecting elements are not covered by protected networks, it's advisable to more explicitly include the landscape matrix and the effects of their land cover change dynamics in conservation and forest planning.

Our results might point out that when designing future conservation networks, these new methodological tools should be introduced as a management alternative in order to ensure species viability under land-use change scenarios. Even so, landscape managers should be aware of not putting all the conservation efforts and management resources in connecting elements or stepping stones only, as they should be always complemented with other conservation strategies that take into account habitat quality or amount among others (Hodgson *et al.*, 2009), which might be quantified by the other two fractions of the habitat availability metrics (Saura and Rubio, 2010).

Acknowledgements

References

Adriaensen F, Chardon JP, De Blust G, Swinnen E, Villalba S, Gulinck H, *et al.* 2003. The application of 'least-cost' modelling as a functional landscape model. Landscape Urban Plan 64, 233-247.

Awade M, Boscolo D, Metzger JP. 2012. Using binary and probabilistic habitat availability indices derived from graph theory to model bird occurrence in fragmented forests. Landscape Ecol 27, 185-198.

Baranyi G, Saura S, Podani J, Jordán F. 2011. Contribution of habitat patches to network connectivity: Redundancy and uniqueness of topological indices. Ecol Indic 11, 1301-1310.

Baskent EZ, Jordán GA. 1995. Characterizing spatial structure of forest landscapes. Can J Forest Res 25, 1830-1849.

Beier P, Majka DR, Spencer WD. 2008. Forks in the road: Choices in procedures for designing wildland linkages. Conserv Biol 22, 836-851.

Bélisle M, Desrochers A, Fortin MJ. 2001. Influence of forest cover on the movements of forest birds: a homing experiment. Ecology 82, 1893-1904.

Bellamy PE, Brown NJ, Enoksson B, Firbank LG, Fuller RJ, Hinsley SA, *et al.* 1998. The influences of habitat, landscape structure and climate on local distribution patterns of the nuthatch (*Sitta europaea* L.). Oecologia 115, 127-136.

Bodin Ö, Saura S. 2010. Ranking individual habitat patches as connectivity providers: Integrating network analysis and patch removal experiments. Ecol Model 221, 2393-2405.

Calabrese JM, Fagan WF. 2004. A comparison-shopper's guide to connectivity metrics. Front Ecol Environ 2, 529-536.

Casterline M, Fegraus E, Fujioka E, Hagan L, Mangiardi C, Riley M, *et al.* 2003. Wildlife corridor design and implementation in Southern Ventura County, California. Available in http://www.bren.ucsb.edu/research/2003Group_Projects/links/Final/links_brief.pdf. [30 January 2011].

De Aranzabal I, Schmitz MF, Aguilera P, Pineda FD. 2008. Modelling of landscape changes derived from the dynamics of socio-ecological systems. A case of study in a semiarid Mediterranean landscape. Ecol Indic 8, 672-685.

Enoksson B, Angelstam P, Larsson K. 1995. Deciduous forest and resident birds: The problem of fragmentation within a coniferous forest landscape. Landscape ecol 10, 267-275.

Gainzarain JA. 2003. Trepador azul (*Sitta europaea*). In: Atlas de las aves reproductoras de España (Martí R, Del Moral JC, eds.). Dirección General de Conservación de la Naturaleza-Sociedad Española de Ornitología, Madrid, Spain. pp. 518-519.

Galpern P, Manseau M, Fall A. 2011. Patch-based graphs of landscape connectivity: a guide to construction, analysis, and application for conservation. Biol Conserv 144, 44-55.

García-Feced C, Saura S, Elena-Rosselló R. 2011. Improving landscape connectivity in forest districts: A two-stage process for prioritizing agricultural patches for reforestation. Forest Ecol Manag 261, 154-161.

Gurrutxaga M, Rubio L, Saura S. 2011. Key connectors in protected forest area networks and the impact of highways: A transnational case study from the Cantabrian

Range to the Western Alps (SW Europe). Landscape Urban Plan 101, 310-320.

Hansen AJ, Neilson RP, Dale VH, Flather CH, Iverson LR, Currie DJ, *et al*. 2001. Global change in forests: Responses of species, communities, and biomes. Bioscience 51, 765-779.

Hodgson JA, Thomas CD, Wintle BA, Moilanen A. 2009. Climate change, connectivity and conservation decision making: Back to basics. J Appl Ecol 46, 964-969.

Janin A, Léna J-P, Ray N, Delacourt C, Allemand P, Joly P. 2009. Assessing landscape connectivity with calibrated cost-distance modelling: Predicting common toad distribution in a context of spreading agriculture. J Appl Ecol 46, 833-841.

Jantke K, Schleupner C, Schneider UA. 2011. Gap analysis of European wetland species: Priority regions for expanding the Natura 2000 network. Biodiversity Conserv 20, 581-605.

Kettunen M, Terry A, Tucker G, Jones A. 2007. Guidance on the maintenance of landscape features of major importance for wild flora and fauna - Guidance on the implementation of Article 3 of the Birds Directive (79/409/EEC) and Article 10 of the Habitats Directive (92/43/EEC). Institute for European Environmental Policy (IEEP), Brussels, 114 pp. & Annexes.

Lindenmayer DB, Franklin JF, Fischer J. 2006. General management principles and a checklist of strategies to guide forest biodiversity conservation. Biol Conserv 131, 433-445.

Manuel C, Gil L. 2002. La transformación histórica del paisaje forestal en Galicia. Tercer Inventario Forestal Nacional, Ministerio de Medio Ambiente, Madrid, Spain. 159 pp.

Ministerio de Medio Ambiente, 2005. Tercer Inventario Forestal Nacional, Galicia. Dirección General para la Biodiversidad, Madrid, Spain.

Mitsova D, Shuster W, Wang X. 2011. A cellular automata model of land cover change to integrate urban growth with open space conservation. Landscape Urban Plan 99, 141-153.

Neel MC. 2008. Patch connectivity and genetic diversity conservation in the federally endangered and narrowly endemic plant species *Astragalus albens* (Fabaceae). Biol Conserv 141, 938-955.

Noss RF, Daly KM. 2006. Incorporating connectivity into broad-scale conservation planning. In: Connectivity Conservation (Crooks KR, Sanjayan M, eds.). Cambridge University Press, Cambridge. pp. 587-619.

Pascual-Hortal L, Saura S. 2006. Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation. Landscape Ecol 21, 959-967.

Pascual-Hortal L, Saura S. 2008. Integrating landscape connectivity in broad-scale forest planning through a new graph-based habitat availability methodology: application

to capercaille (*Tetrao urogallus*) in Catalonia (NE Spain). Eur J For Res 127, 23-31.

Pereira M, Segurado P, Neves N. 2011. Using spatial network structure in landscape management and planning: a case study with pond turtles. Landscape Urban Plan 100, 67-76.

Rayfield B, Fortin M-J, Fall A. 2010. The sensitivity of least-cost habitat graphs to relative cost surface values. Landscape Ecol 25, 519-539.

Ray N. 2005. Pathmatrix: a geographical information system tool to compute effective distances among samples. Mol Ecol Notes 5, 177-180.

Rodríguez-Freire M. 2006. Integración de la conectividad funcional en los procesos de ordenación territorial mediante técnicas SIG. Aplicación a la conservación de la biodiversidad asociada a las formaciones de frondosas caducifolias. Doctoral thesis. Universidad de Santiago de Compostela.

Rodríguez-Freire M, Crecente R. 2006. Application of cost surfaces for mapping connectivity on several scales of a bird species associated with deciduous woodland, the nuthatch *Sitta europaea*. In: Patterns and processes in forest landscapes, consequences of human management (Lafortezza R, Sanesi G, eds.). Proceedings of the 4th Meeting of IUFRO Working Party 8.01.03, Locorotondo, Bari, Italy, pp. 513-522.

Rouget M, Cowling RM, Lombard AT, Knight AT, Kerley GIH. 2006. Designing large-scale conservation corridors for pattern and process. Conserv Biol 20, 549-561.

Rubio L, Saura S. 2012. Assessing the importance of individuals habitat patches as irreplaceable connecting elements: an analysis of simulated and real landscape data. Ecol Complex (in press) DOI: 10.1016/j.ecocom.2012.01.003.

Santos T, Tellería JL, Carbonell R. 2002. Bird conservation in fragmented Mediterranean forests of Spain: Effects of geographical location, habitat and landscape degradation. Biol Conserv 105, 113-125.

Saura S. 2010. Del rodal al paisaje: un cambio de escala, nuevas perspectivas para la planificación y ordenación forestales. Conferencias y Ponencias del 5º Congreso Forestal Español, Cuadernos de la Sociedad Española de Ciencias Forestales 31, 213-239.

Saura S, Pascual-Hortal L. 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: Comparison with existing indices and application to a case study. Landscape Urban Plan 83, 91-103.

Saura S, Rubio L. 2010. A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape. Ecography 33, 523-537.

Saura S, Torné J. 2009. Conefor Sensinode 2.2: a software package for quantifying the importance of habitat patches for landscape connectivity. Environ Modell Softw 24, 135-139.

Saura S, Vogt P, Velázquez J, Hernando A, Tejera R. 2011. Key structural forest connectors can be identified by combining landscape spatial pattern and network analyses. For Ecol Manage 262, 150-160.

Sawyer SC, Epps CW, Brashares JS. 2011. Placing linkages among fragmented habitats: Do least-cost models reflect how animals use landscapes? J App. Ecol 48, 668-678.

Taylor PD, Fahrig L, Henein K, Merriam G. 1993. Connectivity is a Vital Element of Landscape Structure. Oikos 68, 571-573.

Taylor PD, Fahrig L, With KA. 2006. Landscape connectivity: a return to the basics. In: Connectivity Conservation (Crooks KR, Sanjayan M, eds.). Cambridge University Press, Cambridge. pp. 29-43.

Urban D, Keitt T. 2001. Landscape connectivity: A graph-theoretic perspective. Ecology 82, 1205-1218.

Van Langevelde F. 2000. Scale of habitat connectivity and colonization in fragmented nuthatch populations. Ecography 23, 614-622.

Van Langevelde F, Claassen F, Schotman A. 2002. Two strategies for conservation planning in human-dominated landscapes. Landscape Urban Plan 58, 281-295.

Van Langevelde F, Schotman A, Claassen F, Sparenburg G. 2000. Competing land use in the reserve site selection problem. Landscape Ecol 15, 243-256.

Verboom J, Schotman A, Opdam P, Metz JAJ. 1991. European nuthatch metapopulations in a fragmented agricultural landscape. Oikos 61, 149-156.

Vos CC, Berry P, Opdam P, Baveco H, Nijhof B, O'Hanley J, *et al*. 2008. Adapting landscapes to climate change: examples of climate-proof ecosystem networks and priority adaptation zones. J Appl Ecol 45, 1722-1731.