

Enhancing connectivity in agroecosystems: focus on the best existing corridors or on new pathways?

Olivia Dondina  · Santiago Saura · Luciano Bani · María C. Mateo-Sánchez

Received: 23 October 2017 / Accepted: 6 August 2018 / Published online: 12 August 2018
© Springer Nature B.V. 2018

Abstract

Context Restoring or establishing corridors between residual forest patches is one of the most adopted strategies for the conservation of animal populations and ecosystem processes in fragmented landscapes.

Objectives This study aimed to assess whether it is more effective to focus restoration actions on existing corridors or to establish habitats in other strategic areas that can create new dispersal pathways to enhance connectivity.

Methods We considered a real agroecosystem in northern Italy, based our analyses on graph-theory and habitat availability metrics, and focused on the Hazel Dormouse as the target species. We compared the connectivity increase resulting from (i) the simulated restoration of existing priority corridors, i.e., those with significant presence of forest but in which

restoration actions would still result in considerable connectivity gains, or (ii) the simulated plantation of 30 hedgerows along new priority pathways, i.e., those areas with no current forest cover in which habitat creation would be more beneficial for connectivity.

Results Implementing new priority pathways resulted in substantially larger connectivity gains (+ 38%) than when restoration efforts were concentrated in improving already existing corridors (+ 11%).

Conclusions Establishing hedgerows along new pathways allowed enhancing the complementary and functionality of the full set of landscape corridors and proved more efficient than just strengthening the areas where dispersal flows were already concentrated. We demonstrated the importance of analytical procedures able to compare the effectiveness of different management strategies for enhancing connectivity. Our approach may be applied to multiple species sensitive to fragmentation in other heterogeneous landscapes and geographical contexts.

O. Dondina (✉) · L. Bani
Department of Earth and Environmental Sciences,
University of Milano-Bicocca, Piazza della Scienza 1,
20126 Milan, Italy
e-mail: olivia.dondina@unimib.it

S. Saura
Directorate D – Sustainable Resources, European
Commission – Joint Research Centre (JRC), Via E. Fermi
2749, 21027 Ispra, VA, Italy

M. C. Mateo-Sánchez
MONTES (E.T.S.I Montes, Forestal y del Medio Natural),
Universidad Politécnica de Madrid, Ciudad Universitaria
s/n, 28040 Madrid, Spain

Keywords Ecological networks · Forest fragmentation · Habitat availability metrics · Hazel Dormouse · Hedgerows · Wildlife corridors

Introduction

The long-term conservation of animal species in fragmented landscapes considerably depends on the existence of functional connectivity between the spatially separated populations (Bennett 2003; Fahrig 2003; Fischer and Lindenmayer 2007). Conservation studies generally focus on safeguarding or increasing connectivity by conserving or restoring existing minimum resistance paths between habitat patches (e.g., Carranza et al. 2012; Belote et al. 2016; de la Torre et al. 2017; Moqanaki and Cushman 2017; Santos et al. 2018). These paths are usually identified by mapping the matrix surrounding the habitat patches in the form of a resistance map, in which each cell has a value corresponding to the difficulty of species movement through the land cover type present in that area. Subsequently, paths of minimum cumulative resistance, which correspond to the routes across the landscape matrix where individuals' movements are likely concentrated, i.e., existing corridors, are identified between each pair of patches. This identification can be done using different approaches (Correa Ayram et al. 2016), such as least-cost corridor modeling (Adriaensen et al. 2003; Beier et al. 2009), circuit theory (McRae et al. 2008) or a randomized shortest path algorithm (Panzacchi et al. 2016).

In highly modified landscapes, species particularly sensitive to fragmentation, generally characterized by high degrees of habitat specialization (Mortelliti et al. 2009; Bani et al. 2015; Dondina et al. 2017), may hardly move among remnants even along minimum resistance paths. For this reason, some authors have suggested that, in these cases, the conservation of these species may be better promoted by increasing the amount and quality of habitats inside remnant patches, rather than focusing on promoting dispersal processes (e.g., Saura and Rubio 2010). However, isolated patches in highly modified landscapes may be unable to compensate for detrimental fluctuations of population size due to genetic (inbreeding and genetic drift) and stochastic demographic factors, which may lead populations to local extinction. Management measures for the conservation of these species are generally represented by habitat restoration actions that should be located in strategic positions, identified through analyses of effort optimization, in order to increase landscape connectivity (e.g., Clauzel et al. 2015a, b). Practically, one important conservation strategy is the

restoration of priority existing corridors, increasing the amount of optimal or permeable habitat along them.

Considering that habitat should ideally be restored along the entire corridor trajectory, and that existing corridors are often characterized by tortuous patterns, we wondered if it is more efficient to restore existing minimum resistance paths or to locate new habitat in other strategic areas to originate other new movement pathways through the landscape.

Our aim in this study was to explore the relative connectivity benefits of strengthening the quality of existing corridors versus investing efforts in establishing new movement pathways, an issue with important consequences for landscape management. For this purpose, we carried out a comparative study in a real agroecosystem in northern Italy and compared the increase in landscape connectivity for a small forest-dwelling species, the Hazel Dormouse *Muscardinus avellanarius*, obtained by (i) simulating the restoration of existing corridors increasing vegetation quality and filling vegetation gaps or by (ii) planting new hedgerows in alternative areas to create new dispersal routes.

We focused on an agroecosystem because the phenomenon of fragmentation is particularly severe in agricultural landscapes, both in Europe and in other continents, due to the usual spread of intensively cultivated areas, which has dramatically decreased the extent of the original forests, reducing them to small fragments scattered in human-dominated lands (Darby 1956; Williams 2003). In these contexts, semi-natural habitats such as hedgerows, reforestations and tree plantations, play an important ecological role by increasing landscape permeability for multiple species. In particular, hedgerows, that are continuous or closely spaced lines of shrubs and trees, have been proved to be crucial for the long-term survival of different species, acting both as corridors and as additional reproductive habitat (Laurance and Laurance 1999; Hinsley and Bellamy 2000; Hilty and Merenlender 2004; Gelling et al. 2007; Silva and Prince 2008; Wolton 2009; Dondina et al. 2016; Chiatante et al. 2017). For this reason, and given that hedgerows only subtract a small amount of productive crop areas, they are an ideal target for management actions designed to increase connectivity for animal species in heterogeneous landscapes. The plantation of new hedgerows in the agroecosystems of the European

Union is also encouraged by the Common Agricultural Policy (CAP). In particular, specific subsidies issued under the Rural Development Regulation are aimed to fund farmers to implement environmentally beneficial management regimes, such as habitat restoration and management, including rows and hedgerows plantation (Donald et al. 2002).

The focal species in our case study, the Hazel Dormouse, is included in the Annex IV of the Habitats Directive (Council Directive 92/43/EEC), and its major conservation concern largely lies on its sensitivity to fragmentation (Mortelliti et al. 2014; Bani et al. 2017). The optimum habitats for the species are broadleaved forests with a well-developed and diversified shrub layer, which can offer route-ways through branches, suitable sites for building nests and shelter from predators (Panchetti et al. 2007). In highly modified lowland areas of Italy, where broadleaved forests are fragmented in small residual patches, the survival of the Hazel Dormouse also depends on well-structured networks of hedgerows, which are perceived by the species not only as permeable features for movement but also as suitable habitats (Dondina et al. 2016, 2018).

Methods

Study area

The investigated landscape is an area of about 140 km² located in the western part of the lowland area of Lombardy region (northern Italy, 45°25'N 8°98'E). To consider a realistic area for management interventions, the study area was designed to include the entire surface of the municipalities present on the territory (Borgo San Siro, Garlasco, Zerbolò, Bereguardo, Gropello Cairoli and Villanova d'Ardenghi). The elevation of the area ranges between 0 and 100 m a.s.l. and the climate is continental and temperate, with rainfalls (700 mm/year on average) mainly concentrated in spring and autumn.

It is a typical agroecosystem dominated (63% of the area) by intensive field crops, mainly paddies and other annual crops such as wheat, maize, and alfalfa. The remaining surface of the study area is composed of broadleaved forests (14%), human settlements (with three main villages in terms of extension: Bereguardo to the north-east, Garlasco to the west

and Gropello Cairoli to the south-west) and road infrastructures (8%), poplar cultivations (6%), hedgerows (4%), rivers, streams and wetlands (3%), plantations for biomass production (1%) and shrublands (1%) (ERSAF 2014).

Most of the broadleaved forests within the study area are located along the Ticino River and fall within the boundaries of the protected area of the Ticino Natural Park, of which 20% of the total surface is included within the study area. The remaining forest surface is distributed in patches of different size, connected to each other, to some degree, by hedgerows (Fig. 1). Forests are primarily composed of Pedunculate Oak (*Quercus robur*), Common Hornbeam (*Carpinus betulus*), Field Maple (*Acer campestre*), Field Elm (*Ulmus minor*), and Common Ash (*Fraxinus excelsior*), while close to rivers and streams riparian vegetation mainly includes the Common Alder (*Alnus glutinosa*), poplars (*Populus alba*, *P. nigra* and *P. canadensis* cultivar), and willows (*Salix* sp.).

Hedgerows, that are both residuals of native woodlands and new plantations, have a mean length of about 150 m, a mean width of 7 m and are typically composed of trees (mainly oaks, poplars, alders, willows and Locust Tree *Robinia pseudoacacia*) and a more or less developed shrub layer (generally composed by Common Hazel *Corylus avellana*, Hawthorn *Crataegus monogyna*, Bramble *Rubus ulmifolius* and European Elderberry *Sambucus nigra*) (Dondina et al. 2016).

Outside the boundaries of the study area, both moving westward and eastward, the landscape is increasingly dominated by intensive farming and forest patches are virtually absent, apart from few tiny streaks of edging along irrigation canals.

The Hazel Dormouse is relatively widespread within the study area (see Dondina et al. 2018 for information regarding the species distribution in a larger territory including the study area considered in this research). Specifically, it occurs and reproduces in the continuous forests of the Ticino Natural Park as well as in very small forest patches (< 0.1 ha) scattered in the agricultural matrix. It also occurs and reproduces in hedgerows, whether they originate from residuals strip of native woodlands or from new plantations, showing a significant preference for continuous hedgerows with a not so closed arboreal layer and a well-developed shrub layer characterized

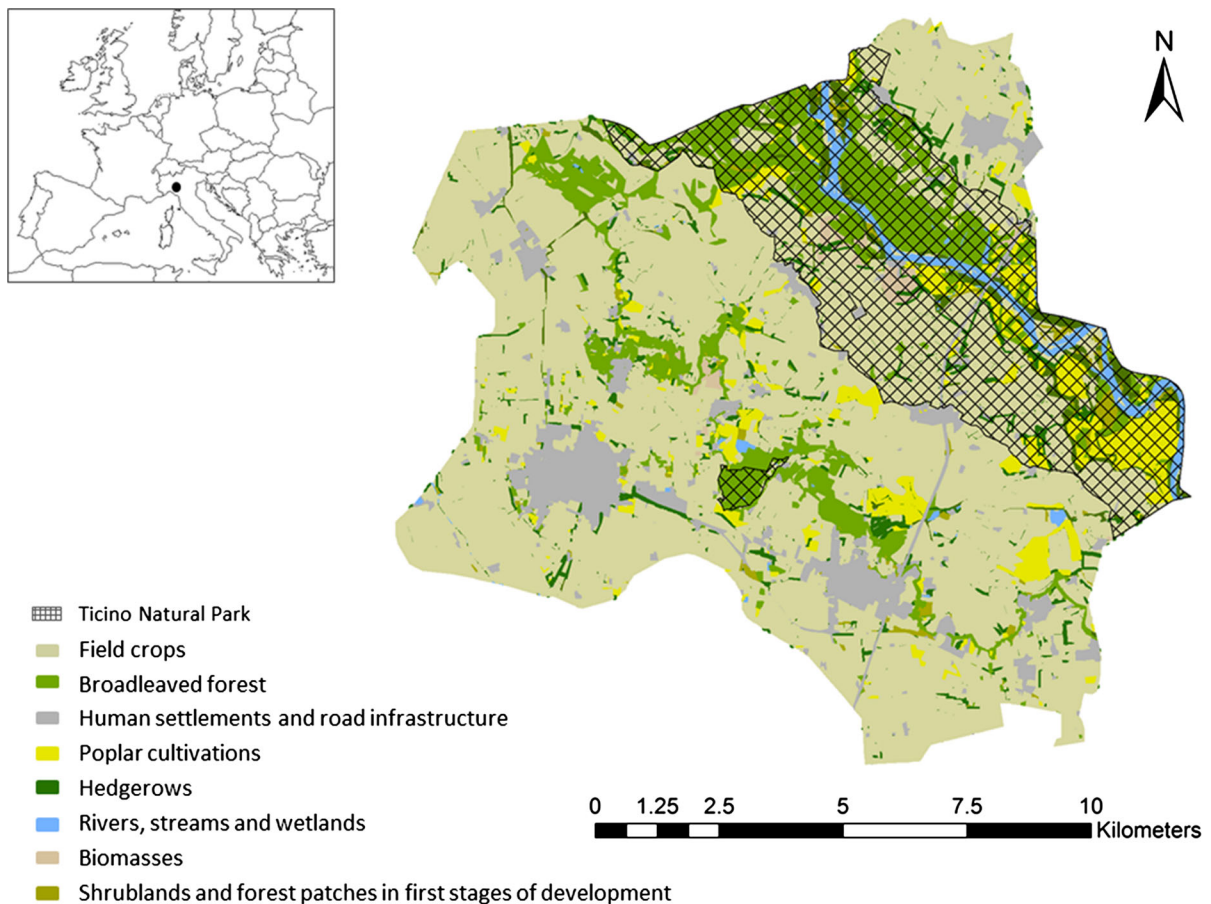


Fig. 1 Study area in northern Italy

by a complex physical structure and composed of native species (Dondina et al. 2016).

The habitat network: patches, landscape resistance and least-cost paths

We defined a graph (network) for the study area and target species as a set of nodes (i.e., habitat areas) and links (i.e., functional connections) between them. In the investigated landscape, patches of broadleaved forest and continuous hedgerows are the habitat areas for the Hazel Dormouse (Dondina et al. 2016, 2018). Based on the digital land-use cartography DUSAF 4 (a 1:10,000 vectorial map update to 2012; ERSAF 2014), a total of 1035 habitat nodes, composed of 599 patches of broadleaved forests (ranging in size from 0.04 to 388 ha) and 436 continuous hedgerows (i.e., hedgerows not presenting extended visible gaps in the tree canopy classified as continuous in the DUSAF 4),

were found in the study area. To define connections, we identified the least cost paths (LCPs) connecting every pair of nodes (Adriaenssen et al. 2003; Beier et al. 2008). Specifically, by using the ArcGis extension Linkage Mapper 1.0.2 (McRae and Kavanagh 2011), we identified all the LCPs between every pair of adjacent nodes and calculated their cumulative resistance (i.e., the effective distance between adjacent nodes). Adjacent nodes were defined as the nearest nodes in terms of cost-weighted distance, creating an allocation zone for each node. If a path from one node to another must pass through the allocation zone of a third node, the two nodes are considered non-adjacent (McRae and Kavanagh 2011).

The resistance map used for the LCPs identification was built up using ArcGis 10.0 (ESRI 2011) by rasterizing the DUSAF 4 cartography (Fig. 2b). We adopted a cell size of 20 m because the smallest linear dimension of polygons in the original cartography is

20 m, and because it is an adequate size considering the movement ability of the target species (see below). The cell values were assigned with an expert-based approach considering the Hazel Dormouse's perception of the different land cover types in the investigated landscape. Lowest resistance values (1) were assigned to habitat nodes (i.e., broadleaved forests and continuous hedgerows) and largest values (1000) to human settlements, road infrastructures and rivers. Within this range, we assigned lower values (8) to discontinuous hedgerows (Dondina et al. 2016) and to poplar cultivations and plantations for biomass production, which can provide permeability for the species movements (Dondina et al. 2018). A slightly higher value (50) was assigned to shrublands (Bright et al. 1994; Juškaitis and Šiožinytė 2008; Ramakers et al. 2014) and to forest patches in first stages of development, because of the lack of sufficiently mature tree cover, which is an important element for the Hazel Dormouse, characterizing these two categories. Higher values (500) were assigned to field crops (Mortelliti et al. 2013).

Management strategies comparison

Identifying priority areas for existing corridor restoration or for new path implementation

Once the nodes and resistance map were defined, and the LCPs along each pairs of adjacent nodes were identified, we evaluated which of the following two strategies would result in larger gains in functional connectivity for the Hazel Dormouse (Fig. 2):

1. Increasing vegetation quality and filling vegetation gaps along the existing paths of minimum resistance that would result in a greater increase in connectivity if they were restored, i.e., prioritization of the already existing corridors for restoration (strategy 1);
2. Establishing new hedgerows along the new paths that would provide a greater increase in connectivity if they were deployed, i.e., creation of new paths in key areas different from those of the already existing corridors (strategy 2).

Both management strategies were evaluated by simulating habitat restoration or creation along the whole length of the existing or new paths. To allow a proper comparison between the two strategies, we

simulated the restoration/creation of 30 completely permeable corridors/new hedgerows in each scenario. We chose 30 as number of management interventions, since it would imply a limited and hence feasible management effort (with less than a 1% increase in the total habitat area in the study area) and, at the same time, we hypothesized it probably corresponds to a sufficient level of interventions as to determine significant variations in landscape connectivity.

For strategy 1, we prioritized the existing corridors (i.e., all the identified LCPs and their respective effective distances) according to the increase of connectivity that they would provide if they were restored. To define restoration, we assumed a total permeabilization of the LCP, i.e., the increase of vegetation quality and the plantation of new vegetation to fill all the gaps along the whole length of the LCP. We used the Probability of Connectivity (*PC*) index, which is a robust index to detect changes in landscape connectivity after corridor restoration (Saura and Pascual-Hortal 2007) (Fig. 2c). *PC* is a probabilistic habitat availability (reachability) metric, which considers that a node is connected to itself (intranode connectivity) and combines nodes' attribute (such as patch size, quality-weighted patch size, habitat suitability) and their connections (links) in a single index (Pascual-Hortal and Saura 2006). Using this index, and the effective distance as the distance measure, the connectivity of the landscape for the analysed species is affected by both the attributes of the source and destination nodes (in our case the size of the patches) and on the effective distance of the LCP connecting the two nodes (Carranza et al. 2012). Specifically, *PC* is given by:

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

where a_i and a_j , in our case, correspond to the area of nodes i and j , respectively; n is the total number of nodes in the investigated landscape; A_L is the total landscape area (considering both nodes and matrix); and p_{ij} is the probability of direct dispersal between each pair of nodes (for more detail see Saura and Pascual-Hortal 2007). p_{ij}^* corresponds to the maximum product probability of all possible combinations of LCPs that can be crossed to reach the node j starting from the node i , passing through other nodes if necessary (where the product probability of a

combination of LCPs is obtained by multiplying the p_{ij} values associated to each single LCP pertaining to the considered combination).

For the index calculation, we derived the dispersal probability along the existing corridors from a negative exponential function of their effective distance. We set the median dispersal distance of the species to 700 m, which corresponds to the median species movement ability through suitable habitats (i.e., within woodlands or hedgerows, where resistance is equal to 1), since, due to the limited dispersal ability of the target species, dispersal mainly occurs through permeable habitats. The median distance of 700 m was derived according to the formula developed for mammals by Bowman et al. (2002), that relates home range and dispersal distance, from a known home range size for the species in suitable habitat of 1 ha (Mortelliti et al. 2013).

To identify the LCPs that would greater increase landscape connectivity if they were restored, we calculated the percentage of variation in the PC index (dPC) caused by the restoration of each LCP, according to the following expression:

$$dPC = \frac{PC_{restore} - PC_{initial}}{PC_{initial}}$$

where $PC_{initial}$ is the value of the PC index in the original landscape (before any restoration) and $PC_{restore}$ is the value of the PC index that would result in the same landscape after the restoration of a given LCP. Specifically, we systematically recalculated the index after changing the effective distance of each LCP to the value that would correspond to the new restored scenario affecting that particular LCP, when the effective distance of all the other LCPs remain unchanged. We simulated a complete restoration of each LCP connecting two nodes, by reducing its cumulative movement cost to the linear distance in meters of the LCP (i.e., simulating that it only crosses habitats with resistance equal to 1). The dPC values for this analysis were calculated through the *link importance* functionality using the *link change* modality in the Conefor software (command line version 1.0.21 of the software Conefor 2.7.1 Saura and Torné 2009; Torné and Saura 2013). The obtained dPC values allowed us to rank the LCPs according to how much they would increase landscape connectivity if they were restored.

We then simulated the restoration of the LCPs associated to the highest values of dPC through the design of 30 completely permeable corridors (assuming to increase vegetation quality and to fill vegetation gaps obtaining a resistance equal to 1 along the whole length of the LCP), comparable to continuous hedgerows for functionality. To delineate the location of the new permeable corridors, we used the software ArcGis. We designed corridors following the LCPs and maintaining a width comparable to that of existing hedgerows. Moreover, to propose feasible interventions, we designed the corridors along crop fields' boundaries, avoiding unrealistic crossings of roads, human settlements or rivers by using the most recent digital orthophotos of the investigated area (available at <http://www.geoportale.regione.lombardia.it>). Finally, we checked that the minimum and maximum length of the new created permeable corridors did not exceed the length range (40–2000 m) of the existing continuous hedgerows within the study area based on DUSAF 4.

For the second management strategy (Fig. 2e), we adopted a different habitat availability index, also based on network analysis as PC : the Integral Index of Connectivity (IIC). We used this index instead of PC considering the effective distance of the LCPs between nodes, because we wanted to identify which currently not connected nodes would increase more landscape connectivity if they were connected regardless the route and the effective distance of the existing corridors connecting them. We did not even used PC in a probabilistic model simply considering the Euclidean (straight-line) distance between nodes, because it affects the original p_{ij} of each link so that dPC does not only reflect the final gain of connectivity obtained when a new link is created, but also the difference between the initial and final p_{ij} of the link. IIC is thus more appropriate to develop strategy 2, since it is essentially the version of PC for networks with unweighted links, as it is based on a simple binary connection model in which two habitat patches are connected or not connected (Saura and Rubio 2010) if they lie, respectively, within or beyond a threshold distance defined by the user. Specifically, IIC is given by:

$$IIC = \frac{\sum_{i=1}^n \sum_{j=1}^n \frac{a_i \cdot a_j}{1 + nl_{ij}}}{A_L^2}$$

where nl_{ij} is the number of links in the shortest path (topological distance) between nodes i and j , and the other terms are the same as defined for PC . Since IIC requires the specification of a threshold distance above which two nodes are treated as not connected, and nodes are supposed to be separated by unsuitable habitats (i.e., the inhospitable matrix), we set it to 200 m, which is the estimated maximum dispersal ability of the Hazel Dormouse through the matrix. We calculated this value of 200 m by averaging different values of Hazel Dormouse dispersal ability in unsuitable open habitats available from literature (100 m Bright 1998; 250 m Büchner 2008; 100–300 m Mortelliti et al. 2013).

Similarly to the first proposed management strategy, to identify which new paths would provide a larger increase in landscape connectivity, we calculated the percentage of variation in the IIC index ($dIIC$) caused by the implementation of each new path, according to the following expression:

$$dIIC = \frac{IIC_{new} - IIC_{initial}}{IIC_{initial}}$$

where $IIC_{initial}$ is the value of the IIC index in the original landscape (before the implementation of any new path) and IIC_{new} is the value of the IIC index that would result in the same landscape after the implementation of a given new path. The variation of the IIC value before and after the addition of each path ($dIIC$) was calculated through the *link importance* functionality using the *link improvement* modality in the Conefor software. We set that the $dIIC$ calculation was performed only for the pairs of nodes not farther than 2000 m in order to not exceed the maximum length of the original continuous hedgerows within the considered landscape. The analysis returned thus the list, and the associated $dIIC$ value, of every possible new path between pairs of nodes separated by more than 200 m (i.e., not already connected in the initial landscape) but not more distant than 2000 m.

Then, we simulated the implementation of the new paths with the highest values of $dIIC$. Since one path could be obtained by planting more than one hedgerow (when the path connects two non-adjacent nodes and is composed of more than one link), we simulated the creation of a feasible number of paths through the plantation of 30 hedgerows, with each hedgerow representing a new link between adjacent nodes. The

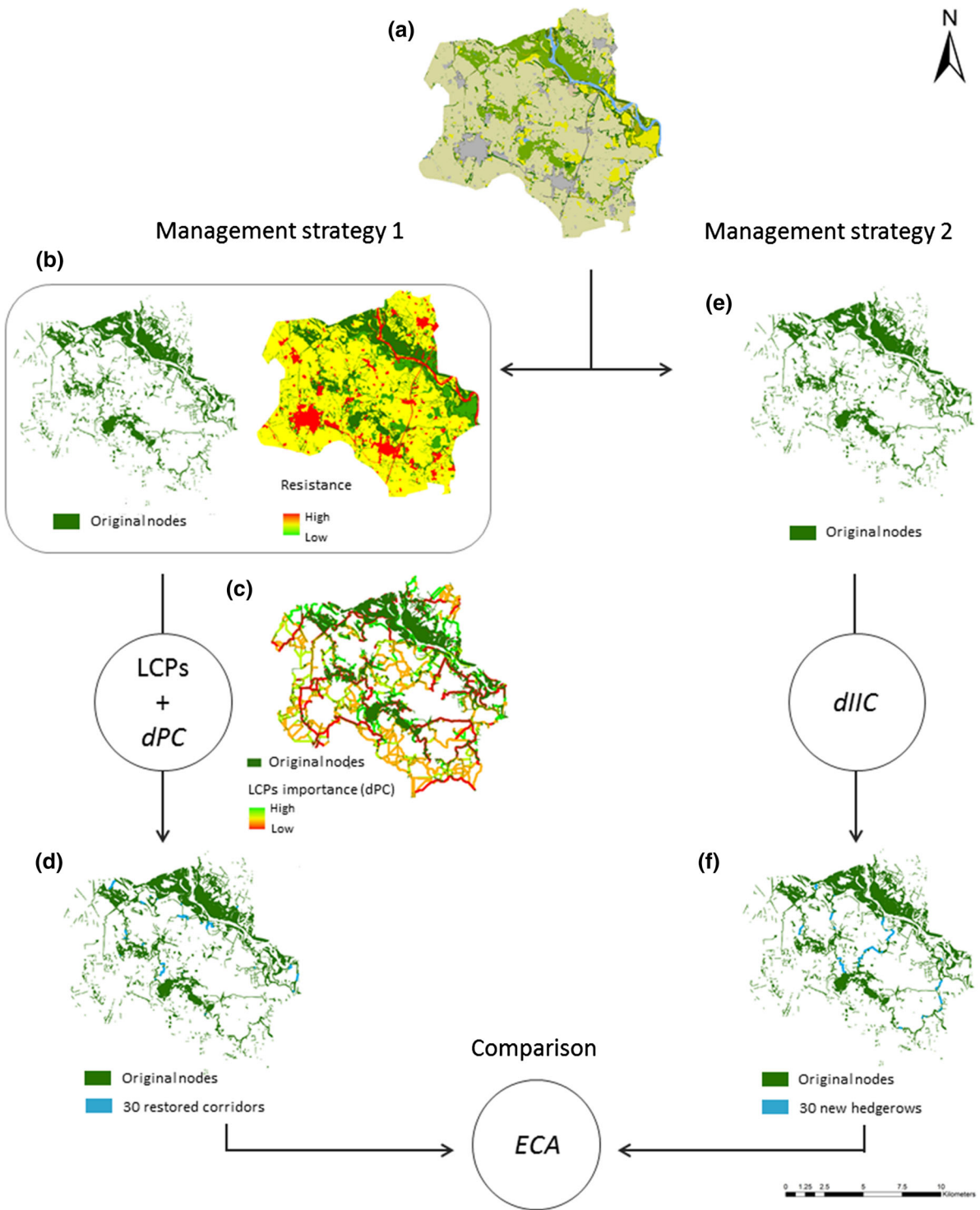
design of the new hedgerows followed the same criteria used for the design of the 30 completely permeable corridors along the most important existing LCPs described above.

To allow for a reasonable comparison, we checked that the total surface affected by management actions to simulate the two alternative management strategies, i.e., the total amount of new suitable habitat added throughout the two strategies, was similar (see “Results” section).

Evaluating how landscape connectivity changes after the implementation of alternative management strategies

To compare the two simulated management strategies, we created four new maps, i.e., two maps of habitat patches (adding to the original nodes the 30 new permeable corridors and hedgerows designed within the strategy 1 and 2, respectively), and two resistance maps (setting to 1 the resistance value associated to the cells corresponding to the 30 new permeable corridors and hedgerows designed within the strategy 1 and 2, respectively), and we re-identified all the LCPs between adjacent nodes for the two new simulated landscapes.

To directly quantify the increase of connectivity that would be obtained with the two strategies, and subsequently select the one providing a larger connectivity benefit, we calculated the overall landscape connectivity using the PC index for the two simulated management strategies separately and compared them to the PC index calculated for the original landscape before any intervention. In this quantification, we expressed the value of the overall landscape connectivity of the three considered landscapes by using the Equivalent Connected Area (ECA) index (Saura et al. 2011), which corresponds to the square root of the numerator of PC . Specifically, ECA is defined as the size of a single habitat patch (maximally connected) that would provide the same value of PC than the actual habitat pattern. Compared to PC , ECA presents the advantages of having area units and of allowing an easier and straightforward interpretation by directly comparing changes in habitat area and in connectivity (amount of reachable habitat). Species dispersal settings for the ECA calculation for both management strategies were those previously specified when using the probabilistic metric (PC).



Additionally, to provide a snapshot of the changes of the connectivity spatial pattern, we provided a visual evaluation of how the areas sustaining animal

dispersal flows would change after the adoption of the two strategies (see Mateo-Sánchez et al. 2014, 2015). For this purpose, we mapped the estimated

◀ **Fig. 2** Flowchart synthesizing the procedure to evaluate the connectivity gains through two alternative management strategies in the original landscape (a). Management strategy 1: restoring existing corridors. Starting from the map of nodes and the resistance map (b) the least-cost paths (LCPs) between adjacent nodes were identified and ranked by their importance for connectivity as given by the dPC values (c). Finally, the restoration of the top-ranked LCPs was simulated by designing 30 new completely permeable corridors along the whole length of these LCPs (d). Management strategy 2: creating new movement pathways. Starting from the map of nodes (e) the $dIIC$ value for every potential link connecting nodes (new potential paths) was calculated, disregarding both the Euclidean distance between the two nodes and the route and the effective distance of the LCP connecting them. Finally, the implementation of the most important new paths was simulated by designing 30 new hedgerows (f). The final connectivity benefits of the two alternatives was then compared using the Equivalent Connected Area (ECA) index

concentration of dispersal flux (estimated as density of LCPs) using the UNICOR software (Landguth et al. 2012). By doing so, we obtained the total number of LCPs crossing each cell of the investigated landscape in the original landscape and in the two simulated landscapes obtained after the implementation of the two proposed management strategies. UNICOR requires a threshold distance corresponding to the maximum path length for the target species given its dispersal ability. In this case, this distance should be set to the maximum dispersal ability of the target species (not the median as for the calculation of PC) in suitable habitat (not through the matrix as for the calculation of IIC). For this analysis, we thus used 4000 m as maximum distance following the relationship between home range size and dispersal ability proposed by Bowman et al. (2002) and based on a recent study carried out in central Italy which found 4000 m as maximum extreme dispersal event of the Hazel Dormouse within hedgerows, i.e., within suitable habitat, on the basis of genetic data (Bani et al. 2018).

Results

Management strategies comparison

Restoring existing corridors or creating new movement pathways

Based on the map of habitat nodes and the resistance map of the original landscape (Fig. 2b) we identified

3158 LCPs between adjacent nodes (strategy 1, Fig. 2c). The value of dPC associated to each LCP ranged between 0 and 65.3%. The simulation of the restoration of the most important LCPs through the implementation of 30 completely permeable corridors (strategy 1, Fig. 2d), led to a total addition of 15.7 ha of new suitable habitat to the original landscape.

With regard to strategy 2 (Fig. 2e, f), the value of $dIIC$ associated to each new path ranged between 0 and 4.3%. The simulation of the implementation of the most important new paths until 30 hedgerows were designed, led to a total addition of 20.2 ha of new suitable habitat to the original landscape.

Evaluating how landscape connectivity changes after the implementation of the alternative management strategies

The increase of habitat area compared to the habitat area in original landscape was similar for both strategies (strategy 1: 0.7%; strategy 2: 0.9%; see Table 1). The connectivity estimates for the entire landscape (i.e., the ECA index) showed that the percentage increase in ECA is much larger than the percentage increase in habitat area, and that such increase was much higher for strategy 2. Indeed, implementing the new pathways increased ECA by 38% while restoring the original LCPs increased ECA by 11% (Table 1).

To exclude the possibility that the difference in the percentage increase of the area covered by nodes between the two strategies (0.7% vs 0.9%), although very small, may have a significant influence on the higher ECA increment obtained for strategy 2, we repeated the analyses for strategy 2 using exactly the same amount of new habitat as in strategy 1. This was accomplished by excluding five hedgerows located along the less important new paths among the 30 hedgerows designed through strategy 2. The computation of the ECA index showed that the increase of the total connected area locating 25 new hedgerows along the most important new paths (37%) is almost identical to that obtained locating 30 hedgerows using the same strategy (38%), and hence still much higher than in strategy 1 (Table 1). This result also indicates that among the 30 new hedgerows designed using the strategy 2, there are a few ones that concentrate most of the importance and some others that are comparatively much less important.

Table 1 Comparison of the two different strategies to increase landscape connectivity for the Hazel Dormouse in northern Italy. Absolute and percentage increase of the total suitable habitat area and of the Equivalent Connected Area (ECA)

Management strategy	Number of actions	Initial habitat area (ha)	Initial connected area (ha)	Final habitat area (ha)	Final connected area (ha)	Increase in habitat area (%)	Increase in Equivalent Connected Area (%)
Strategy 1: restoring existing LCPs	30	2329	791	2344	878	0.7	11
Strategy 2: implementing new paths	30	2329	791	2350	1091	0.9	38
Strategy 2: implementing new paths (with exactly the same amount of added habitat as in strategy 1)	25	2329	791	2344	1082	0.7	37

after simulating the restoration of 30 existing corridors (i.e., least cost path, LCPs) (strategy 1) or after simulating the location of 30 and 25 new hedgerows along new potential paths (strategy 2)

The number of LCPs crossing each cell of the original landscape, of the landscape simulating the strategy 1, and of the landscape simulating the strategy 2 ranged between 0 and 301, 516 and 417, respectively. The representation of the LCPs density for each cell allowed identifying the areas where individuals' movements are potentially concentrated and how they changed after the implementation of the two management strategies.

The movement flows in the landscape simulating the restoration of existing corridors (Fig. 3b) resulted characterized by higher densities of LCPs, both in comparison with the initial landscape and with the landscape simulating the implementation of new paths, and show some new routes mainly concentrated in the northern and north-eastern part of the ecological network. However, despite these changes, the general pattern of movement flows after the simulated restoration of existing corridors appeared very similar to that in the original landscape (Fig. 3a). Conversely, the movement pattern in the landscape simulating the implementation of new paths (Fig. 3c) was characterized by higher densities of LCPs and differed from the original landscape mainly in the emergence of two new principal dispersal routes in the central part of the investigated landscape (black arrows in Fig. 3c).

Discussion

Restoring existing corridors or creating new movement pathways

Conservationists and practitioners urgently need reliable methods to identify priority areas for habitat

conservation and/or restoration that can guarantee the long-term maintenance of functional connectivity. Indeed, managing for connectivity conservation is arduous without the support of maps to guide interventions (Beier et al. 2011). Mapping the degree of landscape permeability (or resistance) to animal dispersal flows, and focusing on the restoration of existing corridors through the implementation of appropriate actions along their extension, is usually proposed as a major option for enhancing connectivity in fragmented landscapes (Watson et al. 2017).

This study was aimed to assess if it may be actually more efficient, in terms of connectivity gains, to concentrate management efforts along existing corridors or, on the contrary, to focus on new strategic areas that provide new dispersal pathways in the landscape. For this purpose, we simulated the implementation of management actions in a case study to increase connectivity for the Hazel Dormouse in an agroecosystem in northern Italy.

European agroecosystems are one of the most modified landscapes in the world because during the period 1950–1990 the intensification and mechanization of agriculture led to a radical structural change of the agricultural landscape (Krebs et al. 1999; Weibull et al. 2003). Many natural and semi-natural elements typical of traditional agroecosystems, such as hedgerows, shelterbelts and small woodland patches, have suffered large decreases in the more developed countries (Burel and Baudry 1995). During the last decades, there has been increasing awareness of the need to conserve diversified landscapes that are accompanied by increased degrees of connectivity. This is reflected in the CAP in the European Union, which provides financial assistance to farmers who

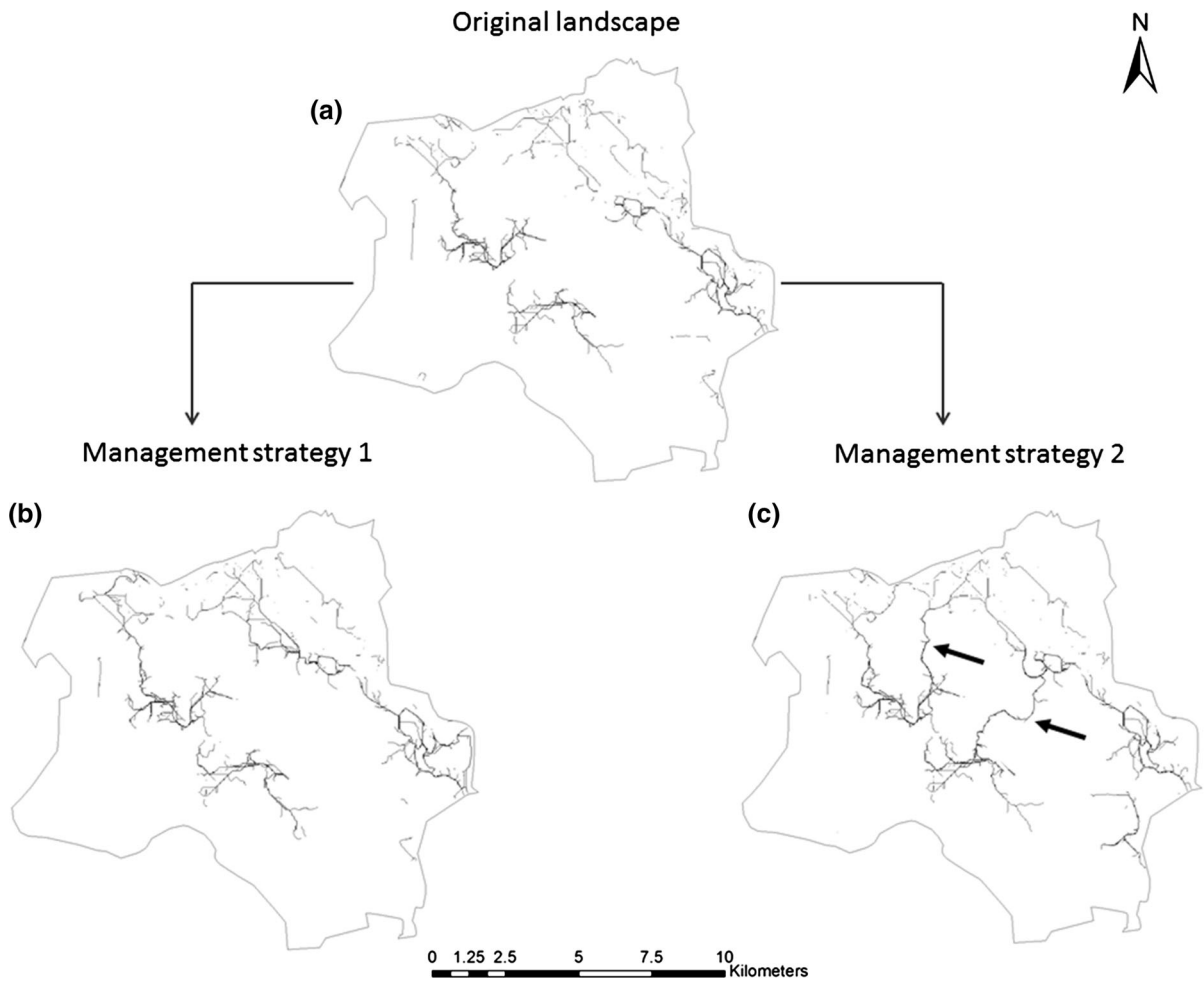


Fig. 3 Least cost path density across the study area in the original landscape (a) and after the implementation of the two management strategies to increase connectivity for the Hazel Dormouse: restoring existing corridors in strategy 1 (b) or

implementing new paths in strategy 2 (c). Darker cells represent the areas of dispersal flows concentration. Black arrows indicate the two new principal dispersal pathways created after the implementation of the management strategy 2

promote set-aside fields or introduce hedgerows or small woodland patches on their farms (Paoletti et al. 1997; Berger et al. 2006). These are all concrete management actions that can be adopted to restore existing corridors or to create new dispersal pathways to enhance landscape connectivity in our study area.

Specifically, new hedgerows plantation is a good and realistic strategy to simulate new pathways implementation. Indeed, from an ecological point of view, the study area is a typical European agroecosystem characterized by a high degree of forest fragmentation where the plantation of new hedgerows could be particularly effective to enhance landscape connectivity due to their importance for wildlife (Dondina

et al. 2016; Chiatante et al. 2017; Dondina et al. 2018). Moreover, from a practical and economic point of view, planting new hedgerows represents a plausible and widely used action that would subtract a very small area for crop production and could be supported by specific financial contributions foreseen in the CAP rural development actions (see the rural development actions 2014–2020 for Lombardy region available at <http://www.psr.regione.lombardia.it>).

Our analyses showed that the percentage increase in habitat reachability (*ECA*) is much larger than the percentage increase in habitat area resulting from both strategies. This finding supports the effectiveness of both corridor restoration and new hedgerow plantation

to enhance landscape connectivity with a modest management effort in these agricultural landscapes.

Moreover, we found that locating hedgerows in new strategic areas is considerably more beneficial for connectivity than restoring already existing corridors (LCPs). This is because through the restoration of LCPs identified in the original landscape (strategy 1), we are further strengthening areas where animal dispersal flows are likely to be already happening or concentrated in the original landscape and that, therefore, may be already well functional to support species movements. This phenomenon can be observed in Fig. 3, where the simulated landscape corresponding to strategy 1 (Fig. 3b), even if shows some new paths in the northern and north-eastern part of the network, is generally characterized by areas of dispersal flow concentration that basically follow the original corridors showed in Fig. 3a. Conversely, by locating new hedgerows in other strategic areas (strategy 2), we are creating new main movement pathways able to support additional dispersal flows through different areas and, possibly, from or to other habitat sources and destinations that were much more isolated before. The new main dispersal pathways in the simulated landscape obtained by implementing strategy 2 are evident in the central and northern part of the study area (Fig. 2c).

While strategy 1 further reinforced already existing and relatively dominant corridors, increasing the maximum LCP density in the study area up to 516, strategy 2 resulted in the distribution of the connecting role among a larger number of pathways (Fig. 3c), with maximum LCP density increasing only up to 417, which seemed to enhance the complementary and functionality of the full set of landscape corridors.

In particular, promoting new pathways (strategy 2) increased connectivity more than threefold compared to concentrating restoration efforts only in the existing corridors (strategy 1). The importance to create new corridors in high resistance areas, rather than strengthening existing permeable corridors, was already highlighted by McRae et al. (2012). By creating new dispersal pathways, we increased the overall connected area within the landscape and simultaneously created alternative routes along which dispersal may occur among nodes. This is crucial because individuals seldom follow a single optimal route (Pinto and Keitt 2009), and because redundant corridors ensure the maintenance of connectivity even in the face of

future landscape changes (McRae et al. 2008), strengthening the effectiveness and resilience of the ecological network.

Interestingly, new dispersal routes were only generated when we focused directly on strategy 2, but it was not obvious that some new pathways could not have been identified in strategy 1 also. Indeed, through the strategy 1, we considered all LCPs between every pairs of adjacent nodes, including those not belonging to the original areas with high LCPs density. Thus, theoretically, the strategy 1 could have had selected the LCPs that, if restored, originated new valuable movements routes, which did not happen possibly due to multiple issues.

A first methodological issue relies on the procedure to identify LCPs, adopted in strategy 1 only, which only considers adjacent nodes. Indeed, if the connection of two non-adjacent nodes would lead to a consistent increase of connectivity, they will be surely associated to a high value of *dIIC* in strategy 2 (if they fall within the 2000 m maximum distance considered), but not necessarily to a high value of *dPC* in strategy 1. This is because the LCPs among adjacent nodes, which, if joined, would connect the two considered non-adjacent nodes, will not necessarily be associated to high values of *dPC* when considered separately.

Another issue relies on the simulation of the complete restoration of a LCP by making the effective distance along the LCP equal to its linear distance in meters (i.e., assumed that it was all covered by suitable habitat). LCPs have a much more tortuous pattern compared to hypothetical direct links between two nodes, since the more permeable areas, surrounded by high resistance ones, often do not follow a straight line between two nodes. It is thus clear that the linear distance in meters along the LCPs will be in some cases much greater than the Euclidean (straight-line) distances between nodes. Considering a species with a very low mobility, the probability that it moves from one node to another crossing this long and tortuous path can be low, as also noted in other context by Pérez-Hernández et al. (2015). Consequently, LCPs with these characteristics will not be associated to a high *dPC* value and will not be selected as priority LCPs to be restored through strategy 1.

The LCPs associated to high *dPC* values are probably those that are not so long (as measured by the linear distance in meters), belong to areas of high

LCPs density in the original landscape, and still have room for improving their conditions for conducting additional species movements. Conversely, strategy 2 does not consider the movement probability of the species among nodes, but just the possibility of some movement being possible or not, regardless both their Euclidean and effective distance. Therefore, strategy 2 does not rely on the longer and more tortuous pathways in these heterogeneous landscapes but highlights the most feasible and direct way of building hedgerow linkages between two nodes, which often involves the prioritization of new movement pathways.

Applicability of analytical results to management

The comparative analysis revealed that, in our case, the best strategy to enhance landscape connectivity is implementing new movement pathways rather than further improving existing corridors. The simulated implementation of new pathways is feasible in our case study, and comparable in the potential resources required to the restoration of existing corridors, as the effort for new hedgerows plantation is generally moderate and economically sustained by financial contributions foreseen in the CAP.

If we would increment landscape connectivity for species with a larger size compared to the Hazel Dormouse, we should certainly consider more intense management actions to simulate the implementation of new pathways, since such species is likely to have wider spatial requirements and to require wider corridors than just hedgerow networks to promote their movement. In this case, when comparing this strategy with the traditional restoration of existing corridors, we should also consider the feasibility and the higher economic cost of the simulated actions (Torrubia et al. 2014; Correa Ayram et al. 2016).

Generally, in these cases, increasing habitat quality along paths already characterized by a low resistance may be a more realistic and cheaper strategy than locating new habitat in new strategic areas to implement an equal number of new movement pathways (Hobbs et al. 2009; Pardini et al. 2010). However, it may be still the case that restoring existing corridors has a much smaller effect in increasing connectivity respect to creating new movement pathways. In this case, the conversion to suitable habitat of small and few priority areas in the landscape could have a greater

effect than restoring a higher number of existing low-resistance routes.

Our results highlighted that it is crucial to develop and apply analytical methods to compare the effectiveness of all the plausible and applicable management strategies in increasing connectivity within a considered landscape (Bottrill et al. 2008; Chazdon 2008; Menz et al. 2013; Gippoliti and Battisti 2017). Indeed, as shown by our findings, the implementation of different management strategies could have a very different potential effect on the degree of ecological connectivity for a given landscape.

In this context, it must also be considered that restoring existing corridors or creating new dispersal pathways should not be necessarily considered as competing strategies. In environmental plans aimed to enhancing connectivity in fragmented landscapes, where the practical feasibility and costs associated with each management strategy should be certainly considered, a good approach could be the integration of the two strategies. For instance, to enhance connectivity for species with a larger size compared to the Hazel Dormouse, an efficient management strategy could be identifying which nodes will provide a higher gain of connectivity if they were connected, using a binary model and disregarding existing corridors in the phase of paths prioritization (strategy 2), and then, where possible, enhancing habitat quality along existing LCPs between the identified pairs of priority nodes. In fact, from a practical point of view, creating new corridors requires generally more efforts and is likely more expensive than restoring existing ones. Developing management actions along existing corridors has indeed several advantages, such as restoring areas already set aside from agricultural production and where natural or semi-natural vegetation elements, even if discontinuous, represent a basic infrastructure for a corridor.

Conclusions and implications

This study has demonstrated, through an illustrative case study, that it is possible to go beyond the usual approach of just identifying the areas that currently best support connectivity, and of prioritizing those that already exist in the landscape, to include a broader array of management options including the identification and prioritization of new complementary

pathways that may be more efficient in reinforcing functional connectivity in fragmented landscapes.

We considered a real landscape and concretely simulated alternative management strategies by proposing specific actions and by evaluating how they would affect landscape connectivity. The maps representing the simulated management actions were designed realistically, as regards both to the number of interventions and to their size and position within the landscape. This way, our results allowed highlighting that, to considerably enhance connectivity for the Hazel Dormouse in an agroecosystem, it may be sufficient to deploy a relatively modest number of hedgerows in new strategic areas, not necessarily corresponding to already existing corridors, adding a comparatively small amount of new suitable habitat to the original landscape.

This study contributed with information about the effectiveness of different management strategies providing insights that could have important implications concerning the conservation of species sensitive to fragmentation in highly modified agroecosystems. In addition, the procedure concerning the identification of strategic areas and priority actions can be easily integrated in landscape management plans for the conservation not only of the Hazel Dormouse but also of other mammals with similar ecological requirements (e.g., Red Squirrels *Sciurus vulgaris*, Mortelliti et al. 2009).

The approach proposed in this study, from the simulation of management strategies' implementation to the final maps of priority actions, may also be applied to other species that are sensitive to fragmentation in other geographical contexts, and for which habitat connectivity may be an important concern for their conservation in highly modified landscapes.

Acknowledgements This study was supported by the PhD Funds of the University of Milano-Bicocca.

References

- Adriaenssens F, Chardon JP, De Blust G, Swinnen E, Villalba S, Gulink H, Matthyssens E (2003) The application of 'least-cost' modelling as a functional landscape model. *Landsc Urban Plan* 64:233–247
- Bani L, Orioli V, Pisa G, Dondina O, Fagiani S, Fabbri E, Randi E, Mortelliti A, Sozio G (2018) Landscape determinants of genetic differentiation, inbreeding and genetic drift in the Hazel Dormouse (*Muscardinus avellanarius*). *Conserv Genet* 19:283–296
- Bani L, Orioli V, Pisa G, Fagiani S, Dondina O, Fabbri E, Randi E, Sozio G, Mortelliti A (2017) Population genetic structure and sex-biased dispersal of the Hazel Dormouse (*Muscardinus avellanarius*) in a continuous and in a fragmented landscape in central Italy. *Conserv Genet* 18:261–274
- Bani L, Pisa G, Luppi M, Spilotros G, Fabbri E, Randi E, Orioli V (2015) Ecological connectivity assessment in a strongly structured fire salamander (*Salamandra salamandra*) population. *Ecol Evol* 5:3472–3485
- Beier P, Majka DR, Newell SL (2009) Uncertainty analysis of least-cost modeling for designing wildlife linkages. *Ecol Appl* 19:2067–2077
- Beier P, Majka DR, Spencer WD (2008) Forks in the road: choices in procedures for designing wildland linkages. *Conserv Biol* 22:836–851
- 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, McKinley PS, Gage JA, Aplet GH (2016) Identifying corridors among large protected areas in the United States. *PLoS ONE* 11:e0154223
- Bennett AF (2003) Linkages in the landscape: the role of corridors and connectivity in wildlife conservation. IUCN, Gland
- Berger G, Kaechele H, Pfeffer H (2006) The greening of the European common agricultural policy by linking the European-wide obligation of set-aside with voluntary agri-environmental measures on a regional scale. *Environ Sci Policy* 9:509–524
- Bottrill MC, Joseph LN, Carwardine J, Bode M, Cook C, Game ET, Grantham H, Kark S, Linke S, McDonald-Madden E, Pressey LR, Walker S, Wilson KA, Possingham HP (2008) Is conservation triage just smart decision making? *Trends Ecol Evol* 23:649–654
- Bowman J, Jaeger JA, Fahrig L (2002) Dispersal distance of mammals is proportional to home range size. *Ecology* 83:2049–2055
- Bright PW (1998) Behavior of specialist species in habitat corridors: arboreal dormice avoid corridor gaps. *Anim Behav* 56:1485–1490
- Bright PW, Mitchell P, Morris PA (1994) Dormouse distribution: survey techniques, insular ecology and selection of sites for conservation. *J Appl Ecol* 31:329–339
- Büchner S (2008) Dispersal of common dormice *Muscardinus avellanarius* in a habitat mosaic. *Acta Theriol* 53:259–262
- Burel F, Baudry J (1995) Social, aesthetic and ecological aspects of hedgerows in rural landscapes as a framework for greenways. *Landsc Urban Plan* 33:327–340
- Carranza ML, D'Alessandro E, Saura S, Loy A (2012) Connectivity providers for semi-aquatic vertebrates: the case of the endangered otter in Italy. *Landscape Ecol* 27:281–290
- Chazdon RL (2008) Beyond deforestation: restoring forests and ecosystem services on degraded lands. *Science* 320:1458–1460
- Chiatante G, Dondina O, Lucchelli M, Bani L, Meriggi A (2017) Habitat selection of European badger *Meles meles* in a

- highly fragmented forest landscape in northern Italy: the importance of agro-forestry systems. *Hystrix* 28:247–252
- Clauzel C, Bannwarth C, Foltete JC (2015a) Integrating regional-scale connectivity in habitat restoration: an application for amphibian conservation in eastern France. *J Nat Conserv* 23:98–107
- Clauzel C, Xiqing D, Gongsheng W, Giraudoux P, Li L (2015b) Assessing the impact of road developments on connectivity across multiple scales: application to Yunnan snub-nosed monkey conservation. *Biol Conserv* 192:207–217
- Correa Ayram CA, Mendoza ME, Etter A, Salicrup DRP (2016) Habitat connectivity in biodiversity conservation: a review of recent studies and applications. *Prog Phys Geogr* 40:7–37
- Darby HC (1956) The clearing of the woodland in Europe. In: Thomas WL Jr (ed) *Man's role in changing the face of the earth*. University of Chicago Press, Chicago, pp 183–216
- de la Torre JA, Núñez JM, Medellín RA (2017) Habitat availability and connectivity for jaguars (*Panthera onca*) in the Southern Mayan Forest: conservation priorities for a fragmented landscape. *Biol Conserv* 206:270–282
- Donald PF, Pisano G, Rayment MD, Pain DJ (2002) The Common Agricultural Policy, EU enlargement and the conservation of Europe's farmland birds. *Agric Ecosyst Environ* 89:167–182
- Dondina O, Kataoka L, Orioli V, Bani L (2016) How to manage hedgerows as effective ecological corridors for mammals: a two-species approach. *Agric Ecosyst Environ* 231:283–290
- Dondina O, Orioli V, Colli L, Luppi M, Bani L (2018) Ecological network design from occurrence data by simulating species perception of the landscape. *Landscape Ecol* 33:275–287
- Dondina O, Orioli V, D'Occhio P, Luppi M, Bani L (2017) How does forest species specialization affect the application of the island biogeography theory in fragmented landscapes? *J Biogeogr* 44:1041–1052
- ERSAF (2014) Destinazione d'Uso dei Suoli Agricoli e Forestali (DUSAF) (Agricultural and Forest Land Use). Ente Regionale per i Servizi all'Agricoltura e alle Foreste della Lombardia, Milan
- ESRI (2011) ArcGIS desktop: release 10. Environmental Systems Research Institute, Redlands
- Fahrig L (2003) Effects of habitat fragmentation on biodiversity. *Annu Rev Ecol Evol Syst* 34:487–515
- Fischer J, Lindenmayer JB (2007) Landscape modification and habitat fragmentation: a synthesis. *Global Ecol Biogeogr* 16:265–280
- Gelling M, Macdonald DW, Mathews F (2007) Are hedgerows the route to increased farmland small mammal density? Use of hedgerows in British pastoral habitats. *Landscape Ecol* 22:1019–1032
- Gippoliti S, Battisti C (2017) More cool than tool: equivoques, conceptual traps and weaknesses of ecological networks in environmental planning and conservation. *Land Use Policy* 68:686–691
- Hilty JA, Merenlender AM (2004) Use of riparian corridors and vineyards by mammalian predators in Northern California. *Conserv Biol* 18:126–135
- Hinsley SA, Bellamy PE (2000) The influence of hedge structure, management and landscape context on the value of hedgerows to birds: a review. *J Environ Manag* 60:33–49
- Hobbs RJ, Higgs E, Harris JA (2009) Novel ecosystems: implications for conservation and restoration. *Trends Ecol Evol* 24:599–605
- Juškaitis R, Šiožinytė V (2008) Habitat requirements of the common dormouse (*Muscardinus avellanarius*) and the fat dormouse (*Glis glis*) in mature mixed forest in Lithuania. *Ekologia* 27:143–151
- Krebs JR, Wilson JD, Bradbury RB, Siriwardena GM (1999) The second silent spring? *Nature* 400:611–612
- Landguth EL, Hand BK, Glassy J, Cushman SA, Sawaya MA (2012) UNICOR: a species connectivity and corridor network simulator. *Ecography* 35:9–14
- Laurance SG, Laurance WF (1999) Tropical wildlife corridors: use of linear rainforest remnants by arboreal mammals. *Biol Conserv* 91:231–239
- Mateo-Sánchez MC, Balkenhol N, Cushman SA, Pérez T, Domínguez A, Saura S (2015) Estimating effective landscape distances and movement corridors: comparison of habitat and genetic data. *Ecosphere* 6:1–16
- Mateo-Sánchez MC, Cushman SA, Saura S (2014) Connecting endangered brown bear subpopulations in the Cantabrian Range (north-western Spain). *Anim Conserv* 17:430–440
- McRae BH, Dickson BG, Keitt TH, Shah VB (2008) Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology* 89:2712–2724
- McRae BH, Hall SA, Beier P, Theobald DM (2012) Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits. *PLoS ONE* 7:e52604
- McRae BH, Kavanagh DM (2011) Linkage mapper connectivity analysis software. The Nature Conservancy, Seattle. <http://www.circuitscape.org/linkagemapper>
- Menz MH, Dixon KW, Hobbs RJ (2013) Hurdles and opportunities for landscape-scale restoration. *Science* 339:526–527
- Moqanaki EM, Cushman SA (2017) All roads lead to Iran: predicting landscape connectivity of the last stronghold for the critically endangered Asiatic cheetah. *Anim Conserv* 20:29–41
- Mortelliti A, Santarelli L, Sozio G, Fagiani S, Boitani L (2013) Long distance field crossings by hazel dormice (*Muscardinus avellanarius*) in fragmented landscapes. *Mamm Biol* 78:309–312
- Mortelliti A, Santulli Sanzo G, Boitani L (2009) Species' surrogacy for conservation planning: caveats from comparing the response of three arboreal rodents to habitat loss and fragmentation. *Biodivers Conserv* 18:1131–1145
- Mortelliti A, Sozio G, Driscoll DA, Bani L, Boitani L, Lindenmayer DB (2014) Population and individual-scale responses to patch size, isolation and quality in the Hazel Dormouse. *Ecosphere* 5:1–21
- Panchetti F, Sorace A, Amori G, Carpaneto GM (2007) Nest site preference of common dormouse (*Muscardinus avellanarius*) in two different habitat types of central Italy. *Ital J Zool* 74:363–369
- Panzacchi M, Van Moorter B, Strand O, Saerens M, Kivimäki I, St Clair CC, Herfindal I, Boitani L (2016) Predicting the continuum between corridors and barriers to animal

- movements using step selection functions and randomized shortest paths. *J Anim Ecol* 85:32–42
- Paoletti MG, Boscolo P, Sommaggio D (1997) Beneficial insects in fields surrounded by hedgerows in north eastern Italy. *Biol Agric Hortic* 15:310–323
- Pardini R, de Arruda Bueno A, Gardner TA, Prado PI, Metzger JP (2010) Beyond the fragmentation threshold hypothesis: regime shifts in biodiversity across fragmented landscapes. *PLoS ONE* 5:e13666
- Pascual-Hortal L, Saura S (2006) Integrating landscape connectivity in broad-scale forest planning: a methodology based on graph structures and habitat availability indices. In: Laforteza R, Sanesi G (eds) *Patterns and processes in forest landscapes. Consequences of human management*. Springer, Berlin, pp 111–116
- Pérez-Hernández CG, Vergara PM, Saura S, Hernández J (2015) Do corridors promote connectivity for bird-dispersed trees? The case of *Persea lingue* in Chilean fragmented landscapes. *Landscape Ecol* 30:77–90
- Pinto N, Keitt TH (2009) Beyond the least-cost path: evaluating corridor redundancy using a graph-theoretic approach. *Landscape Ecol* 24:253–266
- Ramakers JJC, Dorenbosch M, Foppen RPB (2014) Surviving on the edge: a conservation-oriented habitat analysis and forest edge manipulation for the Hazel Dormouse in the Netherlands. *Eur J Wildl Res* 60:927–931
- Santos JS, Leite CCC, Viana JCC, dos Santos AR, Fernandes MM, de Souza Abreu V, do Nascimento TP, dos Santos LS, de Moura Fernandes MR, de Silva GF, de Mendonça R (2018) Delimitation of ecological corridors in the Brazilian Atlantic Forest. *Ecol Indic* 88:414–424
- Saura S, Estreguil C, Mouton C, Rodríguez-Freire M (2011) Network analysis to assess landscape connectivity trends: application to European forests (1990–2000). *Ecol Indic* 11:407–416
- 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* 83:91–103
- 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
- Silva M, Prince ME (2008) The conservation value of hedgerows for small mammals in Prince Edward Island, Canada. *Am Midl Nat* 159:110–124
- Torné J, Saura S (2013) Conefor 2.7.1—command line version 1.0.21. Universidad Politecnica de Madrid, SP. <http://www.conefor.org>
- Torrubia S, McRae BH, Lawler JJ, Hall SA, Halabisky M, Langdon J, Case M (2014) Getting the most connectivity per conservation dollar. *Front Ecol Environ* 12:491–497
- Watson DM, Doerr VA, Banks SC, Driscoll DA, van der Ree R, Doerr ED, Sunnucks P (2017) Monitoring ecological consequences of efforts to restore landscape-scale connectivity. *Biol Conserv* 206:201–209
- Weibull AC, Östman Ö, Granqvist Å (2003) Species richness in agroecosystems: the effect of landscape, habitat and farm management. *Biodivers Conserv* 12:1335–1355
- Williams M (2003) *Deforesting the earth: from prehistory to global crisis*. University of Chicago Press, Chicago
- Wolton R (2009) Hazel dormouse *Muscardinus avellanarius* (L.) nest site selection in hedgerows. *Mammalia* 73:7–12