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Combining multi-species connectivity modelling with expert knowledge to inform the green infrastructure design

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ABSTRACT

The Canton of Geneva is currently working on defining and mapping its green infrastructure (GI), in order to implement its biodiversity protection directives by 2030. Ecological connectivity is considered in the definition of the GI, as it is a key factor in managing the species extinction risk. It is considered a vital aspect of the landscape, because it can indicate how landscape facilitates or influences wildlife movement. In order to assess connectivity, animal movement data is essential as it provides precise behavioral information on the movements of organisms. Unfortunately, this kind of data is often missing or available only at local scales. Ecologists therefore must deal with a lack of data when trying to supply useful spatially explicit ecological models for conservation planning. To help managers in their efforts to define the GI, an alternative is to rely on local expert knowledge. We have thus applied a structured analytical framework to parameterize an ecological connectivity model combining expert opinion with three of the most used methods to assess ecological connectivity: graph theory, circuit theory and cumulative costs algorithm. By considering a selection of focal species representative of the different ecological requirements and movement behaviour of the regional wildlife, maps of priority areas for the promotion of ecological connectivity were obtained for red deer, roe deer, brown hare and common toad. We estimated the principal cross-border corridors at the scale of the Greater Geneva region, between France and Switzerland. Three transboundary high priority areas were highlighted in our maps. The localization of these areas is principally characterized by natural habitats such as forests, grasslands and freshwater ecosystems, but depends also on the agricultural areas. The principal natural barrier to animal movement is Lake Geneva, and the principal human barriers to movement are human settlements and highways that impede the regional displacements for all of the species. Considering the highways, the barrier effect could be diminished thanks to the recent construction of wildlife overpasses. We have seen that a close collaboration between local experts and ecological modelers is necessary when interpreting the conservation value of land potentially capable of promoting wildlife ecological connectivity. When implementing the GI, it will be useful to combine our models with field campaigns to measure the real functionality of the estimated priority areas, in order to guarantee the success of conservation actions.

1. Introduction

The Swiss Biodiversity Strategy 2012 aims to achieve a nationwide ecological infrastructure of protected areas and networking zones by 2040 (Federal Office for the Environment, 2017). Under this impetus, the Canton of Geneva adopted an approach for the development of a green infrastructure (GI), with the particularity of having to reconcile these efforts with intense urban development (Etat de Genève, 2017). GI can be viewed as a network of natural and semi-natural areas allowing the ecological connectivity of the landscape where biodiversity and ecosystem services are concentrated (Benedict et al., 2006; da Silva and Wheeler, 2017; Liquete et al., 2014; Honeck et al., 2020; Sanguet et al.,

2023), fitting the modern view of nature conservation that emphasizes sustainable and resilient interactions between nature and people (Mace, 2014). In this context, ecological connectivity is considered as a pillar for the planning of GI together with species diversity and ecosystems supply, where a resulting map elaborated through a spatial prioritization scheme theoretically represents the most valuable areas to optimize the conservation of natural entities, processes and functions (Honeck et al., 2020). Using this framework, the Canton of Geneva initially mapped its GI for the spatial planning of peri-urban areas, including ecological connectivity by using seven indicators of both structural and functional connectivity (Honeck et al., 2020). Later, the Canton undertook the task of defining the GI across the entire Grater Geneva

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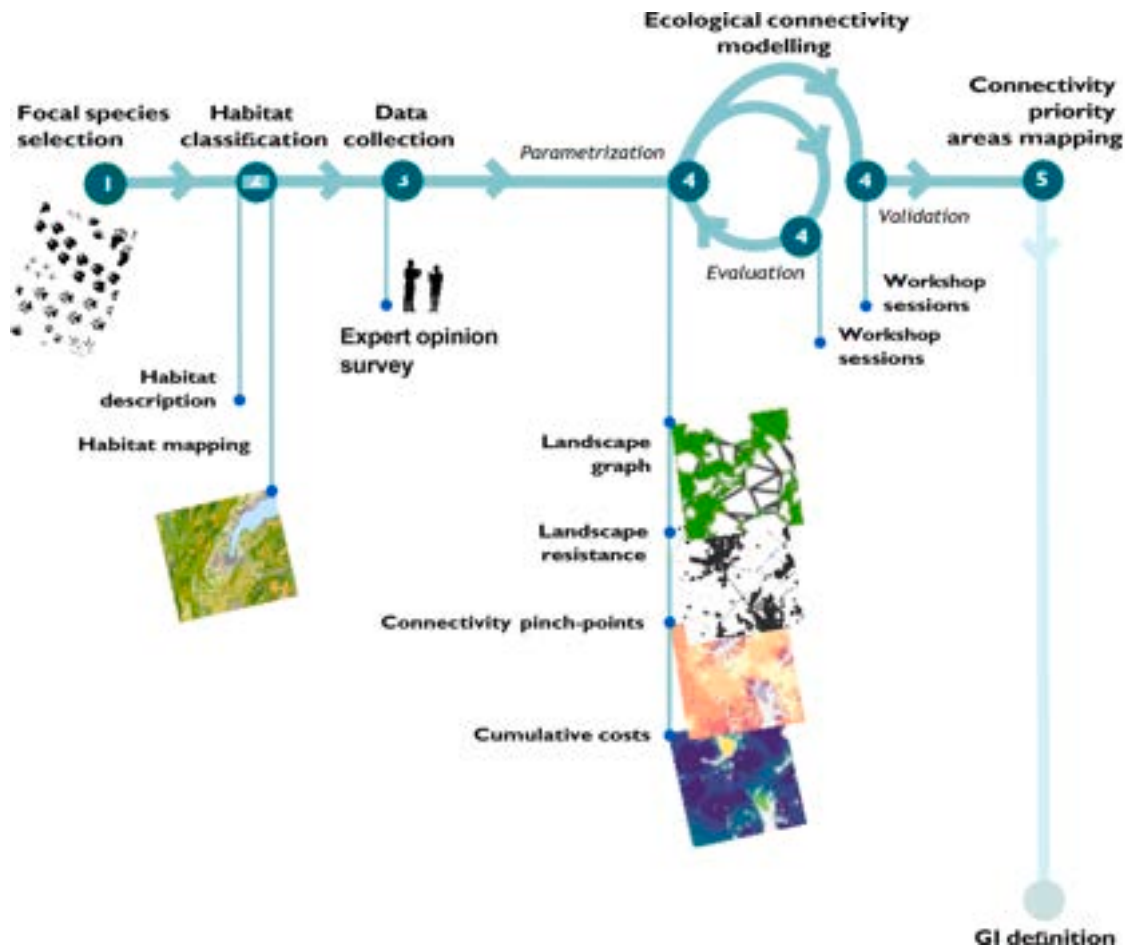


Fig. 1. Diagram of the approach used in this work to inform the GI definition and mapping about ecological connectivity: (1) Selection of target species, (2) Classification of habitats, (3) Data collection by a survey process, (4) Development of ecological connectivity models and (5) Connectivity priority areas mapping.

agglomeration by including the functional connectivity through the development of functional connectivity maps of a set of focal species representatives of the regional fauna.

Ecological connectivity is considered to be a crucial aspect of the landscape since it indicates how the landscape facilitates or impedes the movement of organisms (Taylor et al., 1993). It is considered to be a key factor in managing the risk of species extinction (Fahrig, 2003; Haddad et al., 2015; Hadley and Betts, 2016), as the survival of species depends in part on their ability to move around the landscape to access resources that are often dispersed, particularly in environments influenced by human activities (Goodwin and Fahrig, 2002; Villard and Metzger, 2014). To inform the process of defining GI from the ecological connectivity perspective, it is necessary to provide ecological models that highlight priority areas promoting wildlife movements between habitat patches (Beier et al., 2011; Brodie et al., 2016). The behavioral response of organisms to disturbances in the landscape structure is species-specific, so it is essential to consider a set of focal species that will represent different ecological requirements and responses to habitat loss and fragmentation (Beier et al., 2008; Brodie et al., 2015; Tschamtko et al., 2012). Several software tools have been developed to model ecological connectivity using methods such as graph theory, least-cost path estimation and electrical circuit theory. The usefulness of these tools as decision support for biological conservation planning has been demonstrated in previous research (Kool et al., 2013; Dickson et al., 2019).

Graph theory is particularly useful because it can be used to represent the landscape of a focal species by linking the patches of suitable habitats in accordance with certain rules (Urban and Keitt, 2001).

Generally, the dispersal distance is used to define the maximum length of the links (Urban et al., 2009) and several metrics have been developed to consider the importance of suitable habitat patches in the functioning of an ecological network (e.g. Saura and Pascual-Hortal, 2007; Saura and Rubio, 2010). Suitable habitat patches are considered as core areas or nodal zones, and links are established between nodal zones that are close enough to be reached for a given species. Being able to represent the landscape of a target species in a simplified way, it makes the identification of ecological networks easier (Urban and Keitt, 2001) and allows the estimation of the potential of a landscape to promote the networking of protected areas (e.g. Liu et al., 2020; Iezzi et al., 2022) as well as the evaluation of the impact of changes in land use on the functioning of ecological networks (e.g. Modica et al., 2021).

The cumulative cost algorithm is used to assess the most likely position of biological corridors, by calculating the least cost path in terms of energy and risk between two habitat patches (Adriaensen et al., 2003). This is particularly adequate for the study of organisms that regularly use the same paths according to directed movements (McClure et al., 2016). Electrical circuit theory has also been proposed as a method for defining biological corridors or pinch-points of connectivity, i.e. landscape elements which have a high likelihood of passing (McRae et al., 2008). The estimated current flow between nodal zones also highlights several alternative routes and reveal critical pinch-points that constrain the potential displacements between these areas (Dickson et al., 2019). Having an estimate of multiple movement pathways makes it possible to represent the probability of movement of organisms in the landscape that are not familiar with the landscape (McClure et al., 2016) or that undertake dispersal movements (McRae et al., 2008; Dickson

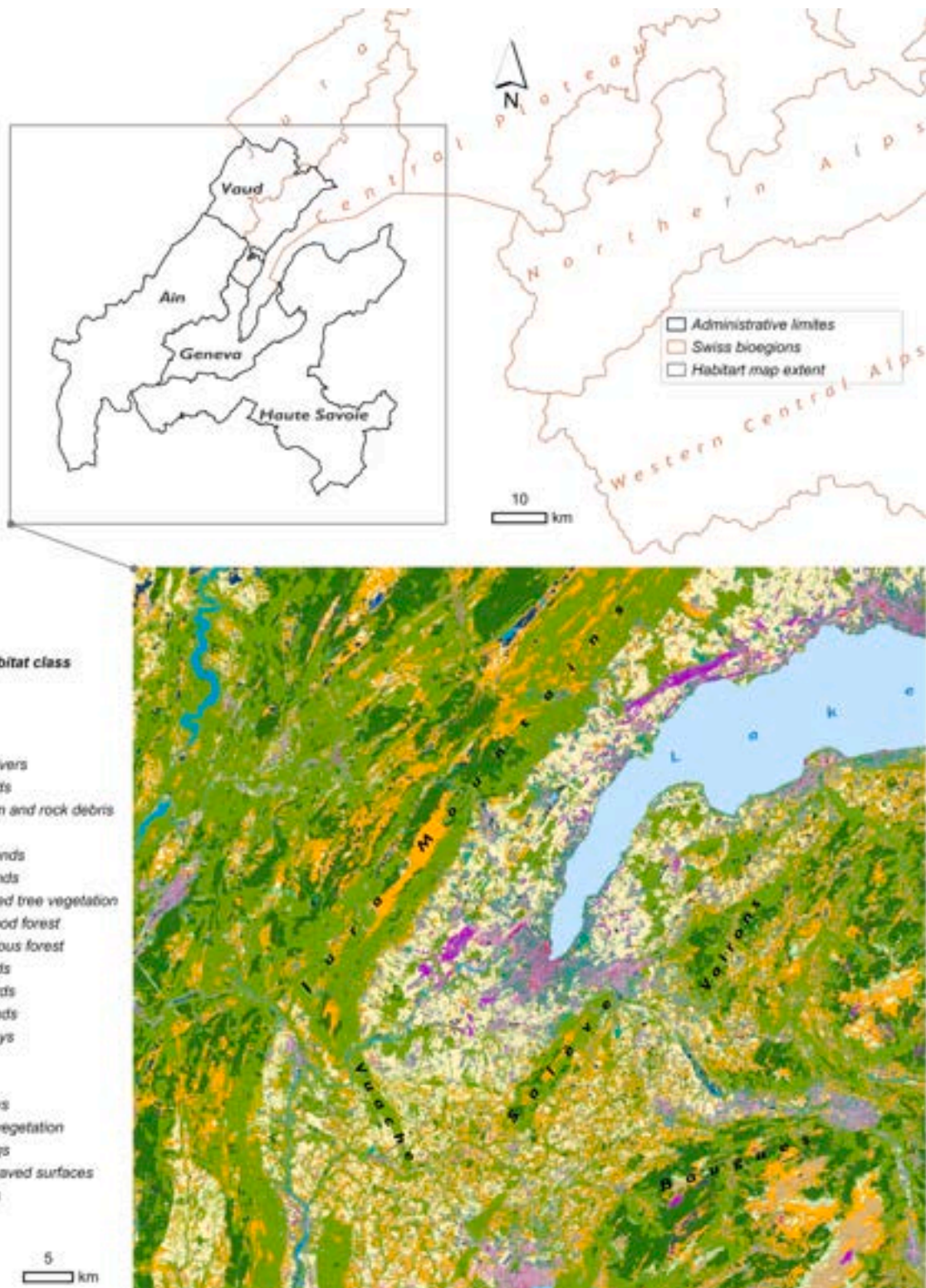


Fig. 2. Map of the study area and the habitat map. A: The different limits of the administrative areas in both France and Switzerland (Source: SITG (2023)). B: The habitat map for the study of multiple-species habitat connectivity and the principal mountains present in the study area (black text). It corresponds to a square around the region of almost six thousand km².

et al., 2019). In order to parameterize this type of models, it is necessary to have a measure of the landscape resistance to movement. From the point of view of an organism, landscape permeability represents either the motivation, the physiological cost, the mortality risk or the integration of all these factors when crossing a particular environment

(Zeller et al., 2012).

The use of data such as occurrence data or GPS tracking data to estimate space use and resource selection is more effective when it is necessary to parameterize connectivity models (Beier et al., 2008; Zeller et al., 2018). This type of data is rare and generally, available on small

Table 1
Focal species, participants and model parameters considered in this work.

	Red deer	Roe deer	Brown hare	Common toad
Scientific name	<i>Cervus elaphus</i>	<i>Capreolus capreolus</i>	<i>Lepus europaeus</i>	<i>Bufo bufo</i>
Number of experts consulted	8	2	5	5
Number of responding experts	3	2	4	4
Habitat continuum	Green	Green	Yellow and Red	Blue
Habitat composition and size	Expertise	Expertise	Expertise	Expertise
Maximal dispersal distance	Expertise	Expertise	Expertise	Expertise
Landscape resistance	Experimental (Urbina et al., 2023)	Experimental (Urbina et al., 2023)		
and expertise	Expertise	Expertise		

scales. This greatly reduces the possibility of making large-scale predictions for several species. When empirical data is not available, the use of expert models based on a review of the literature and expert opinion can be useful, especially when urgent decisions need to be made about planning or restoring connectivity. In order to create large-scale landscape graphs in a qualitative way, a literature review on ecological requirements and dispersal capacity of species is often used (e.g. Albert et al., 2017; Pietsch, 2018). To construct a movement resistance surface using expert opinion, the participants are often interviewed to qualitatively assess the resistance that each land cover offers to movement (e.g. Tarabon et al., 2022). Another way to make a resistance surface is to transform a habitat quality index into resistance, as it seems reasonable that resistance to movement is inversely proportional to how organisms select their habitat (Beier et al., 2008). Furthermore, it is generally easier to study habitat selection than landscape use during prospecting and dispersal movements (Keeley et al., 2016). In this case, experts are asked to develop an index of habitat quality (e.g. Singleton et al., 2002) or naturalness (e.g. Parrott et al., 2019), which is then transformed into resistance. Finally, it is also possible to incorporate several environmental variables into the calculation of landscape resistance (Zeller et al., 2012). In this way, experts can give their opinion on the relative importance of the environmental variables and the final resistance is estimated on the basis of a geometric mean (e.g. Petsas et al., 2020) or a product (e.g. Singleton et al., 2002).

We propose to provide a set of connectivity maps for several species by the development and application of a structured analytical framework. This approach is based on the combination of different types of algorithms parameterized according to the opinion of local experts. Firstly, using graph theory, we can highlight the potential structure of ecological networks, based on expert knowledge about the habitat requirements and movement distances of the regional wildlife populations. Secondly, thanks to the local experts' knowledge it is possible to estimate the resistance of the different types of environments that animals cross during movement. The definition of the structure of the ecological networks and the resistance to movement obtained with the help of the local experts allows us to trace the main corridors followed by the animals, using the cumulative cost algorithm and the electrical circuit theory. Thanks to a limited number of parameters and environmental variables, we can provide a useful framework for evaluating connectivity models, allowing the adjustments of the parameters in an iterative way until the models are in line with the field experience of local biologists and gamekeepers. Finally, the combination of the validated models of core areas, cumulative costs and connectivity pinch-

points is used to obtain a prioritization map of ecological connectivity, which planners can use for themselves and incorporate into the definition and mapping of the GI, together with other pillars of information such as biodiversity and ecosystem services (Honeck et al., 2020; Sanguet et al., 2023).

2. Materials and methods

In this study, a succession of five steps was followed in order to obtain a mapping of priority areas for the promotion of connectivity for several species (Fig. 1): 1) Selection of target species, 2) Classification of habitats, 3) Data collection by a expert opinion survey, 4) Development of ecological connectivity models and 5) Connectivity priority areas mapping.

2.1. Study area and habitat map

The study area corresponds to the Greater Geneva area, a cross-border area encompassing the Canton of Geneva and the District of Nyon (Canton of Vaud) on the Swiss side, and the departments of Ain and Haute-Savoie on the French side (Fig. 2A). The lowlands correspond to a mosaic of arable lands and forests highly fragmented by urban settlements and transport infrastructures. They are surrounded by mountains characterized by forested slopes and pastures along the ridges located at an altitude of between 1000 and 1700 m.a.s.l.

In order to assess habitats in terms of their structure and permeability to animal movement, we first identified and described twenty-five relevant habitat categories (Fig. 2B).

The habitat map was then drawn up on the basis of the land-use map of the Greater Geneva region (Sanguet et al., 2023), reclassifying it into twenty-three habitat categories. As the categories "shrublands", "forest edges" and "urban forests" were not present in the base map, but considered in the survey process, these classes were considered as a part of the class of "disturbed tree vegetation", as in the land cover base map. The "gravel" class was also added to the habitat map, but this was done after the survey process. A raster of close to 240 million cells with a resolution of 5 m was produced to represent the priority habitats for the regional fauna, corresponding to a square of almost six thousand km^2 (Fig. 2B). Open lands (crops, meadows and pastures) represent 29 % of the landscape and forested lands, a 40 % (Fig. 2B). Urban settlements and transport infrastructures correspond to a 17 % of the landscape (Fig. 2B).

2.2. Target species and expert opinion

In a previous work, a set of ten focal species was selected to carry out a preliminary study of the habitat connectivity of several species in the Greater Geneva area (Urbina, 2020). The selection was based on the ecological requirements and movement behaviour of the regional fauna. At the same time, the state of the regional knowledge about the biology and ecology of the species was considered. In order to obtain the information needed to parameterize the functional connectivity models, an online survey was provided to biologists and gamekeepers familiar with observing and monitoring target species in areas similar to our study site. We obtained data about the structure of the core areas, the maximum dispersal distance and the permeability of the landscape elements that form the landscape matrix (Table 1). The survey was developed using the LimeSurvey tool and made available for two months (For more details on the questions, see the A).

Considering the number of responses obtained in this previous work, we chose a subset of three focal species: the red deer, the brown hare and the common toad. In a second phase, and in order to identify biological corridors within the Canton of Geneva (i.e., on a smaller scale), we also added the roe deer, with red deer being an interesting focal species for larger scales (Table 1). As the roe deer exhibits similar habitat requirements to the red deer, the results of the survey concerning the latter

Table 2
Expert participated to model evaluation workshops and adjustments to model parameters.

	Red deer First evaluation	Roe deer First evaluation	Second evaluation	Brown hare First evaluation	Second evaluation	Common Toad First evaluation	Second evaluation
Number of experts involved	1	1	2	1	1	2	2
Adjustment							
Core areas composition		x				x	
Minimal patch size						x	
Dispersal distance		x		x			
Number of core areas			x				
Number of links			x				
Resistance	x	x		x			x

species were attributed to the roe deer and adjusted with the advice of specialist in the telemetry monitoring of roe deer in the study area (Table 1). Finally, the resistance model for red deer estimated on the basis of GPS data in Urbina et al. (2023) was also used in this work in order to produce a habitat resistance map for roe deer (Table 1).

The focal species considered in this work are particularly relevant because they are associated with the following four biological continuums of natural habitats; respectively, green, blue, yellow and red. According to the Geneva Biodiversity Strategy 2030 (Etat de Genève, 2017) these habitat continuums are considered as overlapping habitat networks through which species travel depending on their needs. As a result, they are defined according to their habitat composition as follows: 1) the green habitat network is composed of medium and tall vegetation (bushes, hedges, tree plantations and forests), 2) the blue habitat network by freshwater ecosystems (rivers, permanent or temporary ponds, ditches, marshes, wet meadows, etc.), 3) the yellow habitat network formed by open lands - principally crops, but also forest clearings, screes and others areas with pioneer vegetation; and 4) the red habitat network concerning grasslands. Finally, the selected focal species were also chosen because they are common in the study area, their spatial ecology is well known and it is possible to systematically assess their abundances, as advised by Hilty et al. (2006).

2.3. Connectivity model parameterization

In order to characterise an ecological infrastructure, it is necessary to determine and classify: (1) core areas (reservoirs and stepping-stones); (2) potential corridors providing connectivity between these zones; and (3) potential zones restricting the movement of wildlife.

2.3.1. Core areas

The spatial process of core areas identification was carried out on the basis of the priority habitat map using the Python language and the ModelBuilder tool in ArcGISPro V.2.9.3. Various data supplied by the experts were used for this purpose. The frequency of votes per habitat was used to define the composition of nodal zones. The median of the minimum size of habitat patches that would form a core area was estimated in order to incorporate a measure of patch quality. Finally, habitat patches of suitable patch size were aggregated if they were adjacent to each other to form units defining core areas.

2.3.2. Corridors and constraint zones

Corridors and constraint zones were modelled using three methods (Fig. 1).

Graph theory was used first to represent the landscape of each target species by means of nodes and euclidean links. Because we modeled landscape graphs for each focal species across a vast region, we constructed a planar spatial graph to retain only the most relevant links between the core areas estimated previously. This guarantees that the ecological network is properly representative while reducing computational time and resources needed for the analysis. It also considers the

maximum dispersal capacity of the species and eliminates links between core areas that are too far apart. The links were drawn with a width equal to or less than the dispersion distance of each focal species using GraphV. 2.8 (Foltête et al., 2021).

Then, two algorithms based on landscape resistance were used to determine the position of corridors and constraint zones through the selection of links determined with the help of graph theory.

Electrical circuit theory was used to represent all the possible alternative corridors and, at the same time the critical zones that constrain the potential flow between nodal zones (McClure et al., 2016; Dickson et al., 19). With the help of Circuitscape V. 5 software (Anantharaman et al., 2020) we estimated the electric current density on a matrix with variable resistances depending on the habitat or land-use. Based on circuit theory, current density symbolises the probability of net movement between two habitat patches (McRae et al., 2008). Connectivity pinch points correspond to areas where a high probability of movement is estimated due to the scarcity of alternative passages, indicating that they are particularly vulnerable. The resulting pinch-points of connectivity will therefore represent all the possible alternative corridors and, at the same time the critical zones that constrain the potential flow between nodal zones (McClure et al., 2016; Dickson et al., 2019). The classes of the current density images obtained for each of the focal species correspond to the deciles of the result between 0: Impassable (first decile) and 1: High current density (last decile). In order to parameterize Circuitscape, we used a map of nodes (centroids of core areas), the resistance maps described later and a list of pairs of nodes to be connected.

The cumulative cost surfaces indicate the overall probability of movement between core areas (generalization of the least cost path) and a hierarchy of biological corridors. The values reflect the cost in energy or the theoretical risk-taking by animals during movements (Adriaenssen et al., 2003). Cumulative costs were quantified using a workflow of consecutive tools belonging to the Distance toolset (Spatial Analyst toolbox in ArcGISPro V.2.9.3) grouped into models produced using the ModelBuilder tool in ArcGISPro V.2.9.3. The main workflow is parameterized using the following input data: the core area polygons, the resistance raster and a list of pairs of nodal zones to be connected according to the result of the landscape graph. The process starts with an initialization that prepares the source data and lists the nodal zones and pairs of nodal zones to be analysed. Then, a sub-process calculates the distance accumulation (a tool of Spatial Analyst toolbox in ArcGISPro V.2.9.3) for each core area considered. An additional sub-process generates the least-cost corridors (Corridor tool of Spatial Analyst toolbox in ArcGISPro V.2.9.3) using the results of the previous step, for each pair of nodal zones considered in the landscape graph. Finally, by iteration, the least cost corridors between all considered core areas pairs are aggregated by the Cell Statistics tool using the minimum statistic (Spatial Analyst toolbox in ArcGISPro V.2.9.3), enabling the most favourable cumulative costs to be considered for each cell in the territory. We therefore provided images of the cumulative cost classified in deciles between a low cumulative cost or preferential corridors (first decile) and

Table 3

The evolution of the parameters and estimations of the landscape graph models.

Graph parameters		Red deer	Roe deer	Validated value	Brown hare	Validated value	Common Toad	Validated value
		Median value (Urbina et al., 2023)	First evaluation		Median value (surveys)		Median value (surveys)	
Graph parameters	Minimal patch size (ha)	NA	NA	NA	NA	NA	0.01	0.0025
	Ponds	NA	NA	NA	NA	NA	0.01	0.01
	Wetlands	NA	NA	NA	NA	NA	NA	NA
	Grasslands	1	NA	NA	250.5	10	NA	NA
	Moorlands	15	NA	NA	NA	NA	NA	NA
	Shrubland	4	NA	NA	NA	NA	NA	NA
	Hardwood forests	30	1.7	1.7	NA	NA	NA	0.02
	Coniferous forests	30	1.7	1.7	NA	NA	0.02	0.02
	Forest edges	4	NA	NA	NA	NA	NA	NA
	Orchards	5	NA	NA	NA	NA	NA	NA
	Vineyards	NA	NA	NA	10	10	NA	NA
	Croplands	5	NA	NA	10	10	NA	NA
Dispersal distance (km)	30	8	8	13.5	2	3	3	
Graph estimations	Number of core areas	172	1787	1773	NA	644	188	1526
	Number of links	424	5022	4960	NA	1628	295	4125

a high cumulative cost or barriers (last decile).

The resistance maps for each of the focal species used to estimate the corridors and constraint zones with the help of circuit theory and cumulative costs were estimated using expert opinion, by calculating the median of the given values to each of the categories of the habitat map for brown hare and common toad. The landscape resistance map was constructed by assigning resistance values to each of the environments that form part of the ecological matrix for each focal species according to the experts' replies. For each target species, the map of the landscape resistance was defined using values on a scale of 1: Low resistance to 100: High resistance. A NoData value (infinite resistance) was assigned to impassable barriers represented by buildings and highways only. These spatial analyses were carried out using the *ArcGISPro V.2.9.3 ModelBuilder* tool. The resistance map was constructed with the same resolution and extent as the priority habitats map (Resolution: 5 m, Number of pixels ~ 240 millions). In the case of red deer and roe deer, we used the habitat resistance model proposed by Urbina et al. (2023) for the same region. A buffer zone was built around buildings which are completely impermeable to prevent the presence of corridors and constrained areas in the dense urban area. We estimated the buffer size per focal species with the help of experts during the validation stage (see the next section), by considering the minimal distance needed to avoid corridors and constrained zones passing through habitat of poor quality unlikely in use (Rudnick et al., 2012).

2.4. Models validation

Model validation consisted of a series of expert examinations of each of our models by the group of available local field biologists and rangers (N = 4) familiarised with the population monitoring of focal species (Table 2). These assessments were carried out for each focal species and for the model parameters indicated in Table 2. As the aim was to determine the models' ability to show the areas used by the animals according to the field experience of the panel of experts, the sessions were repeated until the readjusted models were in line with the experts' field observations (Table 2). We applied a sequence of four stages in order to obtain models validated by the experts: (1) Making the models available, (2) Evaluation workshops, (3) Re-calculation of the models and (4) Validation. For this validation session, we made the landscape graph, pinch-points and cumulative cost models available using a web map prepared in ArcGis Online via *ArcGIS Pro 2.9.3* (Yao, 2022). In this way, the experts were able to consult the models two weeks before the evaluation. We also provided two explanatory notes to help the experts

read the maps and to summarize the results and methods used. The same procedure was applied for each of the model recalculation iterations. During the evaluation workshops, the models were adjusted by visual inspection of the maps classified into deciles. If the areas used by the animals for their movements known to the experts were classified in the highest deciles of current density (pinch-points) and in the lowest deciles of cumulative cost (least cumulative cost), the model was judged to be consistent with the knowledge of the local experts. In total, the models had to be adjusted between two and three times (Table 2).

2.5. Spatial prioritization

To help the GI definition and cartography process, the three intermediate results, namely core areas, cumulative costs and connectivity pinch-points, were combined in a single map using a spatial process implemented in *Arcgis Pro 2.9.3* (Yao, 2022). In this tool, datasets are standardized using transformation functions and then added together, generating a single spatial priority map on a scale from 1 (high priority, last decile) to 10 (low priority: first decile). Regions that cannot be crossed by animals during movement were classified as impassable (value = 0).

3. Results

3.1. Connectivity models

The estimated number of potential core areas for each of the target species are shown in Table 3. The expert replies and recommendations made during the workshops led to considering the core areas as a mix of several habitat types for the different target species considered, as set out in Table 3 (for more details on the responses, see B).

Two evaluation sessions with the experts were needed to adjust the model of core areas for roe deer, brown hare and common toad as we shown in Table 3.

Core areas for roe deer were defined on the basis of the estimates made for red deer in the work of Urbina et al. (2023). The first evaluation consisted in a reduction of the number of priority habitats and the minimum size of patches (in relation to core areas for red deer), to include only the deciduous and coniferous forest of 1.7 ha or more (Table 3). The number of nodal zones was reduced for roe deer during the second evaluation. After examination, one of the experts advised us to remove fourteen nodal zones because they were considered to be non-optimal given their location in the urban area (Table 3).

Table 4

Resistance sets validated by expert knowledge for red deer, roe deer, brown hare and common toad.

Habitat class	Red deer and Roe deer		Brown hare		Common Toad		First evaluation	Validated value
	Experimental value (Urbina et al., 2023)	Validated value	Median value (surveys)	First evaluation	Validated value	Median value (surveys)		
Lakes	NA	Impassable	Impassable	Impassable	Impassable	90	Impassable	Impassable
Ponds	30	30	50	50	70	1	1	1
Rivers	7	7	50	50	70	65	Impassable	Impassable
Small rivers	5	5	20	20	50	20	20	20
Wetlands	1	1	40	40	40	1	1	1
Alluvium and rock debris	NA	7	20	20	20	1	1	1
Cliffs	NA	Impassable	45	45	70	Impassable	Impassable	Impassable
Grasslands	1	1	1	1	1	1	1	1
Moorlands	1	1	18	18	18	6	6	6
Disturbed tree vegetation	3	3	17	17	17	2	2	2
Hardwood forest	1	1	33	33	33	1	1	1
Coniferous forest	1	1	20	20	33	1	1	1
Orchards	3	3	11	11	11	2	2	10
Vines	6	6	1	1	1	2	2	10
Croplands	1	1	1	1	1	38	38	20
Highways	100	Impassable	Impassable	Impassable	Impassable	Impassable	Impassable	Impassable
Roads	32	32	80	80	80	50	50	50
Paths	6	6	1	1	40	18	18	3
Railways	6	20	10	10	80	75	75	75
Urban vegetation	41	41	20	20	40	5	5	5
Buildings	92	Impassable	Impassable	Impassable	Impassable	Impassable	Impassable	Impassable
Other paved surfaces	70	70	33	100	100	Impassable	Impassable	Impassable
Gravel quarries	NA	30	NA	70	70	NA	100	100

Regarding the common toad, core areas were firstly estimated as units composed by ponds and wetlands larger than 100 m² with deciduous forest patches larger than 200 m² adjacent to ponds (Table 3). After the first evaluation, the experts consulted recommended to change the priority habitat map for the common toad to the use of a more precise map at the scale of the Canton of Geneva (SIPV, 2020). In addition, the structure of the core areas was adjusted to highlight a higher quantity of ponds and forest patches in the area (Table 3). The minimum surface area of ponds was then reduced to 25 m², and the deciduous and coniferous forest patches that were at a distance of less than the migration distance measured from the ponds and wetlands were added (Table 3).

The maps of landscape graphs for each of focal species obtained by the validated parameters shown in Table 3 can be consulted in C. Considering graphic links, those crossing principal natural barriers such as Lake Geneva were eliminated in all cases; and for the common toad, links crossing the main rivers (the Rhône and the Arve) were also eliminated. For roe deer the reduction of the number of core areas proposed by experts resulted in the elimination of 62 additional links (Table 3).

The sets of resistances (*R*) estimated and adjusted by the experts for each of the species considered are shown in Table 4. These resistances (validated by the experts for each focal species) vary between the target species. The resistance models were adjusted once for the red deer and twice for the other target species (Table 4).

In the case of the red deer, it was necessary to increase the barrier effect of the highways and buildings as compared with the resistance assigned by Urbina et al. (2023). This is because motorways are completely fenced off in the study area and they represent an impassable barrier to movement as also buildings. The expert opinion also made it possible to assign resistance values to habitats that could not be evaluated in our former publication Urbina et al. (2023), because they were absent from the home range of the monitored individuals as shown in Table 4.

In the case of the brown hare, we had to increase the resistance of other paved surfaces from *R* = 33 to *R* = 100, in order to reduce the overestimation of cumulative costs and pinch-points of connectivity in

urban areas. Even though the paths were not considered to be obstacles to the brown hare, their resistance was increased from *R* = 18 (median of values attributed by the experts surveyed) to *R* = 40. This value was estimated on the basis of the resistance value of natural habitats which are crossed by paths and which would be more or less equally favourable to brown hare movements, such as forests (*R* = 33) and wetlands (*R* = 40).

Considering the common toad, the resistance of Lake Geneva and the Rhône and Arve rivers has been increased to "impassable", since they are perceived as natural barriers to the movement of this species. In addition, the resistance of orchards and vineyards has been increased and that of crops reduced. This was done to reduce the importance for the common toad movements of the vineyard regions; and increase that of the region of arable crops. We also added landscape elements, such as a wide strip of fifteen meters around Lake Geneva, with the aim to assign a high permeability to the lakeshore (*R* = 1). Finally, the A1 motorway viaduct, located at the level of the Versoix river (see the Fig. 1), had to be digitized, as this element represents a potential passage under the motorway for the common toad.

During the validation stage, the buffer size used to prevent the emergence of unlikely corridors and constraint zones passing through low quality habitats was estimated for each species, and solely to avoid their emergence on roads inside dense urban areas. For this and with the help of experts, we set these values for red deer and brown hare at 50 m, for roe deer at 20 m and for common toad at 10 m.

Finally, the maps of connectivity pinch-points and cumulative costs obtained with the help of the validated landscape graphs and resistance sets can be also consulted in C.

3.2. The priority areas for ecological connectivity

As shown in the ecological connectivity priority maps of Figs. 3–6, the priority areas for the ecological connectivity of the target species are represented in a gradient between 1: High priority (last decile, in red) and 10: Low priority (first decile, in blue). At the scale of Greater Geneva, we obtained a map of priority areas for red deer, roe deer and brown hare (Fig. 3). For common toad, we obtained only a map at the

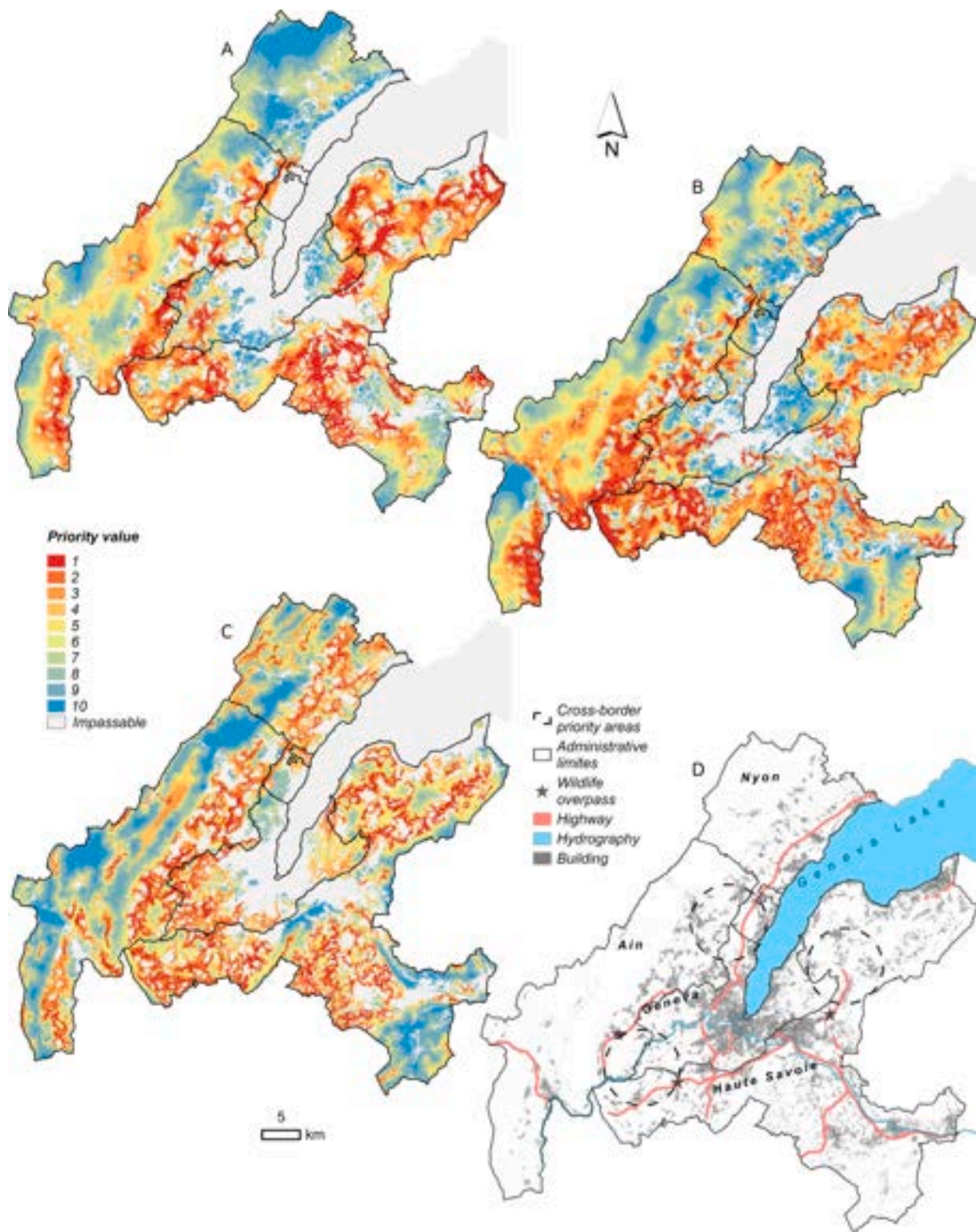


Fig. 3. Ecological connectivity priority maps at the scale of Greater Geneva. A. Red deer. B. Roe deer. C. Brown hare D. The principal cross-border priority areas (dashed black circles) and barriers to movement (pink lines and gray polygons). Three cross-border corridors were identified across Greater Geneva, around the areas encompassed by the dashed black circles.

scale of the Canton of Geneva (Fig. 4).

At the scale of Greater Geneva, it was estimated that the high priority areas to promote connectivity are located in the peripheral areas of the Canton of Geneva for the three studied species at this scale (see areas corresponding to priority levels 1 to 4 in the maps of the Fig. 3, warm colours), principally because the principal cores areas in terms of size

are located in this peripheral area. Moreover, the regional ecological connectivity is hindered by natural barriers, mainly Lake Geneva; and by anthropogenic barriers such as highways and the high density of buildings and roads, especially in the City of Geneva (Fig. 3).

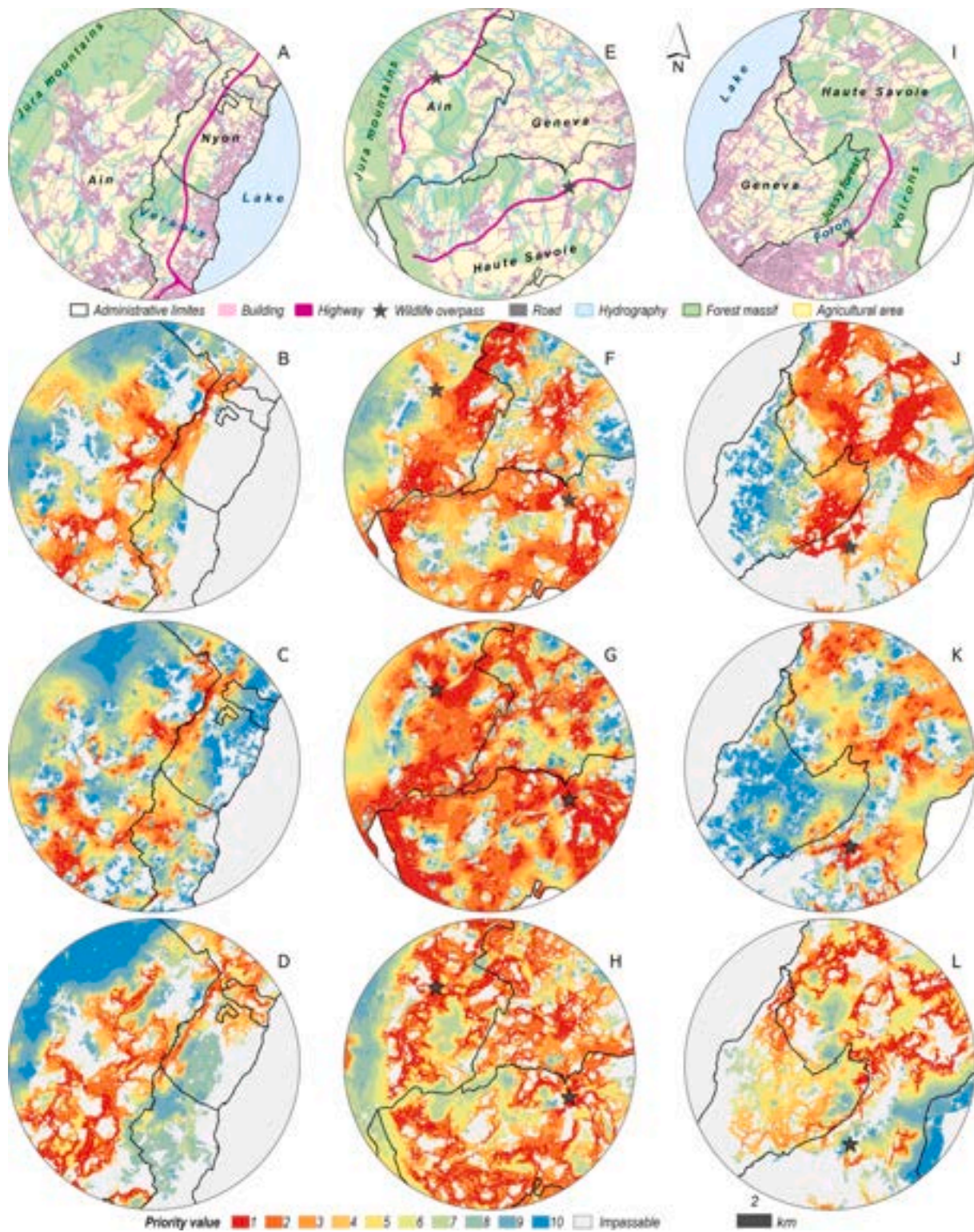


Fig. 4. Details on the three main cross-border priority areas. A: The location of the first transboundary priority area. The estimated high priority areas at the level of the first cross-border priority area for red deer (B), roe deer (C) and brown hare (D). E: The localization of the second transboundary priority area. The estimated high priority areas estimated at the level of the second cross-border priority area for red deer (F), roe deer (G) and brown hare (H). I: The localization of the third transboundary priority area. The high priority areas estimated at the level of the third cross-border priority area for red deer (F), roe deer (G) and brown hare (H).

3.2.1. Cross border priority areas

At the regional scale, we were able to identify three high-priority transboundary areas promoting the connectivity for red deer and brown hare, between the French departments of Ain and Haute Savoie and the Swiss cantons of Geneva and Vaud, as shown in Fig. 3D

(priority levels 1 to 4, warm colours). In these places, located around the dashed black circles illustrated in Fig. 3D, it is possible to observe that the size, shape and level of priority depend on the species concerned, as is shown in more details in Fig. 4.

The first cross border priority area is located towards the north-west

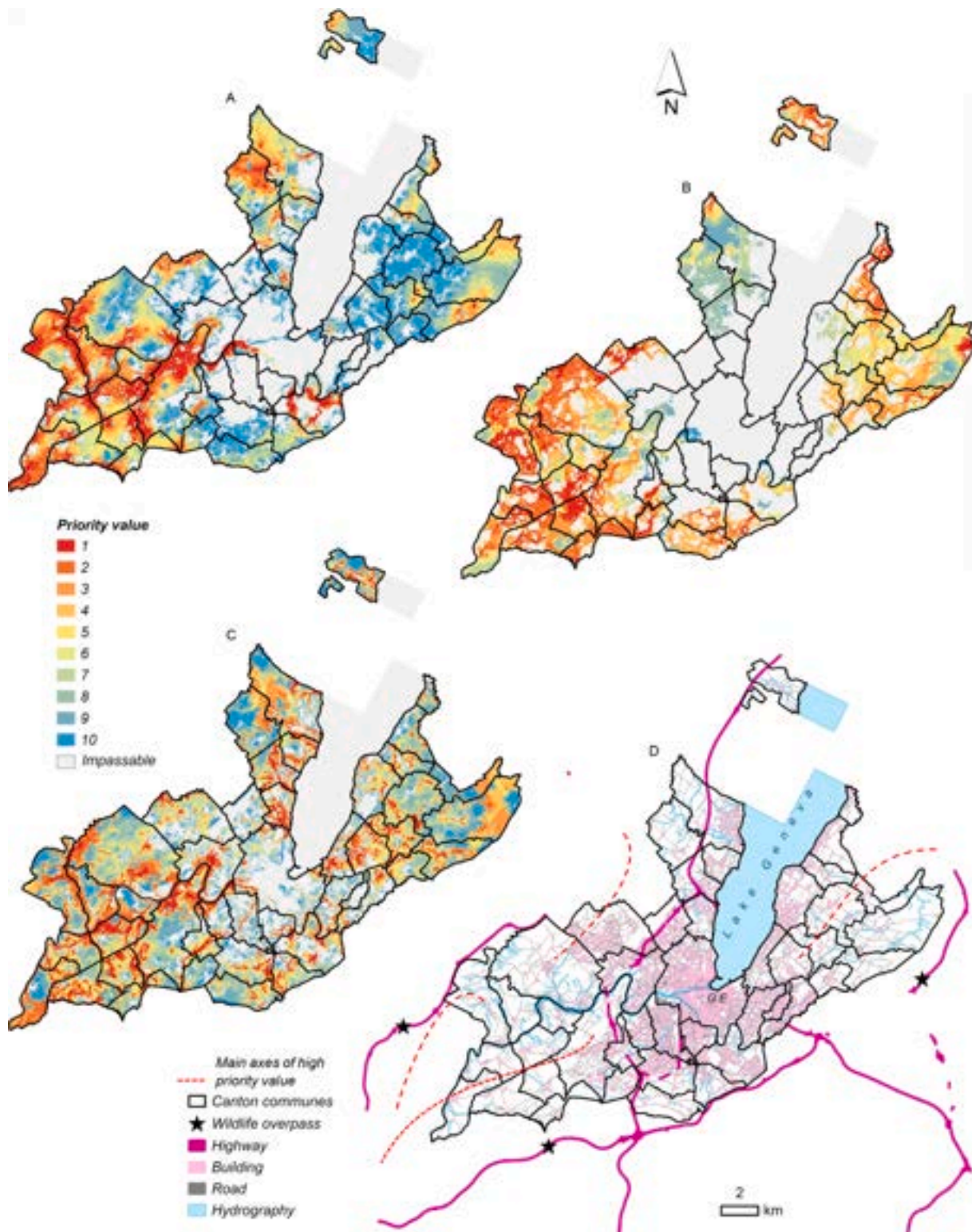


Fig. 5. Connectivity models at the scale of the Canton of Geneva. A. Roe deer. B. Brown hare. C. Common toad. D. The four principal axes of high priority values and barriers to movement at the scale of the Canton of Geneva. The result for red deer has been omitted in this figure because the priority regions are mainly outside the Canton of Geneva, and at cantonal scale it is more appropriate to use the roe deer as a representative species of the continuum of forest environments.

of the conurbation, around the Versoix river (Fig. 4A), between the department of Ain and the cantons of Geneva and Vaud (District of Nyon). The priority map of ungulates showed that this area is characterized by high priority patches mainly connecting the forest massif of the Jura Mountains with the forest massifs located along the Versoix river, through the agricultural lands (Figs. 4B and 4C, respectively).

Corridors for the red deer appear to be more constrained than for the roe deer, because we used a bigger buffer to represent the barrier effect of the buildings than for red deer. Furthermore, with the core areas being smaller they are more numerous and the ecological network is characterised by more numerous and shorter links than for red deer (For more details see the C, Figs. C.16A and C.16B, respectively). For the brown

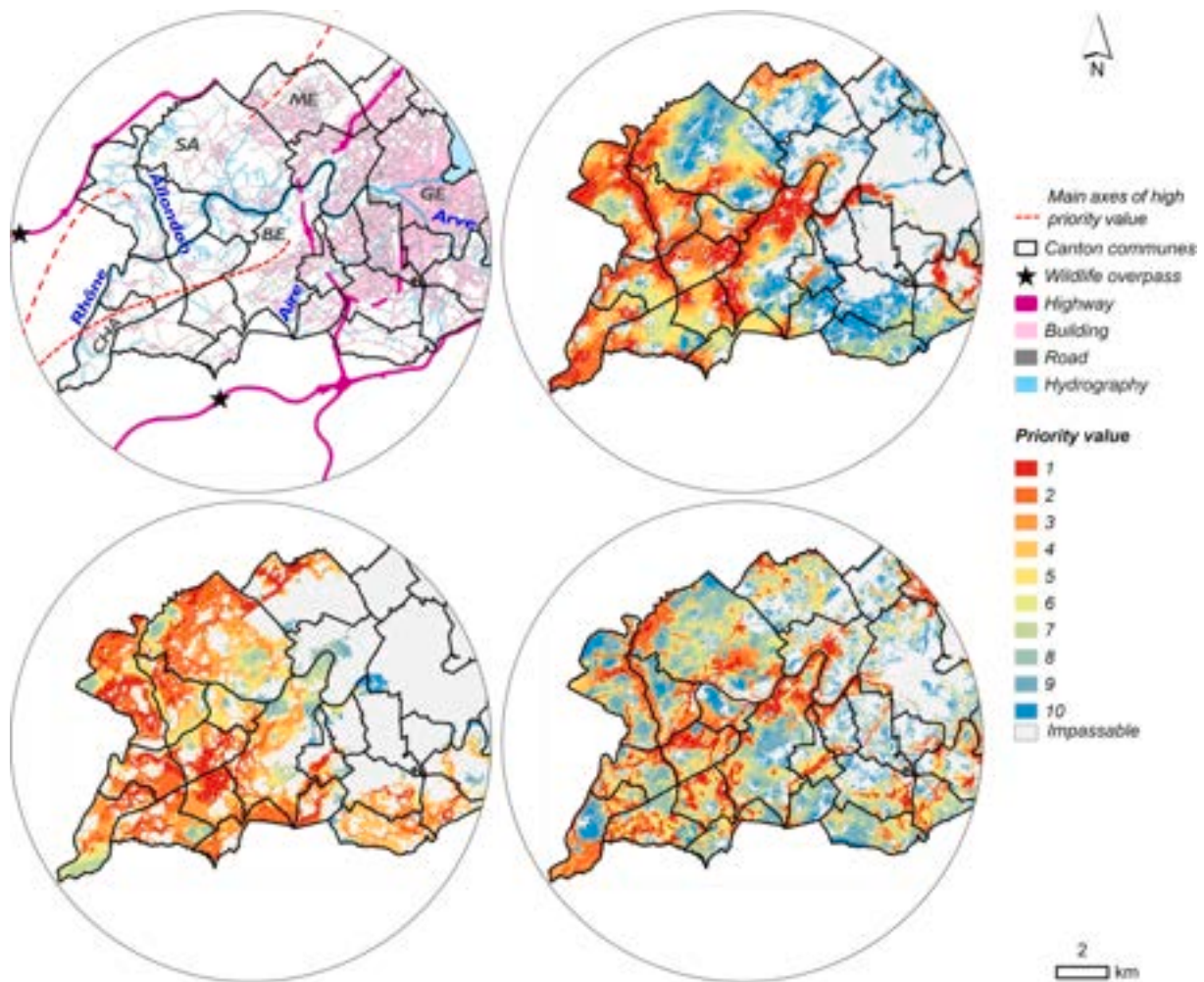


Fig. 6. Details on the three principal axes of high priority areas connecting the western part of the Canton of Geneva with the transboundary high priority areas. A: The location of the cantonal axes connecting the transboundary area with the canton of Geneva (ME: Meyrin, SA: Satigny, CHA: Chancy, BE: Bernex, GE: City of Geneva). The estimated high priority areas at the level of these three axes for roe deer (B), for brown hare (C) and for common toad (D).

here, the open areas surrounding the forests of the Jura Mountains and along the Versoix river represent an important area connecting the Canton of Vaud (District of Nyon) and the Department of Ain with the extreme northwestern part of the Canton of Geneva (Fig. 4D). The main priority areas for the brown hare are located in the region of arable lands in the lowlands. The cumulative costs are low in these areas, and high priority areas for brown hare depend highly on the localization of pinch points of connectivity (for more details see the C, Figs. C.17B and C.17C, respectively). For these three species, the main barrier to connect the priority areas with those located near to Lake Geneva is the highway crossing in this area (Fig. 4A). Although an ecological network is estimated to be near the lake in the case of roe deer (Fig. 4A) and brown hare (Fig. 4D), this network is completely disconnected with the high priority areas at the other side of the highway.

To the extreme southwest of Greater Geneva lies a second cross-border connection between the department of Ain and the department of Haute Savoie with the Canton of Geneva (Fig. 4E). In both cases, the ecological connectivity is possible thanks to the absence of fenced highways (Fig. 4E). Animals are then able to move in a west-east axis along both shores of the Rhône River. For ungulates, this is the only place where it is possible to promote movement from the Jura Mountains to the forested areas of the lowlands (Figs. 4F and 4G). For the brown hare, this area represents an important corridor between the open lands of the lowlands of the French part of the agglomeration with the Canton of Geneva (Fig. 4G). This cross-border ecological connectivity

could also be promoted by the recent construction of the wildlife overpasses for ungulates (Fig. 4G) and brown hare (Fig. 4H).

To the northeast of the agglomeration (Fig. 4I), it is estimated that the main high priority area between the department of Haute Savoie and the Canton of Geneva is located around the Jussy forest (Fig. 4I). This connection is also allowed because the motorway crossing this area, which fragments the department of Haute Savoie with the Canton of Geneva, comes to an end. As in the previous case, the ecological connectivity of this area could benefit from the recent construction of a wildlife overpass. For ungulates, (Figs. 4J and 4K), the Haute Savoie department is connected to the Canton of Geneva by three axes surrounding the fenced highway to finally reach the Jussy forest. The first arrives along the lake and the second, near the fenced highway. The third axis reaches the Canton of Geneva by the south, thanks to the wildlife overpass and the high priority areas located along the forested and agricultural areas along the Foron river. For the brown hare (Fig. 4J), this transboundary area corresponds to a series of larger agricultural core areas surrounding the large forest of the region (for more details on the position of core areas see the C). Here, the Haute Savoie department is connected to the north-eastern part of the Canton of Geneva via two main axes. One reaches the Canton of Geneva through the agricultural lands close to Lake Geneva and the other, through the end of the highway around the Jussy forest. The ecological connectivity for brown hare in this transboundary area is less influenced by the wildlife overpass than in the case of ungulates.

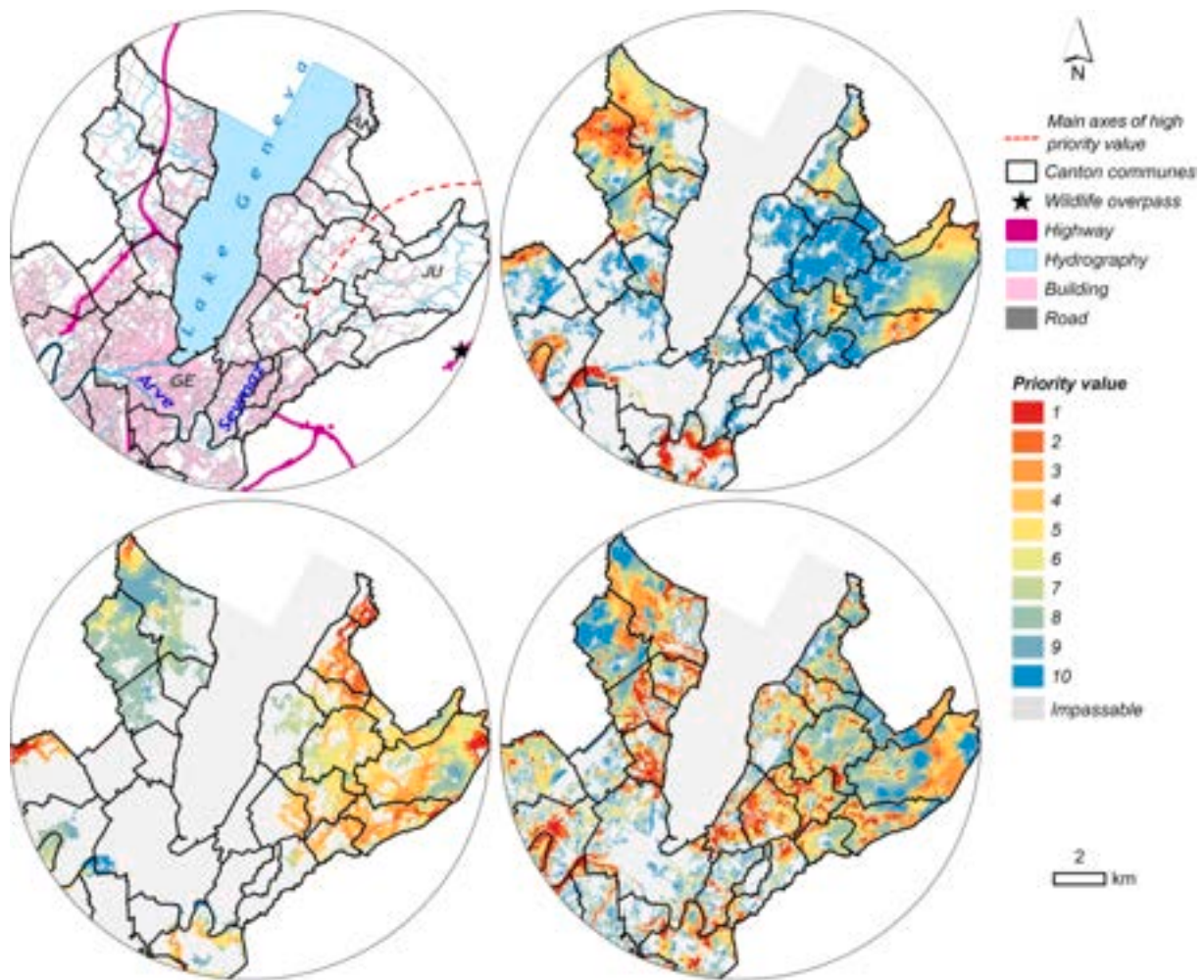


Fig. 7. Details on the fourth principal axis of high priority areas connecting the north-eastern part of the Canton of Geneva with the transboundary high priority areas of the French Department of Haute Savoie (AN: Anieres, JU: Jussy, GE: City of Geneva). A: The location of the fourth axis. The estimated high priority areas at the level of these fourth axis for roe deer (B), for brown hare (C) and for common toad (D).

3.2.2. Cantonal priority areas

At the scale of the Canton of Geneva, most high priority areas are located in the peripheral areas, as the City of Geneva and Lake Geneva are important barriers for the three species studied at this scale: roe deer, brown hare and common toad (Figs. 5A, 5B and 5C, respectively). The maps principally highlight four axes of high priority areas important to connect the cantonal priority areas with the transboundary priority areas for these three species (Fig. 5D).

Figs. 6 and 7 show in detail the main axes of priority areas at the scale of the Canton of Geneva. For roe deer, the high priority area of the northwestern part of the Canton has the potential to connect the first transboundary priority areas with the core areas located in the communes of Meyrin and Satigny, but this connectivity is restricted due to the high density of human settlements and roads (Fig. 6A). For brown hare, the corridors located in this area are more constrained by human infrastructures (Fig. 6B) as is possible to see also in the map of connectivity pinch-points (see the C Fig. C.16B). For common toad this priority area is characterized by a series of core areas with a high value of priority (Fig. 6C) connected by moderate values of priority as for roe deer (Fig. 6A).

The second transboundary high priority region could be extended eastwards around the second and third main axes showed in Fig. 6A, following a series of high priority areas allowing it to connect with the lowlands of the western part of the Canton of Geneva (Fig. 6A). For roe deer, the second transboundary high priority region could be extended

eastwards through the Allondon Valley and the Rhône River and up to the Satigny commune, following a series of core areas allowing the connection with the lowlands of the Canton of Geneva (Fig. 6A) Along the Rhone river, there is also an important corridor that favors the east–west connectivity for roe deer (Fig. 6B). For brown hare the high priority areas located in the agricultural lands are constrained naturally by the Allondon Valley (Fig. 6B). For common toad, the Allondon Valley represents a high-priority area, as with roe deer, which in turn could be connected with the core areas situated along the Rhône riverbank toward the City of Geneva (Fig. 6C).

Around the cantonal third axis of high priority areas, ecological connectivity could be promoted across the agricultural lands of the Canton of Geneva for roe deer, to link with the core areas of Chancy and with those located along the Rhône River and closer to the City of Geneva (Fig. 6A). Although this passage is favoured by the agricultural area, it is highly hindered by the roads and urban areas that fragment the agricultural mosaic of this region. For brown hare, this axis is formed by numerous agricultural core areas (for more details see the C Fig. C.17A) linked by corridors reaching the commune of Bernex from Chancy and constrained principally by human settlements and roads (Fig. 6B). And for common toad, the banks of the Rhône River are connected with core areas located to the south by several north–south axes of high-priority areas, highlighting the importance of a network of wetlands and forested core areas that are interconnected through this agricultural zone (Fig. 6C). We can also mention the high importance of areas



Fig. B.8. Frequency of the votes about the composition of the habitat and the ecological matrix for brown hare ($N = 4$). If the number of votes given by the experts to a habitat (vertical axis) was more than two, then we considered it as a component of the core area or the ecological matrix, respectively (horizontal axis).

connecting the banks of the Arve river with the core areas located toward the south of the Canton of Geneva thanks to a series of north–south corridors for common toad (Fig. 6C). In this area Rhône River represents a completely natural barrier for the cantonal north–south connectivity of common toad.

As for the last transboundary high-priority area linking the northeast of the Canton of Geneva with the department of Haute Savoie, it would partially extend towards the communes of Anières and Jussy to reach the peripheral area of the City of Geneva (Fig. 7A). In the case of roe deer (Fig. 7B), although some nodal zones located towards the interior of the canton could be connected to this latter transboundary area, the

cumulative costs are too high to promote connectivity towards the interior of the Canton of Geneva for this last species (see the C, Fig. C.16F). Towards the northeast of the Canton, the priority areas for brown hare exhibited lower values of priority (Fig. 7B) representing an area of low cost (For more details see the C, Fig. C.17C). Finally, a dense area of high priority zones is estimated in the northeastern part of the Canton of Geneva for common toad, which would represent a high potential for connectivity trough this agricultural and forested region with the City of Geneva (Fig. 7D). A high priority is also estimated for common toad in areas located along the shores of Lake Geneva and along the Seymaz River (Fig. 7D).



Fig. B.9. Frequency of the votes about the composition of the habitat and the ecological matrix for common toad ($N = 4$). If the number of votes given by the experts to a habitat (vertical axis) was more than two, then we considered it as a component of the core area or the ecological matrix, respectively (horizontal axis).

4. Discussions

The approach developed in this work enabled us to provide a structured decision-support tool for managers, allowing them to visualize the position, width and level of vulnerability of existing core areas, biological corridors and constraint zones. When informing a process of defining and mapping GI, it is desirable to provide spatially explicit models of the priority value of potential areas that would favor the movement of several species (Beier et al., 2008; Keeley et al., 2021; Wood et al., 2022). In our case, the models obtained will provide managers with functional connectivity maps on a regional scale, because they are based in the habitat requirements and dispersal distances of

several focal species, which is desired when informing the spatial process of the definition GI (Honeck et al., 2020). Moreover, the accuracy of the resultants maps allows diagnosis on a local scale, which is necessary to guide and undertake preservation or restoration measures. To facilitate the integration of ecological connectivity into the GI, we have developed ecological connectivity priority maps classified into deciles. This will facilitate estimating and visualizing the percentage of connectivity priority values for wildlife focal species that will be effectively integrated in the GI, across both the Canton of Geneva and the Greater Geneva agglomeration. The next step is therefore to integrate our results with the other pillars of the GI to implement its identification and mapping in a specialized spatial prioritization software, as proposed for

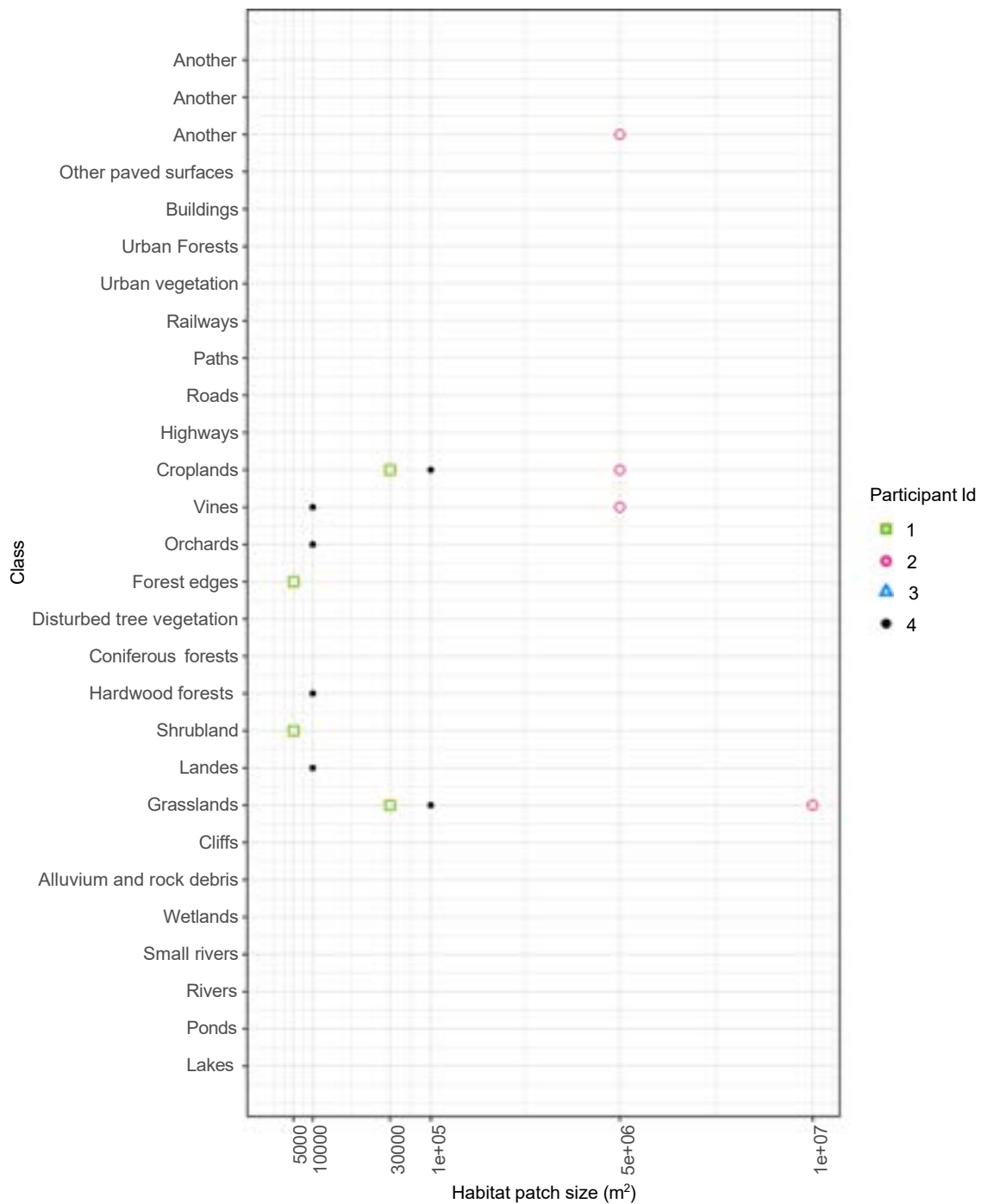


Fig. B.10. Values of minimal patch sizes given for experts (N = 4) to the habitats selected as a component of a core area for brown hare.

the region by Honeck et al. (2020) and (Sanguet et al., 2023).

By using three different connectivity modelling techniques, we provided managers with a tool capable of estimating ecological connectivity in a real conservation planning context, for several species well-known by local experts and using scientifically validated methods, which is essential when mapping the GI (Honeck et al., 2020). We incorporated graph theory, as it enables the visualization and analysis of extensive and complex ecological networks (Urban and Keitt, 2001). The use of circuit theory and cumulative costs allowed to incorporate both biological corridors and constraint zones that animals might use during directed movements (McClure et al., 2016), as well as passages that they might use during dispersal movements (McRae et al., 2008; Dickson et al., 2019). Thanks to the combination of the resulting maps of core

areas, connectivity pinch-points and cumulative costs we were able to identify three cross-border high priority areas highlighting the importance of preserving and revitalizing these areas. We were able to show besides how these transboundary corridors are crucial for animals to be able to reach the Canton of Geneva. The localisation of these priority areas closely depends on the continuum of natural habitats (forest, grasslands and freshwater habitats); connectivity that depends also on the continuum of agricultural lands, in this highly fragmented landscape. Fenced highways, dense urban settlements and the extensive road network impede the transboundary connectivity, and we showed the potential effect of the recent wildlife overpasses to diminish the barrier effect of highways. Together, the cross-border priority areas and the three wildlife overpasses have the potential to favor connectivity at a

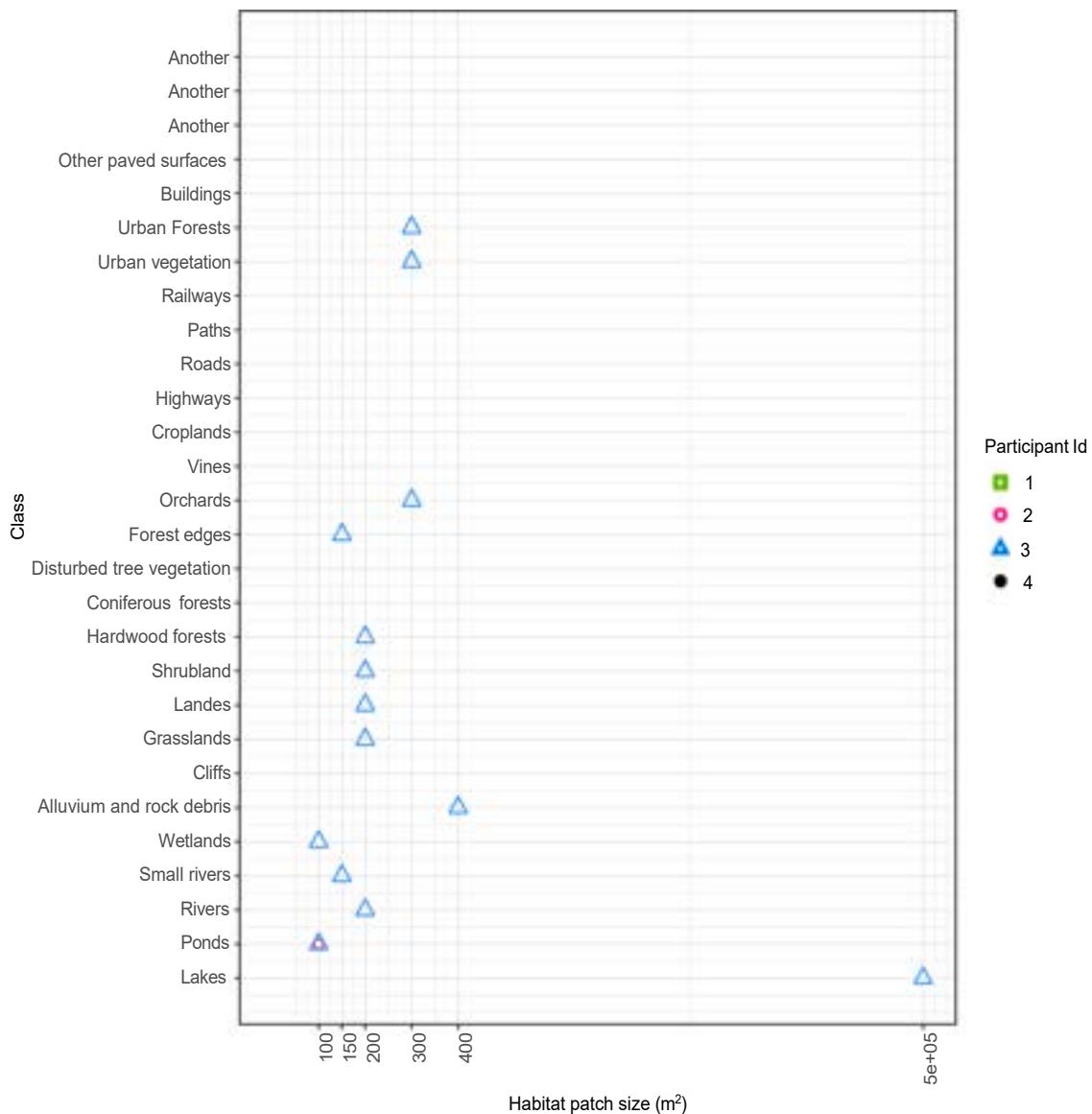


Fig. B.11. Values of minimal patch sizes given for experts (N = 4) to the habitats selected as a component of a core area for common toad.

regional scale: 1) between the Jura mountains and the lowlands of the French department of Ain and the south-west of the Canton of Geneva; 2) between the Salève Mountain and the Jura Mountains, through the lowlands of the French department of Haute Savoie and the southwestern part of the Canton of Geneva; and 3) between the Voirons mountains and the lowlands of the Haute Savoie and the northeastern part of the Canton of Geneva. For species such as the red deer, which exhibits larger displacements than the other focal groups, the protection and restoration of this transboundary core areas, corridors and constrain zones is particularly important to promote the persistence of this population over time, as we noted also in our previous work (Urbina et al., 2023).

Our results allow to spatially guide the resource allocation for the promotion of corridors at a regional scale, but the application of connectivity as a management criterion for several species must be implemented with care and with a robust control of the uncertainties that are specific to this discipline (Kool et al., 2013). One of the principal source of uncertainty of our models is related to the use of expert knowledge. The use of the knowledge from local experts gave us the opportunity to incorporate additional focal species than the red deer, the only population tracked by GPS in the area. We attempted to reduce the

uncertainties associated with the use of expert opinion in the parameterization of connectivity algorithms by adding several expertise and validation sessions of our models, using the opinion of available local experts, before being presented to managers. It should be noted that the number of experts available was too few to perform an uncertainty analysis. Previous research has shown that the use of expert opinion is generally less reliable than the use of movement data, since the recording of GPS trajectories more reliably reflect how organisms react to landscape structure during movement, thus allowing for more robust models (Abrahms et al., 2017). However, the use of expert opinion can be expected to be reliable for well-studied species (e.g. Keeley et al., 2016) or when experts have a good knowledge of the region (e.g. Doswald et al., 2007), but their adequacy will vary depending on the study and both the experience of the expert and the amount of research conducted on the focal species selected (Spear et al., 2010). Because these factors were considered in our case, as well as the fact that group of experts consulted in our study are local conservation biologists or gamekeepers familiar with the wildlife monitoring, we expect that the use of their knowledge is appropriate for the purpose of conservation planning. Because an expert knowledge-based modeling approach will continue to be used in cases where empirical data is not available (e.g.

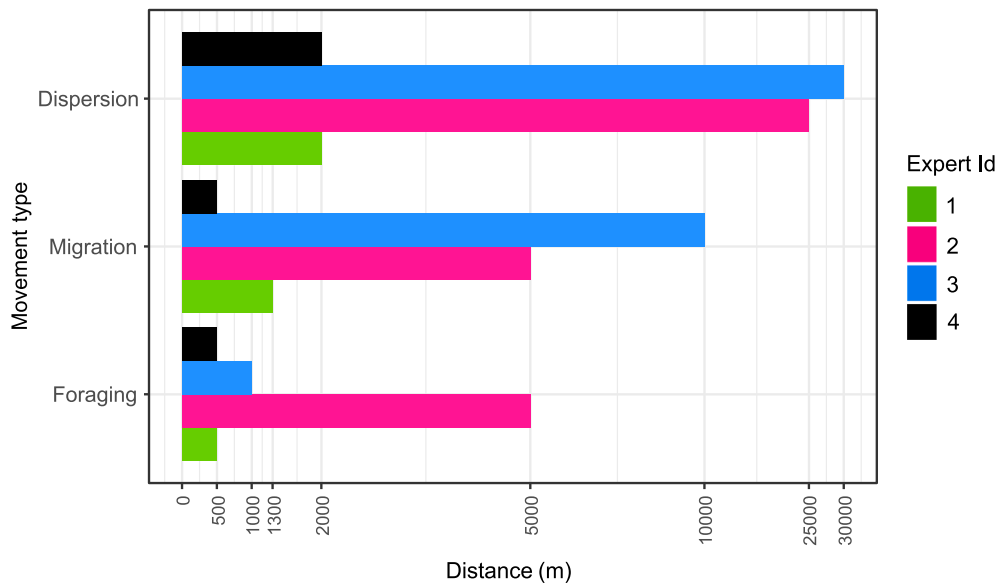


Fig. B.12. Values of maximum distance (m) movement given for experts (N = 4) to the different kinds of behaviour for brown hare.

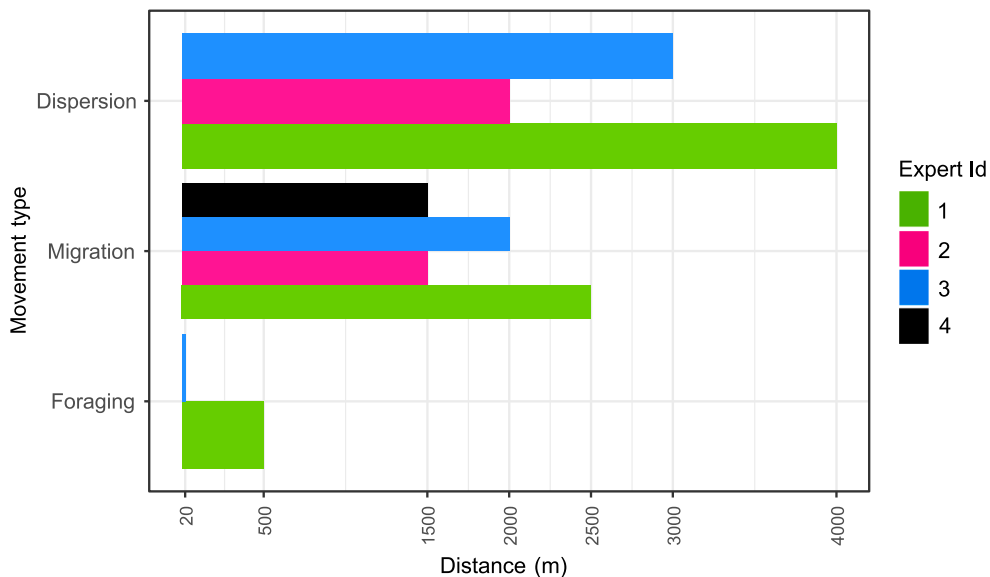


Fig. B.13. Values of maximum distance (m) movement given for experts (N = 4) to the different kinds of behaviour for common toad.

Petsas et al., 2020; Tarabon et al., 2022), to deal with this issue we suggest establishing a framework allowing for close collaboration between conservationist biologists and practitioners, ecological modelers and managers, as well as for the establishment of a structured decision-making process. A framework like this should be viewed as an iterative framework that will allow the refinement of ecological models until more appropriate data is acquired in the region, as was suggested by Kareksela et al. (2020). Moreover, Bowman et al. (2020) suggest that the results of connectivity modelling when using surface costs are more sensible to rank cost than absolute values. This findings highlights the importance to pay attention to rank cost and at the same time, facilitates the work of practitioners interested in building connectivity models for species that are well-known to local experts. On the other hand, it has also been postulated to use a habitat naturalness index in order to assess connectivity at regional scales (Beier et al., 2011; Theobald et al., 2012; Cao et al., 2020), but in any case, the real functionality of delineated corridors with this method must be tested for multiples species (e.g. Krosby et al., 2015). A connectivity model based on a species-agnostic

model can also be seen as a good alternative when no movement data are available or when subjective selection of focal species is desired to be avoided, but this methodological framework still needs to be approved at both scientific and practical levels (Wood et al., 2022).

We also observed that high priority areas can be crossed by roads, because, according to the opinion of experts, these features are not completely impermeable as fenced highways. And while we considered the resistance of the road surface to parameterize our models, it will be useful to differentiate roads in different classes according to their vehicle traffic load when this kind of data becomes available. While roe deer exhibit behavioural plasticity to adapt their movement behaviours to landscape heterogeneity and human disturbances, in highly fragmented landscapes their capacity to memorize roads is constrained by a high density of them, which ultimately diminish their capacity to access essential resources (Seigle-Ferrand et al., 2022). Moreover, previous resource selection analysis shows that during movement, the avoidance of potential sources of human disturbance is a key factor in determining the ranging behaviour of roe deer (Coulon et al., 2008) as with other

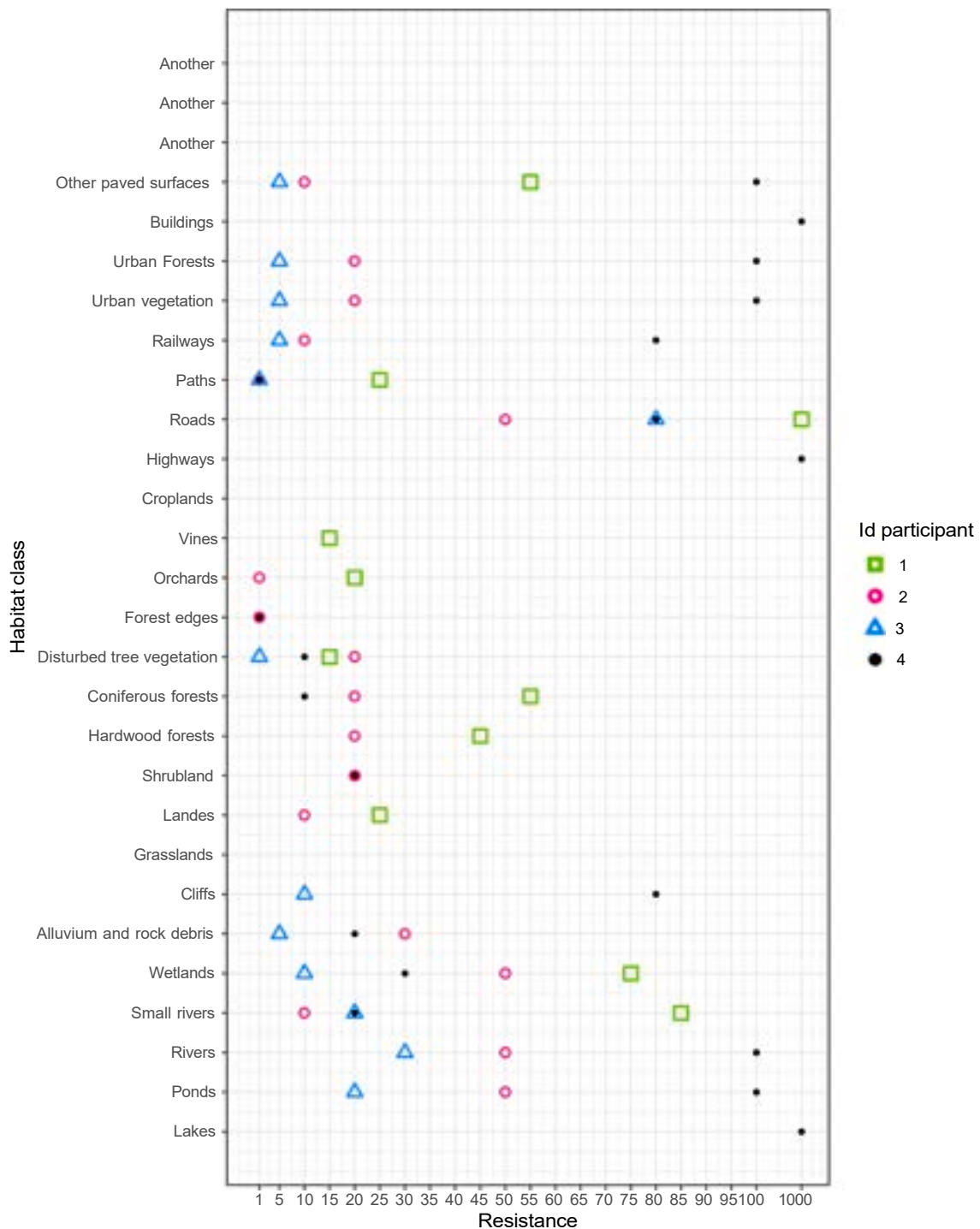


Fig. B.14. Resistances estimated by experts ($N = 4$) to principal environments composing the landscape matrix for brown hare.

ungulates (e.g. Brown et al., 2014) and other mammal groups (e.g. Shannon et al., 2014). Then, if the capacity to memorize a high density of roads is constrained for roe deer, many roads with a high vehicular traffic load will affect the capacity of priority areas to promote connectivity. Roedenbeck and Voser (2008) observed that brown hare avoid the proximity of roads and could be affected negatively by the density of roads. For pond-breeding amphibians such as the common toad, it was established that they are highly affected by road mortality during their migratory movements (Beebee, 2013). To effectively assure the functionality of the estimated priority areas it will be necessary to apply appropriate mitigation measures to reduce the barrier effect of roads.

The success of the measure will depend on whether the animals avoid the road because of its surface or noise or whether they can avoid the cars (Jaeger et al., 2005). For example, it has been shown that small mammals avoid the road surface and not the traffic noise, so measures such as overpasses or underpasses are more appropriate than measures to reduce traffic (McGregor et al., 2008).

Because it will be useful to adapt the GI to changes in landscapes (Honeck et al., 2020), it is desirable to develop a framework for assessing the effect of landscape change on ecological connectivity (Beier et al., 2008; Albert et al., 2017; Keeley et al., 2021). We have developed a tool that could help managers undertake such analyses and help them adapt

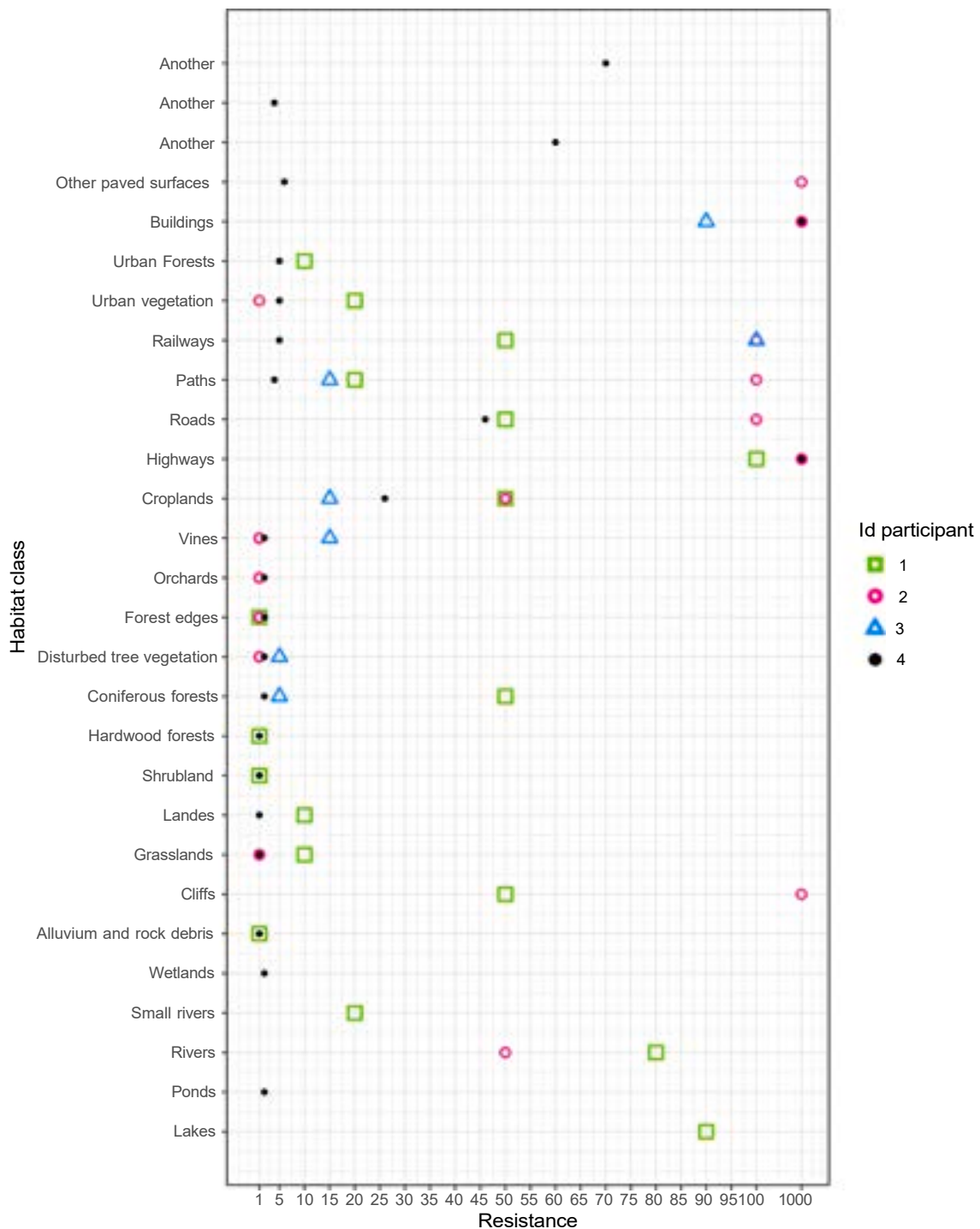


Fig. B.15. Resistances estimated by experts (N = 4) to principal environments composing the landscape matrix for common toad.

GI to landscape changes. Scenarios of land use change can be incorporated to predict the effects on connectivity of urban development projects. Using our approach, it is possible to obtain a measure of change in the landscape graph, which can then be used to re-estimate the pinch-points of connectivity and cumulative costs considering different scenarios. For example, in the case of transport infrastructure development, the theories and concepts used in this work have proved their usefulness in the literature. The electrical circuit theory has been useful in predicting impacts on the connectivity of large migratory ungulates (e.g. Fullman et al., 2021) and other mobile organisms on a regional scale (e.g. Boyle et al., 2017). The same applies to graph theory by using

Graphab software (e.g. Sahraoui et al., 2017), as well as an analysis based on the least-cost path algorithm by using UNICOR software (Landguth et al., 2012) or by using a combination of the least-cost path and graph theory (e.g. Dilts et al., 2016).

5. Conclusions

A combination of expert knowledge and different techniques of connectivity assessment was useful to estimate the value of different habitats to promote wildlife connectivity across the Greater Geneva region and the Canton of Geneva. A close collaboration between

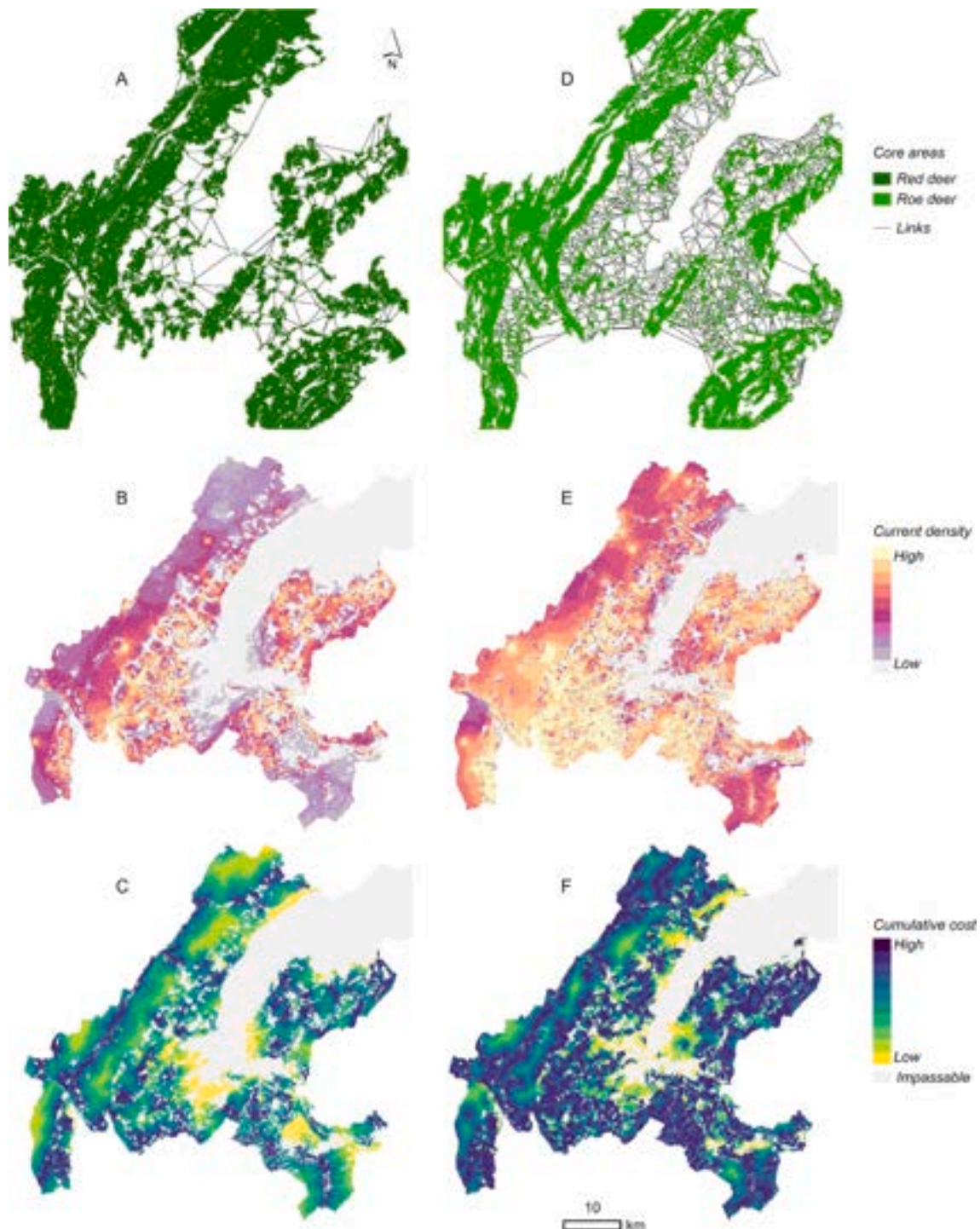


Fig. C.16. Map of landscape graphs, cumulative costs and pinch-points of connectivity for ungulates at the scale of Greater Geneva. A. Landscape graph for red deer (Urbina et al., 2023). B: Pinch-points of connectivity for red deer. C: Cumulative costs for red deer. D: Landscape graph for roe deer. E: Pinch-points of connectivity for roe deer. F: Cumulative costs for roe deer.

modellers, field biologists and local gamekeepers is necessary to parameterize the models and to provide managers with useful connectivity maps. These ecological models will be included in the general process of spatial conservation prioritization of the green infrastructure (GI) in the Greater Geneva region. When implementing the GI, the functionality of core areas and corridors identified with the ecological connectivity priority maps must be validated through field campaigns as a part of a connectivity plan, which aims at ensuring the persistence of wildlife species in the long term.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

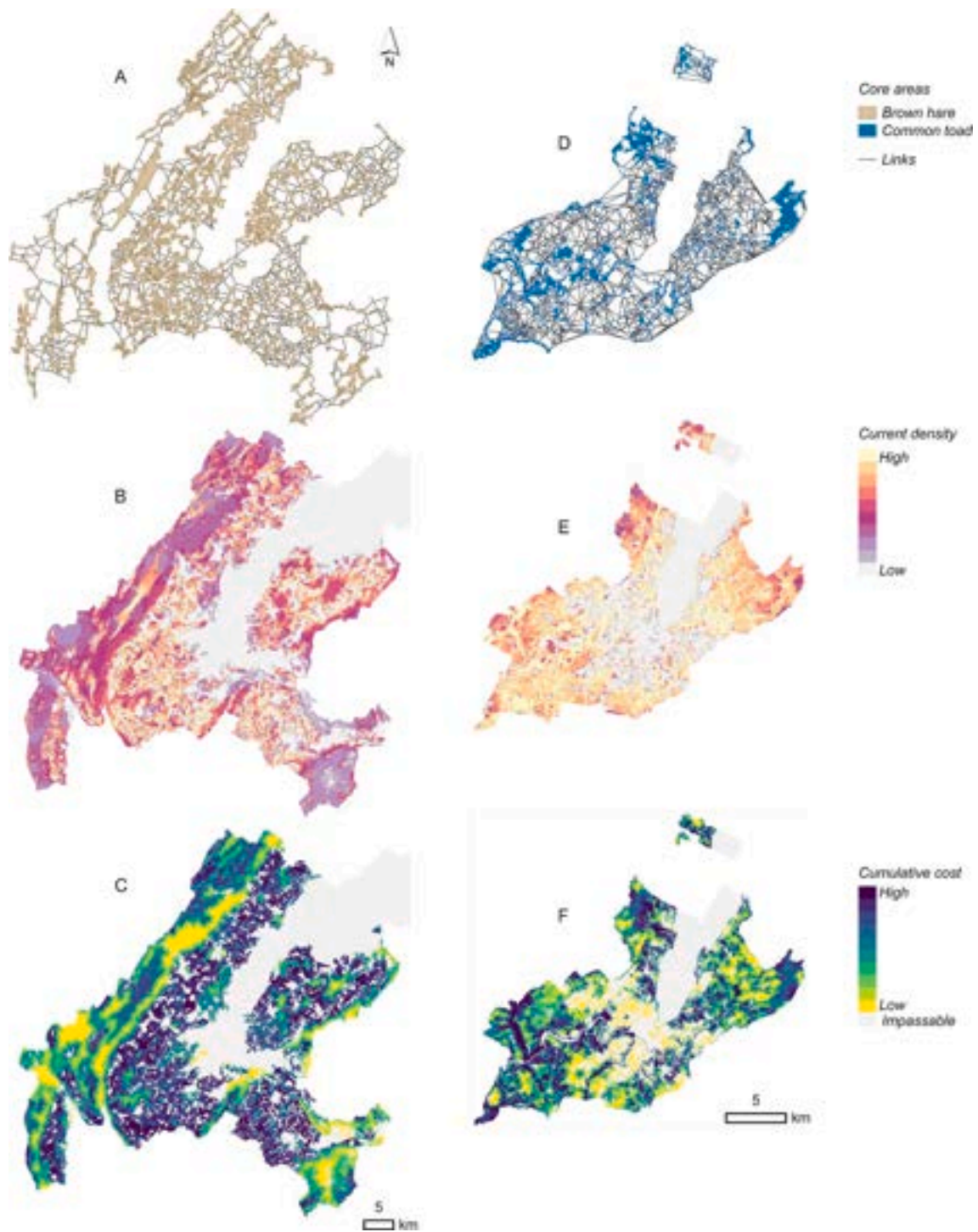


Fig. C.17. Map of landscape graphs, cumulative costs and pinch-points of connectivity for brown hare at the scale of Greater Geneva and for common toad at the scale of the Canton of Geneva. A: Landscape graph for brown hare. B: Pinch-points of connectivity for brown hare. C: Cumulative costs for brown hare. D: Landscape graph for common toad. E: Pinch-points of connectivity for common toad. F: Cumulative costs for common toad.

Appendix A. The Survey

Part I: Identification of the participant and species

1. Personal data

1.1 First name.

1.2 Last Name.

2. Please indicate the name of the species on which we have identified you as an expert:

Red deer (*Cervus elaphus* L.), Brown hare (*Lepus europaeus* P.), Red squirrel (*Sciurus vulgaris* L.), European hedgehog (*Erinaceus europaeus* L.), Horseshoe bat (*Rhinolophus hipposideros* B.), Greater horseshoe bat (*Rhinolophus ferrumequinum* S.), Common toad, (*Bufo bufo* L.), Damselfly (*Coenagrion puella* L.), Dragonfly (*Libellula depressa* L.), Great Capricorn (*Cerambyx cerdo* L.), Glanville fritillary butterfly (*Melitaea cinxia* L.).

Pat Two

1. Definition of zonal nodes (core habitats) and the ecological matrix

Please indicate the key habitats that constitute, on the one hand, the core habitats of the species in question and, on the other hand, the environments that participate in the movement matrix of the target species. In addition, you can add other land uses and ecosystems that would be important to consider and that are not listed below.

In this part of the questionnaire we ask you to identify the landscape structure of the species for which you have been contacted, according to its ecological requirements. To do this, we propose you to evaluate a list of environments in the Greater Geneva region that have been identified through work carried out by the Conservatoire et Jardin Botaniques de Genève (CJB). We call key habitats the most favourable landscape elements for the species that meets all the requirements of the species for their entire life cycle (food, breeding and shelter). Thus a zonal node (core habitat) can be constituted by a single habitat type or several, so you can check one or several types of environments.

We consider that the ecological matrix corresponds to the non-habitat part of the landscape, in which the species is likely to move. This region is not uniform or totally inhospitable, so it can be composed by different types of environments; more or less favourable to animal movements.

Lakes: Deep and large lakes (more than 10 ha)

Ponds: Freshwater environments from temporary to permanent ponds.

Rivers: This category includes the major rivers of the region, more than 2 meters wide.

Small Rivers: Category formed by small streams, less than 2 meters wide.

Wetlands: This group includes wetlands such as river shore vegetation, low marshes and wet grasslands. Shoreline vegetation are located in the immediate vicinity of the water and includes rocky or herbaceous environments. As for the low marshes, they correspond to permanently wet soil environments covered by a large grass cover. Wet grasslands are also shaped by large grasses, but are often found on the periphery of low marshes, in soils with variable moisture content.

Alluvium and rock debris: Category that includes environments formed by a dominance of the mineral substrate. Alluvial deposits are located in the direct vicinity of rivers, while rocky debris corresponds to scree surfaces that are sometimes found at the foot of cliffs.

Cliffs: Environment formed by a dominance of the mineral substrate and characterized by steep slopes that prevent soil deposition.

Grasslands: This category includes herbaceous environments that are covered by a grass cover, such as dry grasslands, extensive grasslands or high-altitude grasslands.

Moorlands: Low woody formations dominated by hardy and persistent small leaf species; often associated with thin herbaceous plants and open coniferous forests.

Shrubland: They are formed by bushes, brambles and bush willows.

Hardwood forests: Hardwood forests are dominant in the region and are mainly represented by beech and oak forests. Other types of hardwood forests can be found, such as humid forests along rivers and streams; these are characterized by the dominance of hydrophilic species (alders, willows, poplars, ash trees) and by the absence of beech.

Coniferous forests: Woodland pine forests can be found in the region; and often at higher elevations, spruce or fir forests.

Disturbed tree vegetation: This category includes various environments which are subject to maintenance or severe human disturbance; such as isolated trees, tree lines, and tree plantations.

Urban Forests: A group of trees and shrubs in urban areas. In some cases they correspond to the relics of vegetation present before urbanization.

Forest edges: Forest edge herbaceous vegetation and pre-forest vegetation.

Orchards: Orchards correspond to woody plant crops, including high stem orchards and intensive orchards.

Vineyards: This environment includes wine-growing crops as well as grass cover and spontaneous vegetation in vineyards.

Croplands: This medium includes herbaceous plant crops with a rotation period of less than one year.

Roads: In Switzerland, this category includes main and wide roads (more than 10 m), well-developed district roads (between 4.21 and 8.20 m) and secondary roads (between 2.8 and 4.20 m). In France, this category includes one-way paved roads and bike paths.

Highways: Motorways are major transit roads that are reserved for fast-motorized traffic; and are also characterized by the presence of impassable fences, including for small animals. Also, this category includes two-ways roads separated by a physical obstacle, possibly open at intersections.

Paths: Category that includes all public roads in urban and rural areas, marked hiking trails and paths. In Switzerland, the width of the roads is less than 1.81 m.

Railways: Rail transport infrastructure includes railways.

Urban vegetation: This category includes urban green spaces, such as public parks and maintained lawns and flower beds, as well as mansion gardens.

Buildings: Different types of buildings, such as residential, industrial and commercial buildings.

Other paved surfaces: Surfaces waterproofed by urbanization such as vehicle parks, airfield runway and other paved areas.

Other environments: Please provide us the name of the other(s) environment(s) that would constitute the species' key habitat or the ecological matrix and that do not appear in the list we have proposed.

2. Evaluation of landscape resistance

Here we need your help to evaluate each environment constitutes the ecological matrix of the target species in terms of resistance to movement. To do this, please give an integer value between 1 and 100 of resistance, in the corresponding box. The value 1 represents the lowest resistance and indicates ease of movement. The value 100 is equivalent to the highest resistance and denotes restricted movement. For a completely impassable environment, please note a value equal to 1000, as they represent an absolute barrier to movement.

Landscape resistance to animal movement represents the motivation of an organism to cross a particular environment, the physiological cost of moving through a particular environment, the risk of mortality for the organism crossing a particular environment, or the integration of all these factors. **3. Assessment of the patch-size of key habitats**

Do key habitat patches need to have a minimum area to support the requirements of the species during its life cycle? If so, please indicate the minimum size of the patch-area so that it can be considered a suitable patch. Please do not forget to note the unit of measurement (e.g. m^2 , km^2).

4. Measure of animal movements

We assume that in fragmented landscapes, animals can use different habitat patches depending on their movement capacities. We would like to evaluate this capacity according to the maximum distance of movement between habitat patches, while considering three types of movement related to: foraging, migration and dispersal.

Please indicate the maximum distance of movement that the species could travel between key habitat patches according to the different types of movement presented below. Please do not forget to note the unit of measurement (e.g. *m, km*).

Foraging: Daily foraging movements, between resting and feeding areas or between two feeding areas.

Migration: Movements between seasonal sectors of activity.

Dispersal: Both natal dispersal and movements during the breeding period can be considered as dispersal movements. In the first case, it is the movement of an animal from its region of origin to another region where it joins the local population, or tries to join it. In the second case, it is the dispersal movements of adults that are motivated by meeting reproductive partners.

Appendix B. Survey responses

Figs. B.8,B.9,B.10,B.11,B.12,B.13,B.14,B.15

Appendix C. Landscape graphs, pinch-points and cumulative costs

Figs. C.16,C.17

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