Landsc Ecol (2023) 38:3751–3765
https://doi.org/10.1007/s10980-023-01789-6

RESEARCH ARTICLE

Identifying a green infrastructure to prioritise areas for restoration to enhance the landscape connectivity and the provision of ecosystem services

Unai Ortega · **Ibone Ametzaga-Arregi** ·
Unai Sertutxa · **Lorena Peña**

Received: 31 January 2023 / Accepted: 29 September 2023 / Published online: 7 November 2023

Abstract

Introduction Habitat fragmentation is one of the major causes of the loss of biodiversity that our planet is experiencing. This has affected the ecosystems functioning and, consequently, the provision of ecosystem services (ES). Therefore, the European Commission, in a 2013 communication, established the concept of Green Infrastructure (GI), which is a strategically planned network of multifunctional areas with the aim of protecting biodiversity and ES supply, as well as improving ecological connectivity. Ecological restoration is an essential element to achieve the objectives of the GI, which if well targeted, could reverse widespread ecosystem degradation and improve landscape connectivity.

Objective In this study, we propose a methodology to prioritise areas to restore by identifying a GI in the Urdaibai Biosphere Reserve (UBR), in the north of the Iberian Peninsula, where forest plantations of exotic species abound.

Methods In order to identify the elements of the GI (core areas and corridors) we integrated a multispecies approach based on the movement of key species and an ES-based approach based on multifunctionality. Subsequently, to prioritise areas to restore we identified sectors in the GI, where connectivity is particularly vulnerable (pinch points) using the circuit theory. Thus, forest plantations around the pinch points were prioritised for a future restoration plans depending on their aim: (1) Improve corridors of high importance and low quality for the multispecies approach (2) Improve corridors of high importance and low quality for the ES-based approach, and (3) Improve the connectivity of the GI for the species movement.

Results The resultant GI included 36% of the UBR surface. We identified 34 pinch points for the corridors of the three especies in the multispecies approach and 64 in the ES-based approach. We prioritised 149 ha of exotic forest plantations around the pinch points to convert into native forest in order to improve the corridors and 167 ha to improve GI connectivity.

Conclusion This information could be useful for organizations and institutions carrying out restoration actions for the recovering of native forests in the territory.

Keywords Biosphere reserve · Circuit theory · Ecological corridors · Multifuncionality · Restoration

---

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10980-023-01789-6.

U. Ortega (✉) · I. Ametzaga-Arregi · U. Sertutxa · L. Peña
Department of Plant Biology and Ecology, University of the Basque Country (UPV/EHU), Barrio Sarriena, s/n, 48940 Leioa, Biscay, Spain
e-mail: Unai.ortegab@ehu.eus

Introduction

Habitat loss and landscape fragmentation are recognised as the major drivers of biodiversity loss and endangerment of species (Gurrutxaga 2010; Haddad et al. 2015). This biodiversity loss compromises the capacity of ecosystems to contribute to a resilient provision of ecosystem functions and services (ES), which underpin human well-being (Cardinale et al. 2012). ES are the benefits provided by ecosystems to human well-being and they are classified into three groups: provisioning services, regulating services and cultural services (Haines-Young and Potschin 2018). Moreover, due to climate change species will have to track climates to which they are accustomed, either by dispersing through changed and fragmented landscapes or by adapting to changing conditions in situ (Root et al. 2003). Therefore, reducing the loss of biodiversity on the planet is one of the environmental policy objectives. Hence, the European Commission, in the Biodiversity Strategy for 2030, proposes to ensure better protection of ecosystems by 2050 and their recovery (European Commission 2020). Nonetheless, there is a broad consensus that it is no longer possible to maintain the planet's biodiversity at an acceptable level exclusively through the designation of protected areas and the conservation inside them, which is why new tools and management models are necessary (Valladares et al. 2017; Mola et al. 2018).

In recent decades a new land management tool has emerged that encompasses, in addition to landscape connectivity, its multifunctionality (capacity to provide a wide range of ES) in order to conserve biodiversity and face future challenges, such as climate change. This tool is the Green Infrastructure (GI), which is defined as a "strategically planned network of high-quality natural and semi-natural areas, designed and managed to provide the greatest amount of ES and protect biodiversity, both in rural and urban settlements" (European Commission 2013). At the European level, the Communication "Green Infrastructure: enhancing Europe's natural capital" lays the foundations for the development of the European Union's GI Strategy. According to that, the GI is not only an ecological network, which maintain o restore ecological functions, but also an instrument that helps to improve the connectivity of the territory and the protection of ES supply. The Biodiversity Strategy for 2030 points out that the ecosystems and ES should be maintained and enhanced by creating and systematically integrating a GI into territorial planning and restoring at least 15% of degraded ecosystems (European Commission 2020). Therefore, ecological restoration is one of the essential instruments to achieve the objectives set by the GI, such as reverse ecosystem degradation and improve landscape connectivity. In the case of Spain, the National Strategy for Green Infrastructure and Ecological Connectivity and Restoration is a fundamental planning tool for identifying, conserving and recovering damaged ecosystems throughout the territory and connecting them with each other, with the surrounding territories and ecological systems (Valladares et al. 2017).

In that sense, maintaining landscape connectivity is essential for the persistence of populations due to dynamic processes such as recolonization, seasonal migration, and dispersal (Beier et al. 2011; Ribeiro et al. 2017). Identifying links or corridors based on actual observations of the movements of species of interest would be an ideal strategy for constructing connectivity networks for a region (Feng et al. 2021). However, because empirical data of this type is few or non-existent for most species, connectivity investigations must rely on models and human judgment (Cushman et al. 2013). In fact, the development of these coherent ecological networks has played a very important role in biodiversity conservation policies, such as the European Union Biodiversity Strategy for 2030 or the Kunming-Montreal Global Biodiversity Framework. Most of these studies focus on the movement of a single species (Ruiz-Gonzales et al. 2014; Feng et al. 2021; Gantchoff et al. 2021), while more recently there has been a growing interest in modelling connectivity for multiple species to address the diverse ecological needs of coexisting species and their ecological processes (Liu et al. 2018; Almenar et al. 2019).

In order to analyse or improve the exiting connectivity, the use of graph theory is thought to facilitate the representation of landscapes as a series of nodes and links between them, from which a connectivity index has been developed to measure changes in structural connectivity or to test different scenarios to improve connectivity (Rayfield et al. 2011). This last goal can be achieved by increasing the size or the quality of existing habitat patches, or by creating new patches through landscape restoration (Foltête et al. 2014). More recently, connectivity models have been developed to measure functional connectivity such as individual responses to landscape mosaic elements and their spatial movement considering landscape heterogeneity. Least cost path analysis and circuit theory are examples of these models, which have drawn an enormous amount of attention as they can help evaluating the features of an ecological network such as the importance of linkages, pinch points and the quality of each linkage (Almenar et al. 2019; Feng et al. 2021). In addition, some studies base their networks specifically on ES to maximize the value of ES in ecological infrastructure planning (Lee et al. 2014; Cannas et al. 2018).

Ecological restoration has been recognized by multiple sectors (scientific, technical, administrative and social) as a fundamental tool to reverse the widespread degradation of ecosystems, replenish natural capital, and guarantee the supply of ES to society (Bullock et al. 2011; Mola et al. 2018; Hua et al. 2022). Moreover, if well targeted, the restorations could improve the connectivity of the landscape and protect existing connectivity (Fagan et al. 2016). To this end, many organisations carry out restoration actions in different ecosystems. One method increasingly used by these organisations is land stewardship, in which voluntary agreements are reached between the owner of a property with natural and cultural value and an organisation. All these actions should be aimed at improving biodiversity, ES provision and landscape connectivity (Račinska et al. 2015). It is therefore very important to look for methods to find areas of higher priority to be restored. In this sense, biosphere reserves, which are figures created by Unesco within its Man and the Biosphere Programme, are good areas of research to develop sustainable practices and restore natural ecosystems, since all the sectoral groups involved in these territories can work together in the search for an integrated management of the territory (Van Cuong et al. 2017). The main objectives for the designation of these areas are threefold: nature conservation, sustainable development and logistical support, referring to scientific knowledge and education for sustainability. They are set up as areas of experimentation to achieve a balance between conservation and sustainable development in order to improve the living conditions of the people who live there (Iswharan et al. 2008).

In this work, we propose a methodology for identifying a GI based on the movement of key species and the provision of multiple ES, in order to find the priority areas for restoration in a biosphere reserve with the aim of improving the landscape connectivity and its multifunctionality. In the case of the selection of the priority areas for restoration, we used the circuit theory to identify the sectors where connectivity is especially vulnerable (pinch points) and then we prioritised their restoration based on the features of the corridors (importance and quality). Taking into account the proposed "Regulation of the European Parliament and of the Council on Nature Restoration", which aims to restore nature to its original state in all ecosystems and 80% of Europe's degraded habitats (European Commission 2022), this methodology can be useful to achieve those objectives at different scales (national, regional or local).

Methods

Study area

This study was carried out in the Urdaibai Biosphere Reserve (UBR) (Fig. 1). The UBR is one of the most important protected natural spaces in the Basque country, north of the Iberian Peninsula that occupies 22,000 ha. This reserve is representative of many regions of the north where the native forests are highly fragmented due to forest plantations of exotic species (*Pinus radiata* D. Don and *Eucalyptus globulus* Labill). In this reserve, forest plantations occupy 50% of the surface (Castillo-Eguskitza et al. 2017). However, a wide variety of flora and fauna with high ecological interest can be found, such as the Cantabrian green oak forests, which occupy 7% of the surface, or the Atlantic mixed forests and riparian forests, which occupy 9% of the territory.

During the last 20 years, some organizations have carried out restoration actions in the UBR to recover native forest. Among them, we found the Lurgaia Foundation, which is a private non-profit entity whose purpose is to promote the conservation of biodiversity and the management of natural heritage in the UBR. This foundation has more than 200 ha of land in custody, in which plantations of exotic species are replaced by native species.

Methdology

The methodological steps followed in this study are shown in Fig. 2.

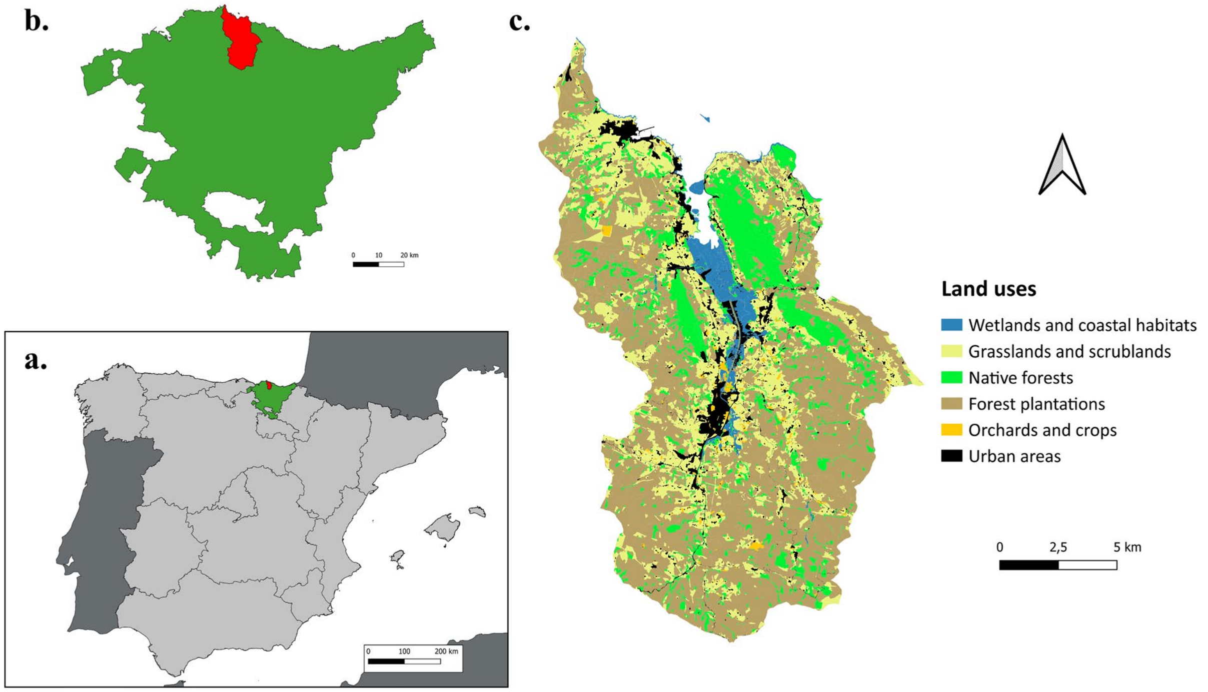
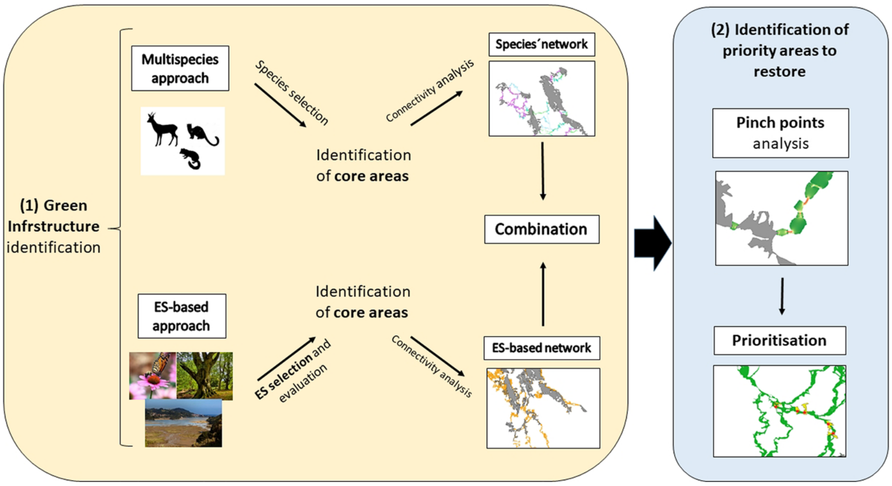


Fig. 1 Maps showing the location of the Basque country in the Iberian Peninsula (**a**), the location of the Urdaibai Biosphere Reserve (UBR) in the Basque country (**b**) and the land uses of the UBR (**c**)

Fig. 2 Flowchart of the methodical steps. *ES* ecosystem service



Identification of GI

To identify the GI components (core areas and corridors) we used two approaches following a similar path for both of them: a multispecies approach and ES-based approach (Liquete et al. 2015).

Identification of core areas For the multispecies approach, we firstly selected three key species in the territory (Basque Government 2016):

- The roe deer (*Capraelus capraelus*) which belongs to the group of large mammals with a maximum dispersal distance of 100 km.

- The pine marten (*Martes martes*) which belongs to the group of mesomammals with a maximum dispersal distance of 30 km.
- The edible dormouse (*Glis glis*): which is a specialist of forest habitats belonging to the group of small mammals with a maximum dispersal distance of 10 km.

Secondly, the core areas to be connected were selected based on the forest type and the size of these forests. Native forests (Atlantic mixed forests, riparian forests, and Cantabrian green oak forests) larger than 20 ha were selected as they are the common habitat in which the three target species coexist (Basque Government 2016). For the identification of these forests, the Forest Inventory of the Basque Country of 2020 was used.

For the ES-based approach, we firstly identified the multifunctional areas. For that purpose, we selected the 7 most important regulating services in the area (Peña et al. 2020) (Water flow regulation, Pollination, Air quality regulation, Climate regulation Habitat maintenance, Maintenance of soil fertility and Fire control service (CICES classification) and mapped them using the following indicators:

- Water flow regulation: We used the water retention index (Peña et al. 2020) calculated as:

$$\mathrm{WRI} = (\mathrm{WRv} * \mathrm{Rv} + \mathrm{WRgw} * \mathrm{Rgw} + \mathrm{WRs} * \mathrm{Rs} + \mathrm{Wslope} * \mathrm{Slope} + \mathrm{WWB} * \mathrm{RWB}) * (1 - \mathrm{Ra}/100)$$

WRI = Water retention index; WRv, WRgw, WRs, Wslope, WWB = Weights assigned to each variable; Rv = Retention by vegetation; Rgw = Retention in ground water; Rs = Retention in soil; RWB = Retention in water bodies; Ra = Soil waterproofing.

- Pollination: We used the index of abundance of nesting pollinators (Peña et al. 2020) by using the pollination module from the *InVEST* program
- Air quality regulation: We used the Capacity to eliminate NO_2 from the air (Peña et al. 2020) calculated as:

$$\mathrm{CE\ NO_2} = \mathrm{C\ NO_2} * \mathrm{Rd\ NO_2}$$

CE NO_2 = Capacity to eliminate NO_2 from the air (μg/m^{2}s); C NO_2 = Mean annual concentration of NO_2 in the air (μg/m^3); Rd NO_2 = Rate of dry deposition of NO_2 in leaves (ms^{-1}).

- Climate regulation (Carbon storage): We used the total carbon storage (Peña et al. 2020) where:

$$\mathrm{TC} = \mathrm{CLB} + \mathrm{CDB} + \mathrm{CS}$$

TC = Total C content (tC/ha); CLB = C content in live biomass (tC/ha); CDB = C content in dead biomass (tC/ha); CS = TC content in the soil (tC/ha).

- Habitat maintenance: we used habitat maintenance index (Peña et al. 2020) where:

$$\mathrm{HM} = \mathrm{W} + \mathrm{S} + \mathrm{P}$$

HM = Habitat maintenance index; W = Native vascular plant species richness; S = Successional state; P = Protected areas or areas of natural interest.

- Maintenance of soil fertility: We used the organic carbon content stored in the top 30 cm of soil (tC/ha) (Guía metodológica para el cartografiado de los Servicios de los Ecosistemas de Euskadi, unpublished).
- Fire control service: We used the forest fuel models established for the Basque Country within the Special Fire Protection Plan for the risk of forest fires in the Basque Autonomous Community (Guía metodológica para el cartografiado de los Servicios de los Ecosistemas de Euskadi, unpublished).

The geographical data used for the calculation of the indicators are shown in the table 3 of the appendix. The resultant values for the indicators were normalised based on maximum and minimum values obtaining values between 0 and 1 (Fig. 8, Online Appendix). Then we calculated a Multifunctionality Index (MI) combining the values of all ES through an arithmetic mean and we reclassified those values into five ranks ranging from minimum (1) to maximum capacity (5) based on a natural breaks' distribution (Fig. 9, Online Appendix). The multifunctional areas of the UBR corresponded to the ranks 4 and 5 (Liquete et al. 2015).

We identified as core areas those multifunctional areas with a size greater than 20 ha.

Connectivity analysis In order to identify the corridors, we performed a connectivity analysis by using the least-cost path method and the circuit theory. *Linkage mapper* program in *ArcMap 10.8* was used to perform the connectivity analysis (Schrott and Shin 2020; Feng et al. 2021; Gantchoff et al. 2021). This program outlines least cumulative cost pathways (LCPs) for the movement of species and, ultimately, creates least cost corridors between core areas. The corridors are wider swaths surrounding LCPs, which have slightly higher cumulative movement costs and are more biologically realistic for conservation planning (Schrott and Shin 2020). With this program, the quality of each LCP was also calculated (the accumulated cost distance of each LCP/the real distance). This value indicates the average resistance found along each LCPs and the values closer to 1 indicate a better quality of the LCP (Feng et al. 2021). Subsequently, the centrality index of each LCP was calculated with the *Centrality mapper tool* of the *Linkage mapper* program (McRae 2012a), which uses the circuit theory to indicate the relative importance of each LCP to keep the whole network connected. These features of the corridors (quality and importance for the network) can help us finding important areas for the connectivity and areas that should be improved.

In the case of the multispecies approach, we assigned resistance values from 1 to 1000 to each land use (Table 3, Online Appendix) (Basque Government 2016) to perform the connectivity analysis. These resistance values represent the difficulty experienced by a species in moving across a landscape. The land uses were taken from the Basque Government (2009), which was reviewed and corrected using the orthophoto from 2021. Moreover, we considered noise and light pollution, as they can alter mammals' habits as their distribution and movement (Slabbekorn et al. 2018; Hoffmann et al. 2019). In this case, a noise map for the area provided by the Provincial Council of Bizkaia was used to assess the noise pollution, where the limit values (65 and 55 dB) were obtained from the Royal Decree 1367/2007 on noise. Regarding light pollution, a kernel density analysis was performed for the light points on the main roads using the light pollution map of Bizkaia. The obtained values for the nightlight density were reclassified into three ranges (High: > 25.6; Medium: 25.6–7.8; Low: < 7.8). Finally, we added to the previous resistances a resistance value of 100 to places with an average noise greater than 65 dB or with a high nightlight density; and a resistance value of 50 to places with an average noise greater than 55 dB or with a medium nightlight density.

In the ES-based approach, we assigned resistance values ranging from 1 to 1000 depending on the MI: 1 to the ranks 4 and 5, 100 to the rank 3, 500 to rank the 2, and 1000 to the rank 1.

Combination of both approaches Finally, we obtained, on the one hand, a multispecies' network and, on the other hand, an ES-based network which were combined into a single network, maintaining the core areas and corridors of both. This final network formed the final GI proposal.

Identification of priority areas to restore

In order to find the areas to restore, we first used the *Pinchpoint mapper tool* of the Linkage mapper program to identify sectors where the movement of organisms is compromised and connectivity is particularly vulnerable (pinch points) due to the absence of alternative routes or the narrowing of corridors caused by land uses that obstruct movement (McRae 2012b). Then, the number of pinch points of each corridor and the cause for the appearance of each pinch point were calculated. The cause of each pinch point was defined as the land use that narrows the preferred land use or replaces it in a corridor. Only the pinch points caused by forest plantations were used for the prioritisation of areas to restore. Subsequently, we prioritised them based on three different purposes:

Improve the quality of the corridors with the highest importance and least quality for the three key species Thus, we only considered to restore those forest plantations that were in or around pinch points of the three species. Then, we prioritised the ones located in the most important corridors and corridors with the worst quality.

Improve the quality of the corridors based on the provision of ES with the highest importance and least quality In this case, we only considered to restore those forest plantations that were in or around pinch points of the ES-based approach. Then, we prioritised the ones located in the most important corridors and the corridors with the worst quality.

Improve the connectivity of the whole GI for the movement of the key species For this purpose, we first identified all the forest plantations in the UBR that, if restored, together with the adjacent native forest, would create a core area of 20 ha. The prioritisation was achieved by using the analysis developed by Foltête et al. (2014) which uses the graph theory to identify the best locations for new core areas based on the connectivity improvement. This analysis was first carried out for the 130 possible new core areas identified as a preliminary test, in order to observe the pattern of the increase in connectivity for each species. Later, the same analysis was performed with the new possible core areas that were located in pinch points for the three key species. The connectivity improvement was analysed using the Probability of Connectivity index (PC) (Saura and Pascual 2007). We chose this index as it is commonly used in heavily modified areas to evaluate the functional and structural connectivity of an existing network (Keeley et al. 2021), and PC is given by the expression:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^{*}}{A^2}$$

where a_i and a_j are the areas of the core areas $_i$ and $_j$, p^{*}_{ij} is the maximum probability of movement between these areas and A is the total area of the study zone. p_{ij} is determined by this exponential function:

$$p_{ij} = \exp(-\alpha d_{ij})$$

where d_{ij} is the least cost distance between the patches $_i$ and $_j$, and α a parameter defining the rate of decline in probability of movement as distance increases. As it is not easy to determine the value of α parameter, we used the maximum dispersal distance of each species to a small value of p (0.05). All the analyses were performed using *Graphab 2.8.1* software (Foltête et al. 2012).

Results

Multispecies' network

In the multispecies approach, we identified 13 core areas. Most of them were located in the half north of the UBR. The largest patches corresponded to Cantabrian green oak forests, which are representative of the UBR. The smallest patches were Atlantic mixed forests, which had a smaller size (Fig. 3). The results indicated that these core areas were connected by 23 corridors for the roe deer (surface: 1042 ha; average length: 4.4 km), by 20 for the pine marten (surface: 1380 ha; average length: 4.8 km), and by 23 for the edible dormouse (surface: 610 ha; average length: 4.5 km) (Table 5, Online Appendix). In total 1900 ha of ecological corridors were identified, where the 26% are useful for 2 species and the 16% for the 3 species (Fig. 3).

ES-based network

There were 27 core areas resultant from the ES-based approach. All the core areas previously identified for the multispecies approach coincided with the multifunctional areas except two of them located in the southern part. The core areas resultant from this approach were connected by 39 corridors (surface: 2586 ha; average length: 2.2 km) (Fig. 3; Table 6, Online Appendix).

Final GI proposal

The corridors of the final GI occupy in total 3872 ha and the core areas 3391 ha, so the final GI proposal includes 36% of the total area of the RBU (Fig. 4). The most common land use in the GI proposal is native forest (37.4%) followed by forest plantations (35.2%).

Priority areas to restore

In the multispecies approach, we identified 137 pinch points for the roe deer corridors, 133 for the pine marten and 195 for the edible dormouse. The major cause of these pinch points was the narrowing or vanishing of mixed forests due to forest plantations. More specifically, 46% of the pinch points were caused by forest plantations, 26% by road junctions, 25% by narrowing of forests due to grassland, 8% by artificial constructions and the remainder were caused by other land uses.

In the ES-based approach, we identified 68 pinch points. Of those pinch points, 57% were caused by forest plantations, 19% by road crossings, 10% by grasslands and 13% by artificial constructions.

In relation to improve the quality of the corridors for the three key species, we identified 34 pinch points, that

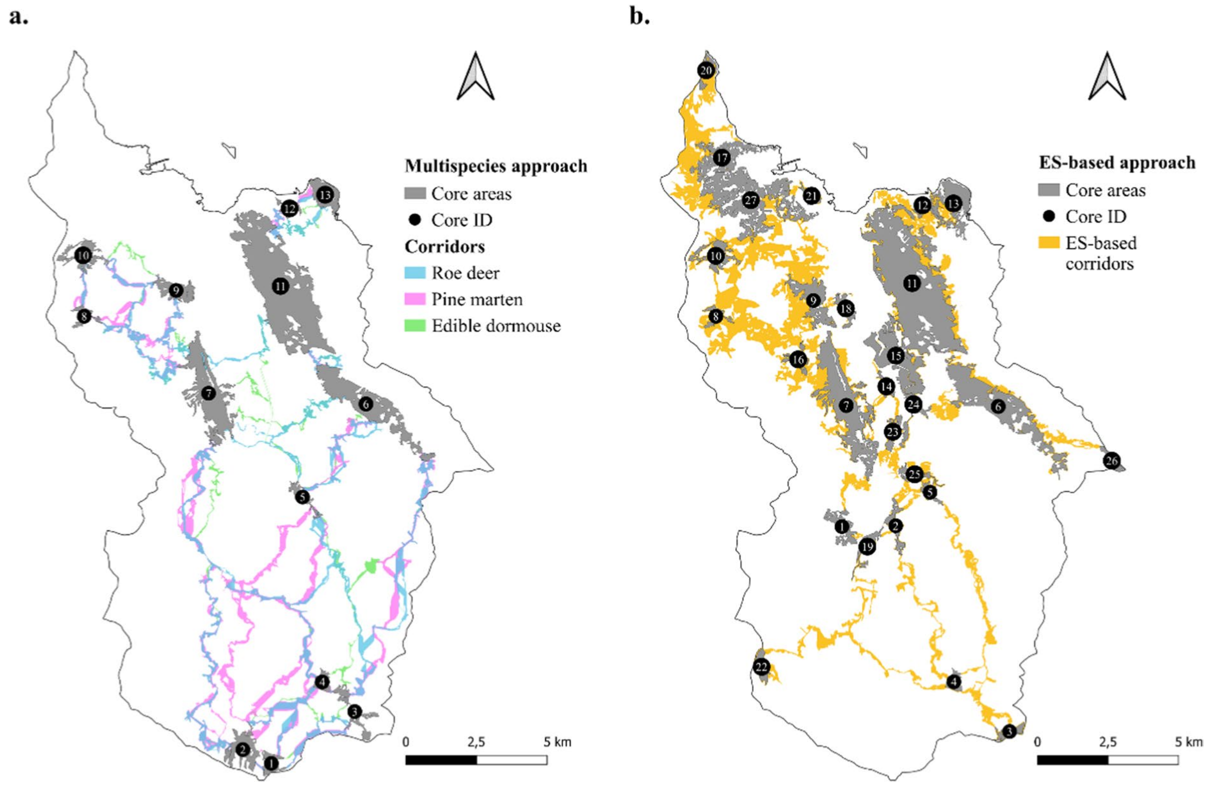


Fig. 3 Distribution of core areas and corridors of the multispecies approach (**a**) and ES-based approach (**b**)

were located in eight different corridors and 13 located in corridors 4–7 and 3–6 were prioritised for reforestation, as they were between the corridors with the highest importance and least quality (Fig. 5, Table 1).

In the case of improving the quality of the corridors for the the ES-based aproach, we found 45 pinch points that were caused by forest plantations, which were located in nine different corridors. Among them, 13 pinch points located in the corridor 19–22 were prioritised for reforestation, as it was between the corridors with the highest importance and least quality (Fig. 5, Table 2). We found 149 ha of forest plantations in or around the pinch points prioritised for the multispecies and ES-based approaches. Among these hectares 20% corresponded to eucalyptus plantations and 80% to pine plantations.

In terms of improving the GI connectivity, it was observed that the increment of the connectivity index with respect to the initial value was constant, and very significant with each core area added and for each species. No maximum value was found in any of the cases (Fig. 6). The average increase per core area added was 5% for roe deer, 4% for pine marten and 2% for edible dormouse.

Finally, we identified nine forest plantations capable of creating new core areas around the pinch points for the three key species. The order of prioritisation was different for each species. Thus, the roe deer analysis tends to prioritise the forest plantations by their size, unlike the gray dormouse analysis that prioritises them depending on their location. The pine marten analysis considers the location and the size of the forest plantations to prioritise them (Fig. 7). The increase in the PC index achieved by restoring the nine forest plantations was 46% for the roe deer, 37% for the pine marten and 24% for the edible dormouse.

Discussion

The GI proposal

In recent years, the loss of biodiversity and ES in the UBR has been evident, different studies have

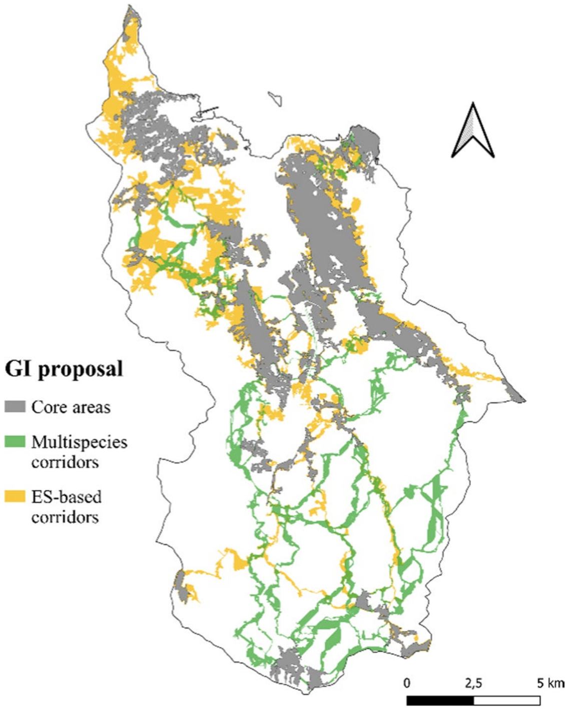


Fig. 4 Final GI proposal resultant from the combination of both approaches (multispecies and ES-based approach)

indicated that the fragmentation of the mixed Atlantic forests has had a negative effect on biodiversity and consequently on the provision of ES in the area (Onaindia et al. 2004, 2013; Rodríguez-Loinaz et al. 2012). Therefore, the proposed methodology to identify a GI and the pinch points, based on a multispecies approach and an ES-based approach, can be an opportunity to prioritise the areas that are most suitable for reforestation in the UBR. Moreover the restauration of these areas will improve the landscape connectivity reducing natural forest fragmentation, as the largest forests are considered as core areas and the rest of them are included within the corridors. Furthermore, it is necessary to develop GIs at these scales in order to connect them with the GIs developed at higher scales (regional, national and European). In fact, all GI strategies recommend the development of a GI at smaller scales in order to achieve a more connected territory. For this reason, different territories have already started to create similar GI such as Central Europe (Fňukalová et al. 2021), Portugal (Cunha and Mgalhaes 2019) or Catalonia (Lanzas et al. 2019).

In this context, to identify the GI it is necessary to define, on the one hand, the core areas, as their conservation can help conserve biodiversity and ES supply. On the other hand, it is necessary to define corridors connecting them, as the movement of organisms and ecological flows that occur in the landscape can help maintain ES (Mitchell et al. 2013; Schindler et al. 2016). In the UBR, the core areas correspond mainly to natural forests, grasslands and wetlands due to their relevance for the conservation and maintenance of biodiversity and ES provision, while the ecological corridors are formed mainly by exotic forest plantations due to the large amounts of these forest plantations found in the UBR. Although many animal species such as, the pine marten or the roe deer, can move without problem through these plantations, they prefer natural forests (Iezzi et al. 2018). However, other more specialist species such as, the edible dormouse, tend to migrate shorter distances and move less through areas that are not their ideal habitats. Additionally, small mammals are the most affected by clear-cutting, which is the method used for harvesting wood in the UBR (Escobar and Estades 2021). Therefore, the edible dormouse corridors are narrower, consist of 63% natural forest, and have a lower quality index than those of marten and roe deer. Furthermore, many studies (Mortelliti et al. 2014; Giubbina et al. 2018) have shown that forest plantations do not improve landscape connectivity, but may worsen the movement of some species. Consequently, the goal of managers should be to minimize the distance between patches of native habitat by promoting habitat restoration and by enhancing the creation of corridors of native vegetation (Mortelliti et al. 2014).

Moreover, by using three species for corridor identification instead of one, as in many other studies (Schrott and Shinn 2020; Feng et al. 2021; An et al. 2021), we achieve a more complex and larger corridor network. The challenge for multispecies connectivity is to determine which method is the most appropriate and what type of connections to use, as different species have different needs and different habitat preferences. In this work, we have chosen to model the connectivity of each species separately and combine the resulting connections (Liu et al. 2018; Khosravi et al. 2018), as analysing the areas where the corridors of different species overlap helps us to find areas of high importance for connectivity (Liu et al. 2018). However, other studies identify the connecting pathways

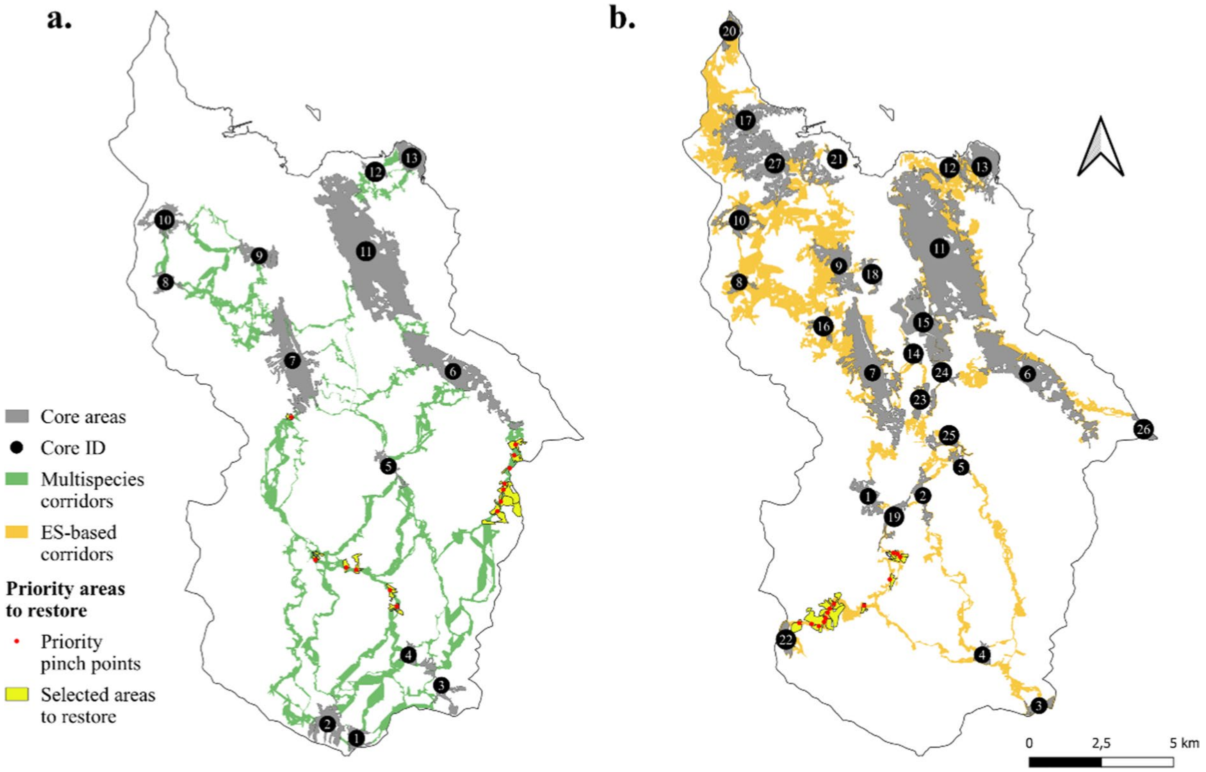


Fig. 5 Priority areas to restore around the most vulnerable zones (priority pinch points) for the multispecies approach (**a**) and ES-based approach (**b**)

Table 1 Quality and importance of the corridors that had pinch points for the three species. The lowest quality values for each species are represented with the bold and the highest importance values with the italic

Corridors	Roe deer		Pine marten		Edible dormouse	
	Quality	Importance	Quality	Importance	Quality	Importance
1–3	**15.34**	8.36	**7.79**	8.04	**46.49**	7.55
2–7	10.44	9.54	**6.58**	11.85	29.27	10.14
3–6	**11.07**	*12.47*	**5.01**	*14.62*	**33.98**	*10.31*
4–7	**12.18**	*12.20*	**5.84**	*14.02*	**32.77**	*11.34*
5–6	10.50	*15.77*	3.39	*26.95*	25.40	*18.71*
7–8	6.20	*17.57*	3.98	*16.39*	16.59	*16.65*
8–9	**11.23**	5.51	4.74	5.63	**36.21**	4.74
8–10	10.09	11.77	4.94	11.80	32.21	10.02

that have the highest landscape integrity, rather than modelling the actual needs of each species (Koen et al. 2014; Belote et al. 2016).

Similarly, corridors resultant from the ES-based approach take advantage of grasslands, native forests and scrublands to create minimum-cost routes. Although grasslands in the study area are ecosystems that are maintained by human management (mowing and livestock grazing), they provide ES relevant to human well-being, such as pollination. While most studies on ES focus on forests, wetlands and urban areas, grasslands are a crucially important ecosystem for conserving and enhancing ES (Zhao et al. 2020). Contrary, forest plantations are the main reason why these ES-based corridors are endangered in the UBR. This is because they are the most abundant land use

Table 2 Quality and importance of the ES-based corridors that had pinch points caused by forest plantations. The lowest quality values are represented with the bold and the highest importance values with the italic

Corridors	Quality	Importance
1–7	19.12	*58.77*
2–4	**51.97**	12.67
3–4	32.13	*27.11*
3–5	28.50	19.98
4–5	34.84	16.61
4–19	**42.01**	13.38
4–22	**66.04**	13.06
17–20	3.93	*26.00*
19–22	**37.10**	*22.52*

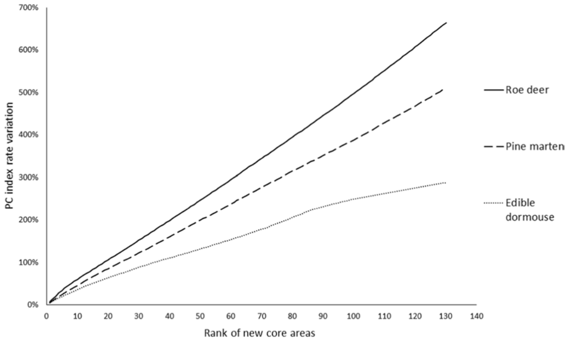


Fig. 6 Graph showing the increase in connectivity (PC index) provided by new core areas for each species, which have different preferences and dispersal distances

and their typically lower biodiversity levels and intensive management result in a reduced capacity of these systems to provide biodiversity-linked ES, which are often regulating ES (Brockerhoff et al. 2013). This highlights the importance of actions, such as, those of the Lurgaia Foundation, to improve the provision of ES from the UBR and thus, benefit the environment and society.

Prioritisation of forest plantations to convert in native forests

The European Commission has attached great importance to restoring the forest ecosystems by increasing their biodiversity and having positive trends for forest connectivity (European commission 2022). In fact, the proposal for a regulation of the European Parliament and of the Council on Nature Restoration is the first legislation in history to explicitly aim to restore Europe's nature and has set itself the goal of repairing 80% of Europe's degraded habitats and restoring nature to its original state in all ecosystems (European Commission 2022). For these targets to be met, it would require Member States to develop national restoration plans, in close cooperation with scientists, stakeholders and the public. In that sense, this methodology could be very useful for organisations working in the UBR, whose objective is the transformation of forest plantations into native forests, as is the case of the Lurgaia Foundation, as it provides scientific evidence on which areas should be restored in the first place.

However, depending on the objective, the prioritisation of areas for restoration given may be very different as seen in this study. Firstly, with the aim of improving the species corridors by acting in the most vulnerable areas, we prioritised restoration actions of the forest plantations around 13 pinch points located in the species corridors with high importance and low quality. Secondly, in order to improve the provision of ES in the most vulnerable areas, the restoration of forest plantations around another 13 pinch points in a corridor with high importance and low quality were prioritised. All these plantations were located in the southern half of the UBR, where the longest corridors and the largest number of forest plantations are found, which may have had a significant influence on the lower quality of these corridors. As many other works (Dutta et al. 2015; Feng et al. 2021), this study has shown that the evaluation of the features of a network (pinch points, quality and importance of corridors) can be helpful to find important vulnerable areas for the connectivity.

In relation with the aim of improving the GI connectivity, we observed that the greater the dispersal distance the greater the variation of the PC index was. In all cases, it had a similar increase with each core area added without reaching any maximum, unlike other works where a maximum was reached when adding less than 10 core areas (Foltête et al. 2014; Li et al. 2017). This was due to the fact that the species chosen had a very high dispersal distance compared to the size of the UBR. Thus, each added core area could create connections to almost all the other core areas increasing the connectivity equitably and reducing the importance of each link (Blazquez-Cabrera

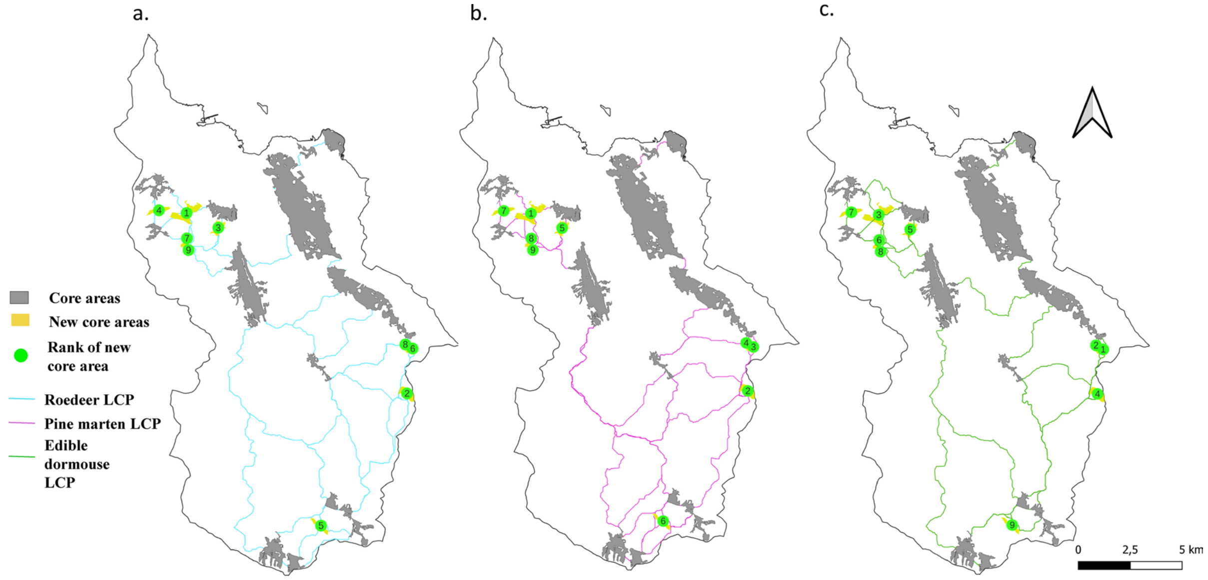


Fig. 7 Prioritisation of forest plantations around the priority pinch points to restore based on the increase in connectivity they provide for each species: Roe deer (**a**), pine marten (**b**) and edible dormouse (**c**)

et al. 2019). Indeed, the edible dormouse, that has the lowest dispersal distance, was the one with the least increment in connectivity with each core area added that agrees with other studies (Li et al. 2017, 2022). Therefore, we recommend analysing the GI connectivity at this scale using species with shorter dispersal distances. Although, in this case, the maximum value of areas that improve GI connectivity is not specified, the prioritisation of core areas obtained serves to meet more than one of the defined objectives. As an example, we have the forest plantation in second position for the roe deer and the pine marten, whose restoration would increase considerably the connectivity of the GI and would improve a corridor with high importance and low quality for the three species.

The proposed methodology to determine a GI and to identify areas to restore could be very useful to apply in other territories, in order to comply with the recommendations implemented by the different strategies and laws at European (Strategy of GI, Biodiversity Strategy for 2030 and Proposal for a regulation on nature restoration), national (Law 42/2007 on Natural Heritage and Biodiversity and the National Strategy for Green Infrastructure and Ecological Connectivity and Restoration) and regional level (Law 9/2021 on the conservation of the Basque Country's natural heritage). These strategies and laws recommend identifying a GI at different scales and obtaining a bank of areas to be restored in order to conserve biodiversity and mitigate the effects of climate change. In the UBR, due to the large abundance of exotic forest plantations and their management, we have used this methodology to find the best areas to convert to native forest, but depending on the area and the objective, it could be used for other purposes and scales. For example, we could use this method to determine which highways are the ones that disrupt more the connectivity in a certain region (Feng, et al. 2021) or which crops are the best to reforest to improve the movement of a given specie (Li et al. 2017).

Conclusion

By connecting large native forests and multifunctional areas through the multispecies and ES-based approach, we have created a GI that can help maintain and improve connectivity and ES provision at the same time. The UBR has a very fragmented landscape mostly due to exotic forest plantations; therefore, we identified the forest plantations that have the highest priority for conversion to native forests in order to improve species movement and ES provision. Moreover, using the graph theory we have prioritised forest plantations depending on the connectivity enhancement their restoration would provide. This method can help foundations such as the Lurgaia Foundation or landscape management agents to prioritise actions based on scientific evidences to improve ES provision and biodiversity. Furthermore, this methodology could be used not only to prioritise exotic forest plantations to convert into native forests in a biosphere reserve, but also to prioritise other types of restoration actions and at different scales with the aim of improving landscape connectivity and ES provision.

Acknowledgements We acknowledge the funding provided by the Basque Government through the given grant (GIC21/201-IT1648-22) and doctoral fellowship (PRE_2022_2_0194). We are also indebted to the University of the Basque Country (UPV/EHU) for the given fellowship (PIF20/27) that has partially supported this research.

Author contributions UO, IA and LP contributed to the conceptualization of the study. The methodology of the study was designed by UO and LP. The software and analysis were performed by UO and US. The first draft of the manuscript was written by UO and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. This work was supported by the Basque Government (Grant numbers: PRE_2022_2_0194 and GIC21/201-IT1648-22) and the University of the Basque Country (PIF20/27). Author U. Ortega has received a doctoral fellowship by the Basque Government (PRE_2022_2_0194). Authors I. Ametzaga and L. Peña have received a research group grant by The Basque Government (GIC21/201-IT1648-22). Finally, Author U. Sertutxa has received a doctoral fellowship by the University of the Basque Country (PIF20/27).

Declarations

Competing interest We declare that the authors have no competing interests, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

References

Almenar JB, Bolowich A, Elliot T, Geneletti D, Sonnemann G, Rugani B (2019) Assessing habitat loss, fragmentation and ecological connectivity in Luxembourg to support spatial planning. Landsc Urban Plan 189:335–351

An Y, Liu S, Sun Y, Shi F, Beazley R (2021) Construction and optimization of an ecological network based on morphological spatial pattern analysis and circuit theory. Landscape Ecol 36(7):2059–2076

Basque Government (2009) Hábitats EUNIS in 1:10,000 Scale. Environmental and Landscape Policy Department of the Basque Government

Basque Goverment (2016) Propuesta metodológica para la identificación y representación de la infraestructura verde a escala regional de la CAPV. https://www.euskadi.eus/contenidos/informacion/infrverde/es_def/adjuntos/infraestructura_verde.pdf

Beier P, Spencer W, Baldwin RF, McRae BH (2011) Toward best practices for developing regional connectivity maps. Conserv Biol 25:879–892

Belote RT, Dietz MS, McRae BH, Theobald DM, McClure ML, Irwin GH et al (2016) Identifying corridors among large protected areas in the United States. PLoS ONE 11(4):e0154223

Blazquez-Cabrera S, Ciudad C, Gastón A, Simón MÁ, Saura S (2019) Identification of strategic corridors for restoring landscape connectivity: application to the Iberian lynx. Anim Conserv 22(3):210–219

Brockerhoff EG, Jactel H, Parrotta JA, Ferraz SF (2013) Role of eucalypt and other planted forests in biodiversity conservation and the provision of biodiversity-related ecosystem services. For Ecol Manag 301:43–50

Bullock JM, Aronson J, Newton AC, Pywell RF, Rey-Benayas JM (2011) Restoration of ecosystem services and biodiversity: conflicts and opportunities. Trends Ecol Evol 26(10):541–549

Cannas I, Lai S, Leone F, Zoppi C (2018) Green infrastructure and ecological corridors: a regional study concerning Sardinia. Sustainability (Switzerland). https://doi.org/10.3390/su10041265

Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, Narwani A, Mace GM, Tilman D, Wardle DA, Kinzig AP, Daily GC, Loreau M, Grace JB, Larigauderie A, Srivastava DS, Naeem S (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67

Castillo-Eguskitza N, Rescia AJ, Onaindia M (2017) Urdaibai biosphere reserve (Biscay, Spain): conservation against development. Sci Total Environ 592:124–133

Cunha NS, Magalhaes MR (2019) Methodology for mapping the national ecological network to mainland Portugal: a planning tool towards a green infrastructure. Ecol Ind 104:802–818

Cushman SA, McRae B, Adriaensen F, Beier P, Shirley M, Zeller K (2013) Biological corridors and connectivity. Key Top Conserv Biol 2:384–404

Dutta T, Sharma S, McRae BH, Roy PS, DeFries R (2015) Connecting the dots: mapping habitat connectivity for tigers in central India. Reg Environ Change 16:53–67

Escobar MAH, Estades CF (2021) Differential responses of small mammals immediately after clearcutting in forest plantations: patterns and mechanisms. For Ecol Manag 480:118699

European Commission (2013) Green Infrastructure (GI). Enhancing Europe's Natural Capital. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. http://eur-lex.europa.eu/resource.html?uri=cellar:d41348f2-01d5-4abe-b817-4c73e6f1b2df.0014.03/DOC_1&format=PDF

European Commission (2020). EU Biodiversity Strategy for 2030. Bringing nature back into our lives Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. Brussels 380. https://eur-lex.europa.eu/resource.html?uri=cellar:a3c806a6-9ab3-11ea-9d2d-01aa75ed71a1.0007.02/DOC_1&format=PDF

European Commission (2022). Proposal for a regulation of the European Parliament and of the council on nature restoration. https://environment.ec.europa.eu/publications/nature-restoration-law_en

Fagan ME, DeFries RS, Sesnie SE, Arroyo-Mora JP, Chazdon RL (2016) Targeted reforestation could reverse declines in connectivity for understory birds in a tropical habitat corridor. Ecol Appl 26(5):1456–1474

Feng H, Li Y, Li YY, Li N, Li Y, Hu Y, Luo H (2021) Identifying and evaluating the ecological network of Siberian roe deer (*Capreolus pygargus*) in Tieli Forestry Bureau, northeast China. Global Ecol Conserv 26:01477

Fňukalová E, Zýka V, Romportl D (2021) The network of green infrastructure based on ecosystem services supply in Central Europe. Land 10(6):592

Foltête JC, Clauzel C, Vuidel G (2012) A software tool dedicated to the modelling of landscape networks. Environ Model Softw 38:316–327

Foltête JC, Girardet X, Clauzel C (2014) A methodological framework for the use of landscape graphs in land-use planning. Landsc Urban Plan 124:140–150

Gantchoff MG, Erb JD, MacFarland DM, Norton DC, Tack JP, Roell BJ, Belant JL (2021) Potential distribution and connectivity for recolonizing cougars in the Great Lakes region, USA. Biol Cons 257:109144

Giubbina MF, Martensen AC, Ribeiro MC (2018) Sugarcane and Eucalyptus plantation equally limit the movement of two forest-dependent understory bird species. Austral Ecol 43(5):527–533

Gurrutxaga M, Lozano PJ, del Barrio G (2010) GIS-based approach for incorporating the connectivity of ecological networks into regional planning. J Nat Conserv 18(4):318–326

Haddad NM, Brudvig LA, Clobert J, Davies KF, Gonzalez A, Holt RD, Townshend JR (2015) Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci Adv 1(2):1500052

Haines-Young R, Potschin-Young M (2018) Revision of the common international classification for ecosystem services (CICES V5.1): a policy brief. One Ecosyst 3:27108

Hoffmann J, Schirmer A, Eccard JA (2019) Light pollution affects space use and interaction of two small mammal species irrespective of personality. BMC Ecol 19(1):1–11

Hua F, Bruijnzeel LA, Meli P, Martin PA, Zhang J, Nakagawa S, Miao X, Wang W, McEvoy C, Peña-Arancibia JL, Brancalion PHS, Smith P, Edwards DP, Balmford A (2022) The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. Science 376(6595):839–844

Iezzi ME, Cruz P, Varela D, De Angelo C, Di Bitetti MS (2018) Tree monocultures in a biodiversity hotspot: impact of pine plantations on mammal and bird assemblages in the Atlantic Forest. For Ecol Manag 424:216–227

Ishwaran N, Persic A, Tri NH (2008) Concept and practice: the case of UNESCO biosphere reserves. Int J Environ Sustain Dev 7(2):118–131

Keeley AT, Beier P, Jenness JS (2021) Connectivity metrics for conservation planning and monitoring. Biol Cons 255:109008

Khosravi R, Hemami MR, Cushman SA (2018) Multispecies assessment of core areas and connectivity of desert carnivores in central Iran. Divers Distrib 24(2):193–207

Koen EL, Bowman J, Sadowski C, Walpole AA (2014) Landscape connectivity for wildlife: development and validation of multispecies linkage maps. Methods Ecol Evol 5(7):626–633

Lanzas M, Hermoso V, De-Miguel S, Bota G, Brotons L (2019) Designing a network of green infrastructure to enhance the conservation value of protected areas and maintain ecosystem services. Sci Total Environ 651(1):541–550

Lee JA, Chon J, Ahn C (2014) Planning landscape corridors in ecological infrastructure using least-cost path methods based on the value of ecosystem services. Sustainability 6:7564–7585

Li W, Clauzel C, Dai Y, Wu G, Giraudoux P, Li L (2017) Improving landscape connectivity for the Yunnan snub-nosed monkey through cropland reforestation using graph theory. J Nat Conserv 38:46–55

Li Y, Zhang Y, Xue Y, Zhang Y, Zhang Y, Gao Y, Li D (2022) Analysis of conservation gaps and landscape connectivity for snow leopard in Qilian mountains of China. Sustainability 14(3):1638

Liquete C, Kleeschulte S, Dige G, Maes J, Grizzetti B, Olah B, Zulian G (2015) Mapping green infrastructure based on ecosystem services and ecological networks: a Pan-European case study. Environ Sci Policy 54:268–280

Liu C, Newell G, White M, Bennett AF (2018) Identifying wildlife corridors for the restoration of regional habitat connectivity: a multispecies approach and comparison of resistance surfaces. PLoS ONE 13(11):0206071

McRae BH (2012a) Centrality Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle WA. Available from http://www.circuitscape.org/linkagemapper

McRae BH (2012b) Pinchpoint Mapper Connectivity Analysis Software. The Nature Conservancy, Seattle, WA. Available from http://www.circuitscape.org/linkagemapper

Mitchell GE, Bennett EM, Gonzalez A (2013) Linking landscape connectivity and ecosystem service provision: current knowledge and research gaps. Ecosystems 16:894–908

Mola I, Sopeña A, Torre R (2018) Guía Práctica de Restauración Ecológica. Fundación Biodiversidad del Ministerio para la Transición Ecológica. Madrid. https://ieeb.fundacion-biodiversidad.es/content/guia-practica-de-restauracion-ecologica. pp. 77

Mortelliti A, Westgate MJ, Lindenmayer DB (2014) Experimental evaluation shows limited influence of pine plantations on the connectivity of highly fragmented bird populations. J Appl Ecol 51(5):1179–1187

Onaindia M, Domínguez I, Albizu I, Garbisu C, Amezaga I (2004) Vegetation diversity and vertical structure as indicators of forest disturbance. For Ecol Manag 195:341–354

Onaindia M, Fernández de Manuel B, Madariaga I, Rodríguez-Loinaz G (2013) Co-benefits and trade-offs between biodiversity, carbon storage and water flow regulation. For Ecol Manag 289:1–9

Peña L, Fernández de Manuel B, Méndez-Fernández L, Viota M, Ametzaga-Arregi I, Onaindia M (2020) Co-creation of knowledge for ecosystem services approach to spatial planning in the Basque Country. Sustainability 12(13):5287

Račinska I, Barratt L, & Marouli C (2015) LIFE and land stewardship. Current status, challenges and opportunities. Report to the European Commission

Rayfield B, Fortin MJ, Fall A (2011) Connectivity for conservation: a framework to classify network measures. Ecology 92(4):847–858

Ribeiro JW, Silveira dos Santos J, Dodonov P, Martello F, Brandão Niebuhr B, Ribeiro MC (2017) LandScape Corridors (lscorridors): a new software package for modelling ecological corridors based on landscape patterns and species requirements. Methods Ecol Evol 8(11):1425–1432

Rodríguez-Loinaz G, Amezaga I, Onaindia M (2012) Does forest fragmentation affect the same way all growth-forms? J Environ Manag 94(1):125

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421(6918):57–60

Ruiz-Gonzalez A, Gurrutxaga M, Cushman SA, Madeira MJ, Randi E et al (2014) Landscape genetics for the empirical assessment of resistance surfaces: the European pine marten (*Martes martes*) as a target-species of a regional ecological network. PLoS ONE 9(10):110552

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. Landsc Urban Plan 83(2–3):91–103

Schindler S, O'Neill FH, Biró M, Damm C, Gasso V, Kanka R, Wrbka T (2016) Multifunctional floodplain management and biodiversity effects: a knowledge synthesis for six European countries. Biodivers Conserv 25(7):1349–1382

Schrott GR and Shinn J (2020) A Landscape Connectivity Analysis for the Coastal Marten (*Martes caurina humboldtensis*). U.S. Fish & Wildlife Service, Arcata, CA. p 123

Slabbekoorn H, McGee J, Walsh EJ (2018) Effects of man-made sound on terrestrial mammals. In: Slabbekoorn H, Dooling R, Popper A, Fay R (eds) Effects of anthropogenic noise on animals. Springer Handbook of Auditory Research, Springer, New York

Valladares F, Gil P, Forner A (2017) Bases científico-técnicas para la Estrategia estatal de infraestructura verde y de la conectividad y restauración ecológicas. Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, Madrid, p 357

Van Cuong C, Dart P, Hockings M (2017) Biosphere reserves: attributes for success. J Environ Manag 188:9–17

Zhao Y, Liu Z, Wu J (2020) Grassland ecosystem services: a systematic review of research advances and future directions. Landscape Ecol 35(4):793–814