



HAL
open science

Assessing the strategic role of urban green spaces for habitat connectivity in multi-family residential plots

Marc Bourgeois, Thomas Boutreux, Gilles Vuidel, Paul Savary, Pauline Piot,
Arnaud Bellec, Bernard Kaufmann

► **To cite this version:**

Marc Bourgeois, Thomas Boutreux, Gilles Vuidel, Paul Savary, Pauline Piot, et al.. Assessing the strategic role of urban green spaces for habitat connectivity in multi-family residential plots. *Urban Forestry & Urban Greening*, 2024, 99, pp.128471. <10.1016/j.ufug.2024.128471>. <hal-04693393>

HAL Id: hal-04693393

<https://hal.science/hal-04693393v1>

Submitted on 12 Sep 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Assessing the strategic role of urban green spaces for habitat connectivity in multi-family residential plots

Marc Bourgeois¹, Thomas Boutreux^{1,2}, Gilles Vuidel³, Paul Savary⁴, Pauline Piot¹, Arnaud Bellec^{1,5}, Bernard Kaufmann²

¹Univ. Lyon, Université Jean Moulin Lyon 3, Environnement Ville Société, UMR 5600 CNRS, F-69007-Lyon, France

²Univ. Lyon, Université Claude Bernard Lyon 1, ENTPE, LEHNA, UMR 5023 CNRS, F-69622, Villeurbanne, France

³Université Bourgogne-Franche-Comté, ThéMA, UMR 6049 CNRS, F-25030, Besançon, France

⁴Department of Biology, Concordia University, Montreal, QC, Canada

⁵Alkante, F-35207, Noyal-sur-Vilaine, France

This is a postprint version, the definitive version of this paper is :

Bourgeois, M., Boutreux, T., Vuidel, G., Savary, P., Piot, P., Bellec, A., & Kaufmann, B. (2024). Assessing the strategic role of urban green spaces for habitat connectivity in multi-family residential plots. *Urban Forestry & Urban Greening*, 99, 128471. <https://doi.org/10.1016/j.ufug.2024.128471>

Abstract

Urban green spaces are key for maintaining and restoring habitat connectivity within cities. Despite substantial investigations on the contribution to connectivity of different types of urban green spaces, the specific contribution of green spaces located in multi-family residential (MFR) plots has yet to be assessed. Estimating this contribution is crucial given the multiple roles fulfilled by these green spaces in urban planning. To achieve this goal, we focused on four taxa: the European hedgehog (*Erinaceus europaeus*), the Red squirrel (*Sciurus vulgaris*), forest passerine birds and moths. We assessed the potential habitat connectivity for each taxon across the metropolitan urban area of Lyon (France), with landscape graphs built using 1-metre resolution land cover maps. Considering the current state as a reference, we then designed five land cover change scenarios affecting habitat distribution in the MFR plots: (i) maximum and (ii) minimum theoretical connectivity (references), (iii) improve quality of existing green spaces, (iv) improve quantity of green spaces with sub-optimal quality and, (v) maximum restoration (management scenarios). The taxon- and scenario-specific impacts highlight the crucial contribution of private spaces to habitat connectivity. For all taxa, while the MFR only cover 8% of the study area, connectivity would increase by up to 60% if these plots were greened. In contrast, sealing these plots could reduce overall connectivity by up to 40%. The interpolation of local connectivity metrics for each habitat patch and each MFR plot allowed us to identify the most relevant plots for urban greening. Because our approach can improve habitat connectivity at different scales, from neighbourhoods to entire urban areas, it could prove useful for landscape planning in most urban settings.

Keywords: habitat connectivity, landscape graphs, urban green spaces, multi-family residential plots, urban greening, urban biodiversity

Highlights:

- Urban green spaces are crucial to habitat connectivity but the contribution of green areas located in multi-family residential plots is all too often overlooked/under-appreciated.
- We modelled the habitat networks of four taxa with landscape graphs, using a 1-metre resolution land cover map.
- Five land-cover change scenarios affecting multi-family residential plots were compared: two references (maximum and minimum theoretical connectivity) and three management scenarios (improve quality of existing green spaces, improve quantity of green spaces with sub-optimal quality and maximum restoration).
- The city-level and plot-level connectivity metrics computed for each scenario and taxon highlight the key contribution to connectivity of urban green spaces included in multi-family residential plots.
- Interpolated maps of connectivity metrics can support citizen commitment and help planners prioritise (re)greening actions.

Introduction

Over half of the global human population already lives in urban areas and this proportion is expected to reach 70% by 2050 (United Nations, 2018). This trend results in an expansion of built-up areas at the expense of natural and agricultural areas associated with a densification of the cities centres and a reduction in the size of urban green spaces, isolated from fragments of natural habitat and exhibiting various design and composition. Nonetheless, these remaining urban green spaces provide a wide variety of ecosystem services such as pollution reduction (air, water, noise) (Bolund and Hunhammar, 1999), urban heat island reduction (Gill et al., 2007) or recreational opportunities (Carpenter, 2013; Chiesura, 2004). They also contribute to the desirability and value of housing (Geoghegan, 2002; Irwin, 2002). Aside from benefitting human well-being (Tzoulas et al., 2007), urban green spaces are also suitable habitats for biodiversity (Kong et al., 2010; Rudd et al., 2002). Consequently, they are key targets for urban planning and biodiversity conservation policies (Aronson et al., 2017; Lepczyk et al., 2017).

However, the contribution of urban green spaces to biodiversity depends on several factors. First, their suitability to species varies strongly depending on anthropogenic management in cities (Gaston et al., 2005; Loram et al., 2011; Teillac-Deschamps et al., 2009). Second, their availability within cities depends on the number and area of patches (Kong et al., 2010; Sandström et al., 2006). Finally, urban green spaces have to be reachable for species, which critically depends on their distribution across urban landscapes and on urban matrix permeability (Penone et al., 2012; Vergnes et al., 2012). Indeed, habitat connectivity plays an important role in maintaining ecosystems and resilience to global environmental change (Thompson and Gonzalez, 2017). Improving habitat connectivity among green spaces in urban areas is therefore a key objective of current conservation strategies.

Although it is well established that large habitat areas are essential to biodiversity, several studies highlight the role of small fragments such as urban green spaces to improve connectivity in highly fragmented environments (Beninde et al., 2015; Fahrig, 2019; Ribeiro et al., 2022). Accordingly, the connectivity of particular urban green spaces has been extensively studied, including urban parks (Melles et al., 2003), green spaces of business sites (Serret et al., 2014), green roofs (Louis-Lucas et al., 2022), small residential green spaces (Lynch, 2021), public and private gardens (App et al., 2022; Gaston et al., 2005; Mimet et al., 2020; Smith et al., 2006), school green areas (Iojă et al., 2014), or isolated trees (Von Thaden et al., 2021). However, to our knowledge, no study has focused specifically

on green spaces in multi-family residential (MFR) plots. In contrast to single-family homes, multi-family residential housing is mostly composed of flats for residential use with two types of ownership (condominiums or social housing). These buildings are built on plots varying in size and green space cover. Beyond the significant areas that MFR plots add to the overall vegetation area of some neighbourhoods or cities (Bellec, 2018), their green spaces have a strategic situation in the urban matrix. They could provide ecosystem services directly where people live. In European cities, they are mostly located at the interface between suburbs and centres (inner and outer city). In these spatially constrained areas, they come into conflict with other non-greened land uses (*e.g.*, car parks). Additionally, the dense population living within and around MFR plots reinforces the social importance of these green spaces, while putting pressure on local biodiversity. In this context, quantifying and mapping the contribution of MFR plot green spaces to connectivity is of paramount importance to sustainable urban planning.

In this study, we demonstrate the strategic contribution of green spaces located in MFR plots to the connectivity of habitat networks. To that purpose, we modelled urban ecological networks using landscape graphs (Urban and Keitt, 2001). These graph-theoretical tools have been widely used in urban settings for analysing the habitat connectivity of green spaces or the effects of urban dynamics and land cover changes on connectivity (Bourgeois and Sahraoui, 2020; Tannier et al., 2016; Tarabon et al., 2020). We here assessed habitat connectivity for four animal taxa with distinct life history traits/dispersal strategies at the scale of the metropolitan area of Lyon (France). Then, we tested the impact of five scenarios of land cover changes in MFR plots. Finally, we tested a strategic action case study with selected sites to assess their greening priority, *i.e.* which sites best improve overall connectivity at the metropolitan scale.

1. Material and methods

2.1 Study area

Our study area is the metropolitan area of Lyon (France), which counted 1,411,571 inhabitants in 2019 and spread over 538.4 km² (Figure 1). Its population density ranges from 194.4 inhabitants/km² in the most rural municipalities to 10,899 inhabitants/km² in the centre of Lyon. According to CORINE Land Cover 2018 data, 62% of the metropolitan area is made up of built-up areas, 27% of agricultural areas, 6% of forest areas and 4% of wetlands or water areas.

To avoid edge effects in the connectivity analyses, we applied a 1 km buffer around the metropolitan area. This is the maximum distance for which high resolution vegetation data were available (see below). We also removed four municipalities from the study area to keep the final study area (491.3 km²) as compact as possible, which is preferable for studying ecological processes (Figure 1A). We focused specifically on the green spaces located in multi-family residential plots (MFR plots). Therefore, we identified 1) the plots associated with MFR dwellings and 2) the green spaces included in these plots.

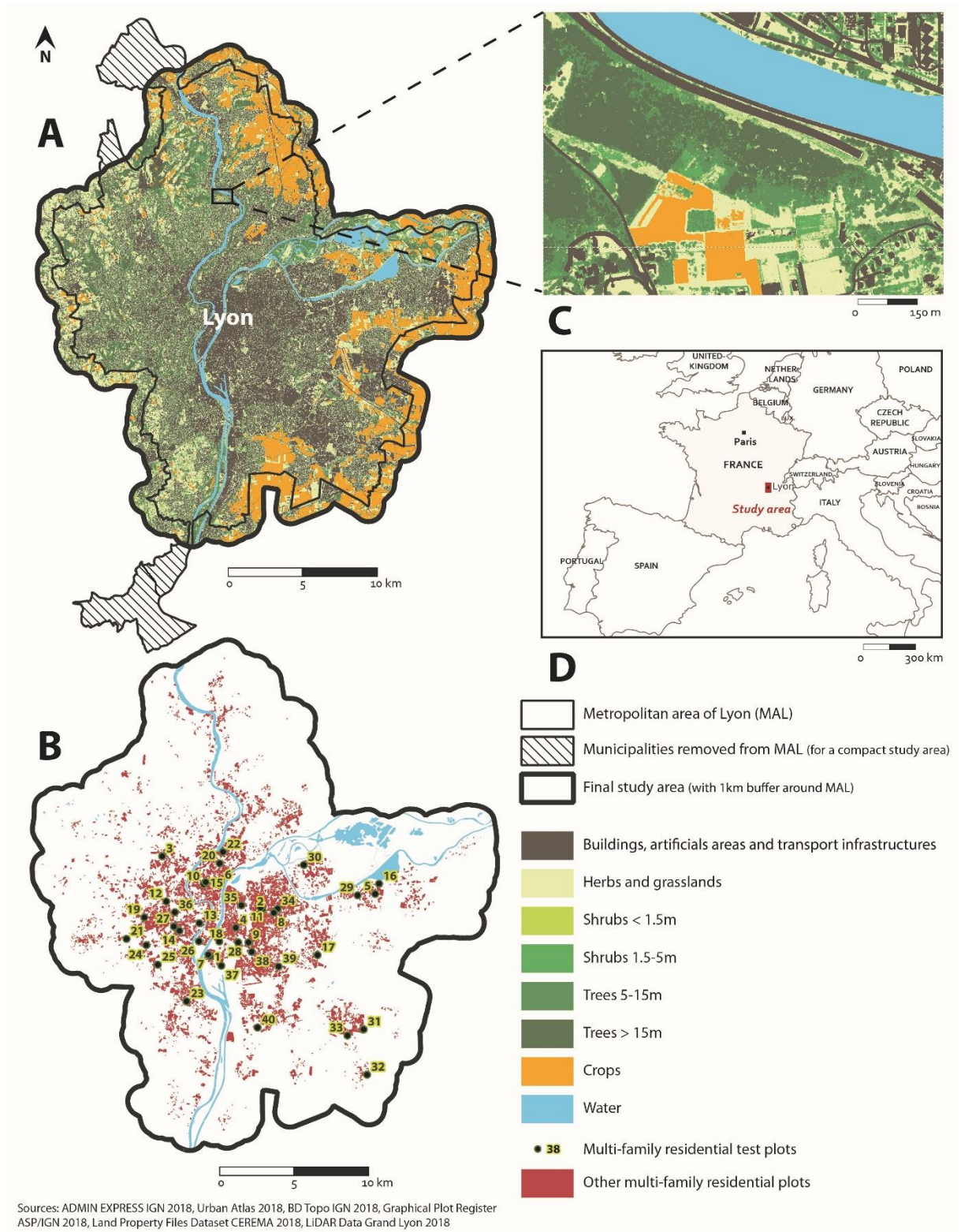


Figure 1: Study area. (A) Land cover map and administrative zoning. For better readability, some land cover classes have been aggregated (see details in Appendices 1, 2, 3, and 4). (B) Map of the MFR plots of the study area. The 40 MFR test plots are highlighted by a green dot and their ID number. (C) Zoom showing the high-resolution of the land cover map. (D) Location of the study area.

2.2 Definition and mapping of the MFR plots

To map the MFR plots, we used the Land Property Files Dataset provided by the French government institute of planning (CEREMA). The final plots included at least three dwellings per plot. Following the method proposed by the Paris Region Institute to map urban fabrics (Delaville et al., 2020), we selected the plots for which more than 70% of the dwellings are flats and more than 70% are for residential use. These last two criteria conserved 98.2% of the flats, located in 20,978 plots. These plots represent 15% of all plots (MFR, individual, business and public), and cover 8.2% of the metropolitan area of Lyon.

To assess in more detail the connectivity benefits resulting from the (re)greening of particular plots, we focused on 40 plots, specifically studied in another work. These plots were selected to optimise the diversity of available study sites, resulting from a call for expressions of interest on biodiversity in green spaces with the approval of the union council. The selection was carried out on a Principal Component Analysis of the interesting variables for this study (i.e., green area, vegetation composition, age of planning, urban density and built morphology with the best possible representation of the two main principal components (Figure 1B). These 40 MFR plots are analysed in more detail in section 2.8.

2.3 High-resolution land cover mapping

Land cover data with high resolution allowed us to map very small urban green spaces, which can contribute urban biodiversity and connectivity to a disproportionate extent (Braaker et al., 2014; Cameron et al., 2012; Von Thaden et al., 2021). We used a 1 metre resolution map of ground cover, obtained from image analysis of remote sensing data (Bellec, 2018). In order to represent the habitat and movements of urban species throughout highly heterogeneous urban settings, we discretised the vegetation layer into classes, each representing a vegetation stratum. For this purpose, we used high-resolution continuous altimetry data (Lidar) at 1 metre resolution. Although some studies have used such a high spatial resolution, few, if any, have taken advantage of it to distinguish different vegetation layers (Mimet et al., 2020; Von Thaden et al., 2021; Zhang et al., 2019). Here, we created five vegetation height classes: large trees (>15m), small trees (5 - 15m), shrubs (1.5 - 5m), bushes (0.5 – 1.5m), and herbaceous (<0.5m).

To represent accurately the ecological processes affecting species in urban areas (Zhang et al., 2021), we mapped other land cover classes that could substantially influence species movements, using several up-to-date and accurate land cover database. We used the BD Topo (IGN), the Registre Parcellaire Graphique (ASP/IGN), the Urban Atlas and the OSO map (Inglada et al., 2017) to map built-up areas, agricultural areas, and other land cover features not accurately mapped from remote sensing data (see details in Appendices 1, 2, 3 and 4). The final land cover map is a categorical raster with 35 land cover classes, distinguishing different vegetation types inside and outside the MFR plots.

2.4 Selection of focal species

As pointed out by LaPoint et al. (2015), many landscape connectivity studies focus on a single species (e.g., Bond et al., 2017; Clauzel et al., 2013). However, planners have to consider multiple taxa when designing biodiversity conservation strategies (Lechner et al., 2017). We therefore focused on "urban tolerant" species, with two non-flying species and two groups of flying species (i.e., species able to live in urban and suburban environments). The two non-flying species are the European hedgehog (*Erinaceus europaeus*) and the Red squirrel (*Sciurus vulgaris*). The two selected groups of flying species are forest-dwelling passerines and grassland-dwelling moths. These four species or groups of species (hereafter referred to as "taxa") encompass a substantial phylogenetic and functional diversity (mammals, birds and insects), occupy contrasted habitats preferences (various vegetation heights) and

have different movement abilities (Appendix 1, 2, 3 and 4) (e.g. App et al., 2022; Bednář et al., 2020; Schneider et al., 2020; Tarabon et al., 2019; Von Thaden et al., 2021).

2.5 Modelling of land cover change scenarios in MFR plots

We modelled the initial land cover state and five different land cover change scenarios affecting the 20,978 MFR plots (Figure 2). Two of these scenarios correspond to reference states (RS1 and RS2) with the theoretical maximum and minimum connectivity that could be achieved for each species in the study area. The objectives of these simulated land cover changes were (i) map and quantify habitat connectivity variations for each scenario and taxon, ii) address the dilemma between improving quality of existing green spaces or extend their quantity with sub-optimal quality, (iii) contextualise and frame the theoretical gains in connectivity between the theoretical minimum and maximum, and (iv) show the contribution of specific green spaces to habitat connectivity.

Reference 1: Maximum theoretical connectivity

All MFR plots were converted into the best habitat for each of the four taxa (e.g., into “large trees” for the red squirrel). This scenario therefore represents the highest theoretical gain in connectivity, and is unrealistic since even the buildings are removed. It is meant as a reference baseline to compare with other scenarios.

Reference 2: Minimum theoretical connectivity

All MFR plots were converted into artificial/impervious surfaces. This scenario assumes that all the plot vegetation is replaced by, for example, car parks. It therefore represents the worst possible development for the focal species populations.

Management scenario 3: Improve habitat quality (without extending quantity)

All existing vegetation in MFR plots was assigned a higher ecological quality, thereafter being equivalent to the best habitat class of the focal taxon. For example, if the habitat class is “large trees”, then all other vegetation classes such as “bushes” or “herbaceous areas” became “large trees”. The rest of the plot land cover, (e.g., impervious surfaces) did not change. This scenario assumes that all conservation measures target a given focal taxon.

Management scenario 4: Extend quantity (with sub-optimal quality)

All unbuilt surfaces in MFR plots, including non-habitat vegetation, were converted into sub-optimal vegetation for the considered taxa. It therefore represents “poor quality greening” (such as highly managed lawns), which often contributes to recreative human use but less so to the specific requirements of animal taxa.

Management scenario 5: Maximum restoration

As in reference 2, modifications affected the whole MFR plots but only excluded buildings. All unbuilt spaces were converted or upgraded to the habitat class of the focal taxa. It therefore represents the most favourable changes achievable while keeping present buildings.

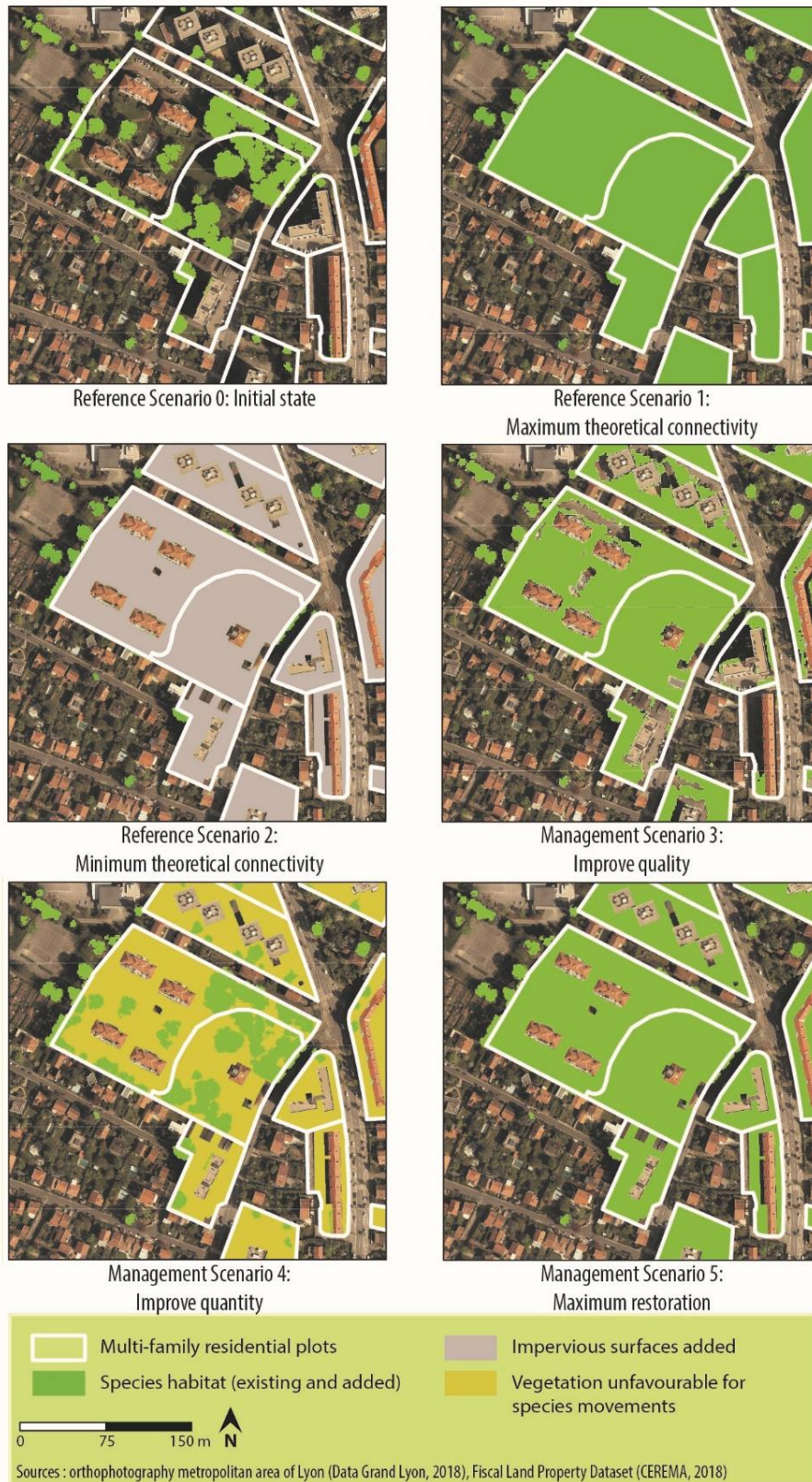


Figure 2: Example of an initial MFR plot with initial state and of the effect of the five simulated scenarios.

2.6 Construction of landscape graphs

We built landscape graphs from the land cover map to model the habitat patch networks of the four focal taxa, using Graphab 2.8 software (Foltête et al., 2021). A landscape graph is composed of nodes, representing habitat patches, and links, connecting these patches to represent potential functional connections (*i.e.*, a dispersal path between these patches). In highly fragmented environments including dense urban fabrics, urban tolerant species can still occupy very small habitat patches. We therefore considered adjacent vegetation pixels totalling at least 20 m² as suitable habitat patches. The vegetation classes defining habitats taxon and maximum dispersal distances were determined from the scientific literature available for each taxon. The European hedgehog occupies habitats made of bushes and shrubs, and can disperse up to 500 metres (Balbi et al., 2019; Rasmussen et al., 2019). The Red squirrel needs large trees and disperses up to 1000 metres (Wauters et al., 1994, 2010). We considered forest passerines usually found in habitats made of either shrubs, small trees, or large trees, and dispersing up to 2000 metres, as they are common study species in urban ecology (Balbi et al., 2021; Paradis et al., 1998). Finally, open-habitat moths were assumed to occupy herbaceous habitats and grasslands, and to disperse up to 3000 metres (Balbi et al., 2021; Jones et al., 2016).

To create the graph links modelling the potential movements of each taxa, we assigned each land cover types a cost value representing its resistance to species movements: habitat (1), very favourable (10), neutral (50), slightly unfavourable (100), unfavourable (500), very unfavourable (1000), barrier (10000) (see details in Appendix 1, 2, 3 and 4). This range of cost values has already been used in many studies based on landscape graphs to allow the identification of least cost paths between habitat patches (*e.g.* Bourgeois and Sahraoui, 2020; Clauzel et al., 2013; Tannier et al., 2016). Despite the known limitations of this method (Zeller et al., 2012), its relevance has been demonstrated in empirical studies in urban environments (Balbi et al., 2019). We then constructed 24 landscape graphs, corresponding to each taxon, in the initial state and for each scenario (4 x [5+1]).

2.7 Computation of connectivity metrics

From these graphs, we computed several metrics to quantify functional connectivity at different scales. To assess the contribution of land cover changes in MFR plots over the whole study area, we compared the Equivalent Connectivity (*EC*) metric computed from each of the 24 graphs. This metric represents the area of the unique patch that would provide species with the same amount of reachable habitat as the entire habitat graph, given its degree of subdivision and the resistance of the matrix (Saura et al., 2011). It therefore makes all scenarios comparable on a common basis. We used the following formula:

$$EC = \sqrt{\sum_{i=1}^n \sum_{j=1}^n a_i a_j p_{ij}}$$

where n is the total number of patches, a_i and a_j are the areas of patches i and j , and p_{ij} is the dispersal probability between i and j when following the least-cost, and potentially indirect, path on the landscape graph. p_{ij} was calculated with a negative exponential function such that:

$$p_{ij} = e^{-\alpha d_{ij}}$$

where d_{ij} is the least-cost distance between i and j , and α ($0 < \alpha < 1$) sets the shape of the dispersal probability exponential decay as d_{ij} increases.

To quantify connectivity at the scale of each habitat patch, we chose the local metric Interaction Flux (*IF*) (Foltête et al., 2014) which is the local contribution of each patch to the global *EC* metric. For a given patch *i*, *IF_i* is given by:

$$IF_i = \sum_{j=1}^n a_i a_j p_{ij}$$

where *n* is the total number of patches, *a_i* and *a_j* are the areas of patches *i* and *j*, and *p_{ij}* is the dispersal probability between *i* and *j*, as in the *EC* metric formula above.

Local metrics are computed for habitat patches and therefore prevent from making comparisons when species do not share the same habitat patches. To make this comparison between species possible, we assigned *IF* values to each MFR plot. To that end, when a MFR plot overlapped several habitat patches, we summed the *IF* values of each intersected habitat patch to obtain an *IF* value for each MFR plot. Applying this to each taxon and each scenario made the results comparable and showed which MFR plots contribute most to connectivity.

2.8 Patch addition in MFR test plots

In order to go further in the connectivity analyses at the local level, we carried out additional analyses on 40 selected MFR test plots. Among these 40 plots, we aimed at identifying the most relevant to consider for implementing measures to improve overall connectivity. For this purpose, we implemented a method initially framed by Foltête et al. (2014) to prioritise ecological restoration measures, and then implemented by Clauzel et al. (2015) or Tarabon et al. (2021), among others. Here, for each of the 40 MFR plots, we added habitat patches, one by one, for the four taxa studies, while preserving the existing buildings. Here, we replaced the entire surface excluding buildings of these 40 MFR plots by habitat for the four taxa studied.

We calculated the new global connectivity (*EC*) values for each of the 40 MFR test plots. Comparing these new *EC* values with the initial values, we ranked the 40 MFR plots according to the potential gain in connectivity they would provide if converted into habitat patches. We also compared the new *IF* value with the initial value for each MFR plot.

To make the outputs of connectivity analysis easier to understand for non-specialist readers (Bourgeois et al., 2022), we interpolated the local connectivity metric values across the whole landscape matrix, following Sahraoui et al. (2017). This spatial generalisation evaluates the potential accessibility of any point (*i.e.*, pixel) of the study area for the four species, based on its connectivity with several habitat patches. For each pixel, we summed the weighted *IF* values of several nearby patches, by considering least-cost distances as follows:

$$gIF(i)_i = \sum_{j=1}^n IF_{(j)} \times \omega_{ij}$$

where *gIF(i)* is the generalised value of *IF* for pixel *i*, and *ω_{ij}* is the weighting of patch *j* for point *i*. As a result, we obtained for each of the four taxa a 1 metre resolution map in the initial state and in the final state (after adding new patches on each of the 40 MFR test plots), on which each pixel took a value representing its location in the overall connectivity network. We obtain the ranking of the 40 MFR test plots with regard to their potential gain in connectivity which was not possible from the previous methodology (2.7) where everything evolved at the same time. For each of the four taxa, a

new map was created, resulting from the calculation of the rate of change between the initial and final state for each pixel of the map.

3. Results

3.1 Global connectivity metrics

In reference 1 (Maximum theoretical connectivity), all MFR plots were replaced by habitat favourable to each taxon, which increased the area of habitat patches for all taxa (up to twice the initial area for Red squirrel). However, for all taxa, the gain in connectivity was lower than the gain in habitat area (Figure 3 and Table 1). The difference in relative increases is greater for terrestrial species than for flying species. The same connectivity gain trends were observed for scenario 5 (maximum restoration), and to a lesser extent for scenario 3 (improve habitat quality). Scenario 4 (improve quantity of green spaces with sub-optimal quality), which did not change habitat area but increased the overall vegetation quantity, only slightly increased connectivity for the passerines but decreased it for the other taxa (Table 1). In the reference 2 (minimum theoretical connectivity), where all MFR plots were transformed into impervious surfaces, the rate connectivity loss was higher than the loss of habitat for the hedgehog and passerines; and slightly lower for squirrel and moths. All these results show that changes between the amount of habitat and the value of *EC*, depending mainly on both taxon dispersal distances and urban matrix changes and are not always strongly correlated (Figure 3 and Table 1).

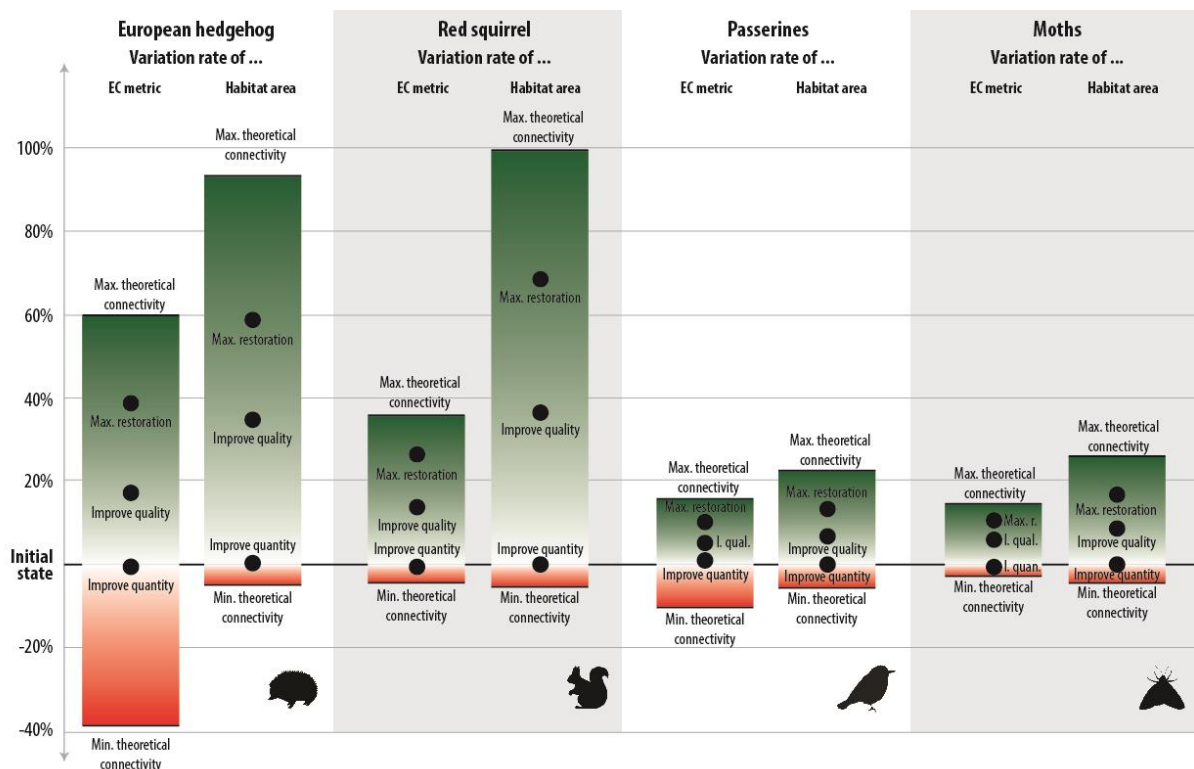


Figure 3: Values of global metric *EC* and habitat patch areas for each focal taxon with variation rates between the five scenarios and the initial state (0 % horizontal reference line).

	European hedgehog				Red squirrel			
Dispersal distance (metres)	500				1000			
Dispersal distance (cost units)	10585				38458			
	EC metric		Habitat patches		EC metric		Habitat patches	
	Value (m ²)	Variation rate	Area (m ²)	Variation rate	Value (m ²)	Variation rate	Area (m ²)	Variation rate
S0: Initial state	1456266		39730443		6062528		37209169	
S1: Maximum theoretical connectivity	2330541	60,0%	76767632	93,22%	8235892	35,8%	74229409	99,49%
S2: Minimum theoretical connectivity	1429864	-38,6%	37874733	-4,67%	5786017	-4,6%	35336510	-5,03%
S3: Improve quality	1704057	17,0%	53800984	35,42%	6905539	13,9%	50812286	36,56%
S4: Improve quantity	1451962	-0,3%	39730443	0,00%	6021753	-0,7%	37209169	0,00%
S5: Maximum restoration	2019640	38,7%	63218260	59,12%	7661059	26,4%	62789677	68,75%
	Passerines				Moths			
Dispersal distance (metres)	2000				3000			
Dispersal distance (cost units)	258213				36774			
	EC metric		Habitat patches		EC metric		Habitat patches	
	Value (m ²)	Variation rate	Area (m ²)	Variation rate	Value (m ²)	Variation rate	Area (m ²)	Variation rate
S0: Initial state	37535711		137523687		2,25E+07		126982436	
S1: Maximum theoretical connectivity	43444800	15,74%	168779441	22,73%	2,58E+07	14,63%	160348718	26,28%
S2: Minimum theoretical connectivity	33637355	-10,39%	129886542	-5,55%	2,18E+07	-2,98%	121455819	-4,35%
S3: Improve quality	39508458	5,26%	146604768	6,60%	2,39E+07	6,07%	138173476	8,81%
S4: Improve quantity	37871584	0,89%	137523687	0,00%	2,24E+07	-0,71%	126982436	0,00%
S5: Maximum restoration	41366336	10,21%	155742798	13,25%	2,49E+07	10,52%	148121461	16,65%

Table 1: Values of global metric EC and habitat patches areas for each focal taxon with variation rate between scenarios and initial state.

3.2 Local connectivity metrics

For all four taxa, the *IF* values were higher in the more forested western portion of the study area at the initial state (Figures 1 and 4). Overall, despite differences among the four taxa, adding habitat patches on plots in the already greener neighbourhoods allowed for a higher potential connectivity flux, as compared with additions affecting the most urbanised neighbourhoods (Figure 5). Nonetheless, connectivity flux is not explained only by the position in the urban-rural gradient because it remains variability in connectivity gains within neighbourhoods (e.g. eastern side of the map). The *IF* metric gain is spatially differentiated according to the taxa studied and shows various spatial pattern. For example, the Figure 6 suggests that greening operations could be slightly more effective in the city centre (between the rivers Rhône and Saône) for the hedgehog than for the squirrel.

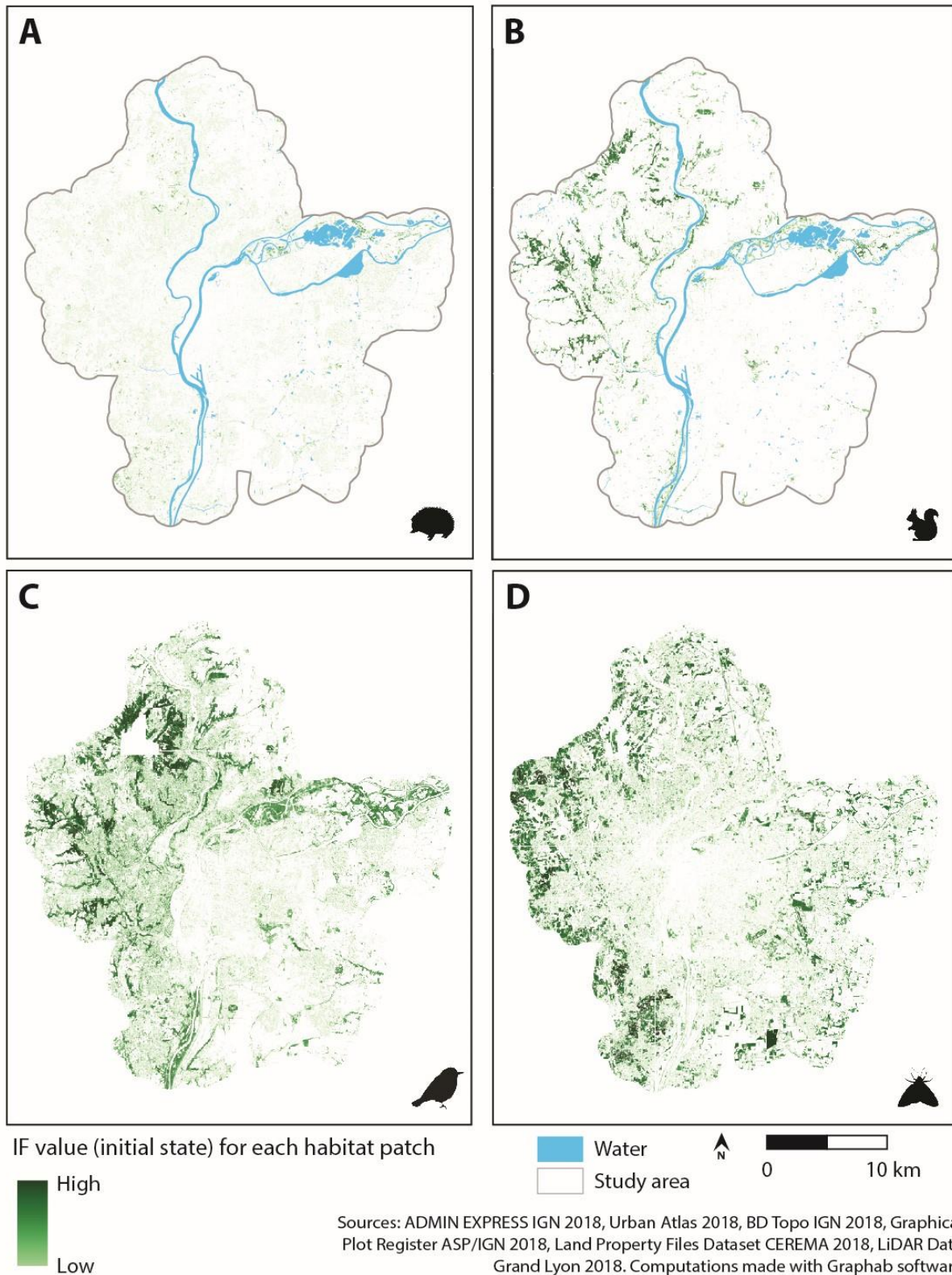


Figure 4: *IF* metric of habitat patches in the initial state for the four focal taxa: European hedgehog (A), Red squirrel (B), passerines (C) and moths (D). The class values are the same for all taxa to make maps comparable.

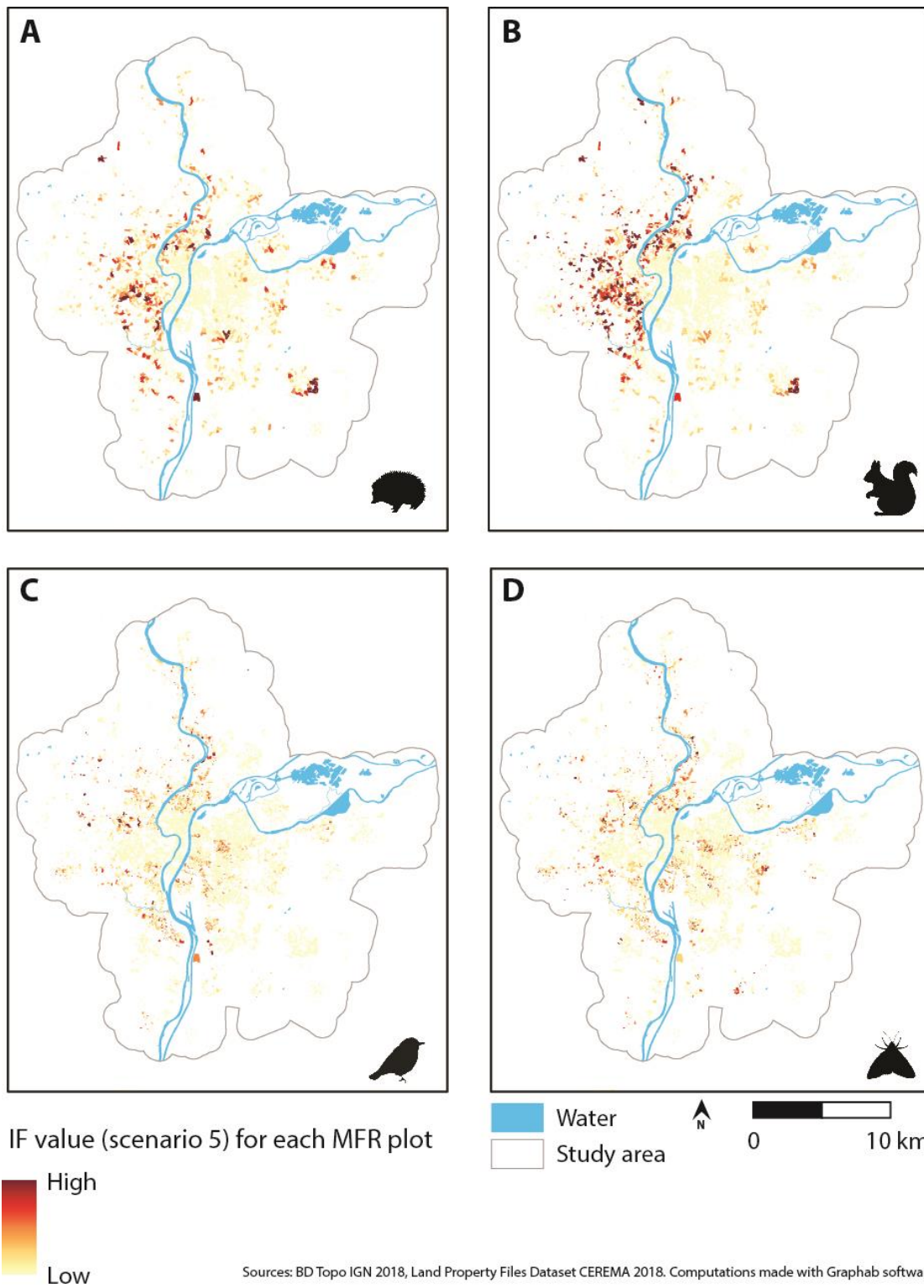


Figure 5: *IF* metric in MFR plots for scenario 5 for the four focal taxa: European hedgehog (A), Red squirrel (B), passerines (C) and moths (D). The classes values are the same for all taxa to make maps comparable.

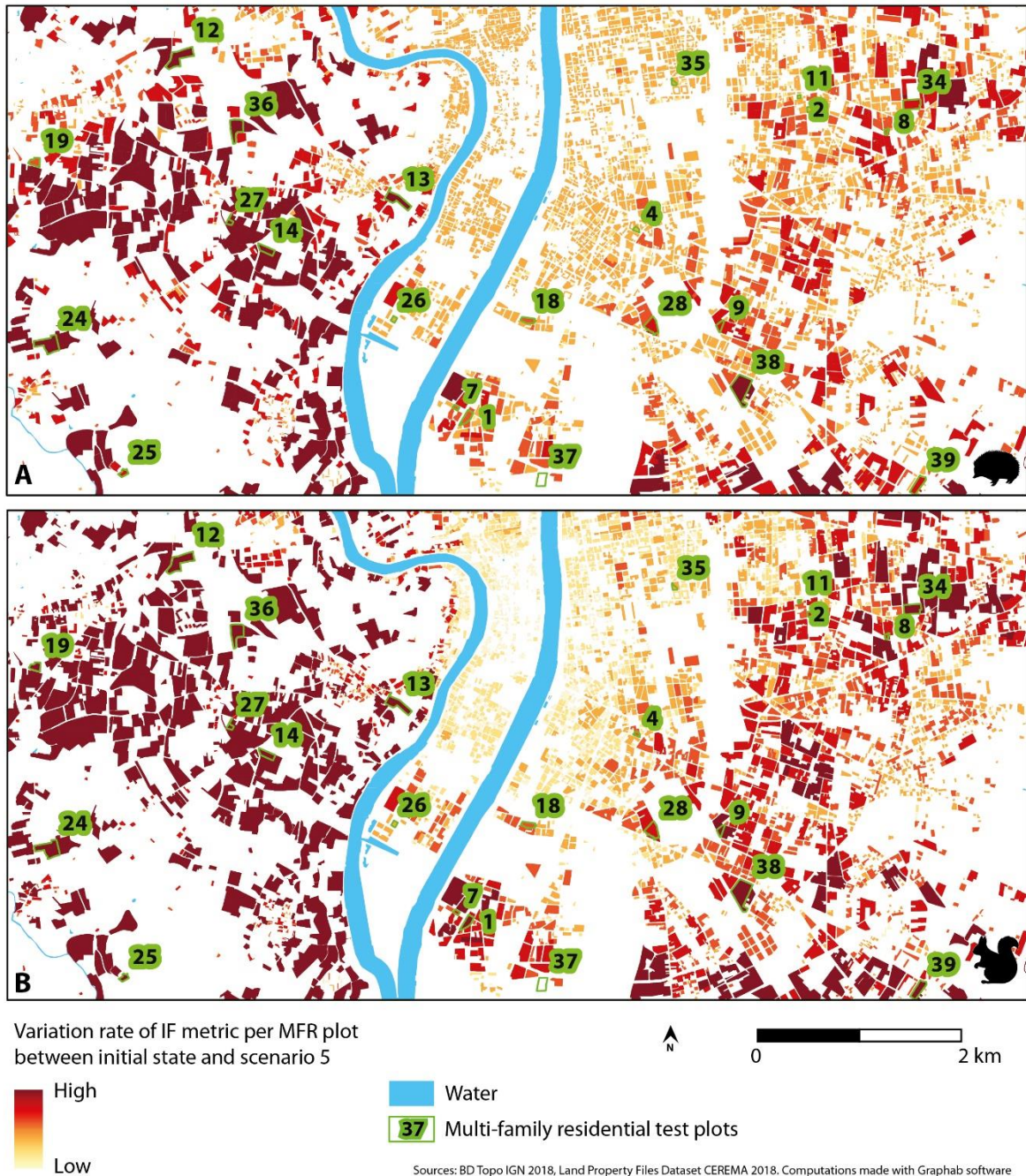


Figure 6: Evolution of *IF* metric between initial state and scenario 5 for each MFR plot. Examples for European hedgehog (A) and Red squirrel (B).

3.3 Patch addition in MFR test plots

Adding a single habitat patch in an MFR plot only affected the global connectivity of the study area very slightly. Thus, for the sake of brevity, patch addition results are only reported for hedgehog and squirrel, which are the two taxa benefitting from the highest potential connectivity gains. As an example, for all taxa and all MFR plots, the largest rate of change was only 0.013%, obtained for hedgehogs for MFR plot n°23 (Appendix 5). For each of the 40 MFR test plots, we show the potential impact of each patch addition for hedgehogs and squirrels (Figure 7). These maps show that the addition of habitat patches in the MFR plots would have been prioritised differently with connectivity

evaluations based on a single taxon. For example, in the south-west of the area, MFR plot 25 is one of the most interesting for regreening to benefit the red squirrel, whereas it has much less interest for the hedgehog. The results are reversed for MFR plot 23, which is close to plot 25. These results also show that regreening operations seem to be more effective in improving connectivity in areas that already have high connectivity values in the initial state (Figure 4). These trends can also be seen in Figures 5, 6 and 8 where the western part of the study area, which was initially greener, offers better opportunities to increase the ecological connectivity of the taxa studied. Spatial interpolations show the connectivity values obtained per pixel (Figure 8). Since they only represent a theoretical connectivity potential, these maps make it possible to show, for each MFR plot and for each taxon, the potential increases in connectivity at the scale of the neighbourhood, and not only on the MFR plot subject to greening. These calculations could combine multiple taxa by averaging the values obtained after normalisation.

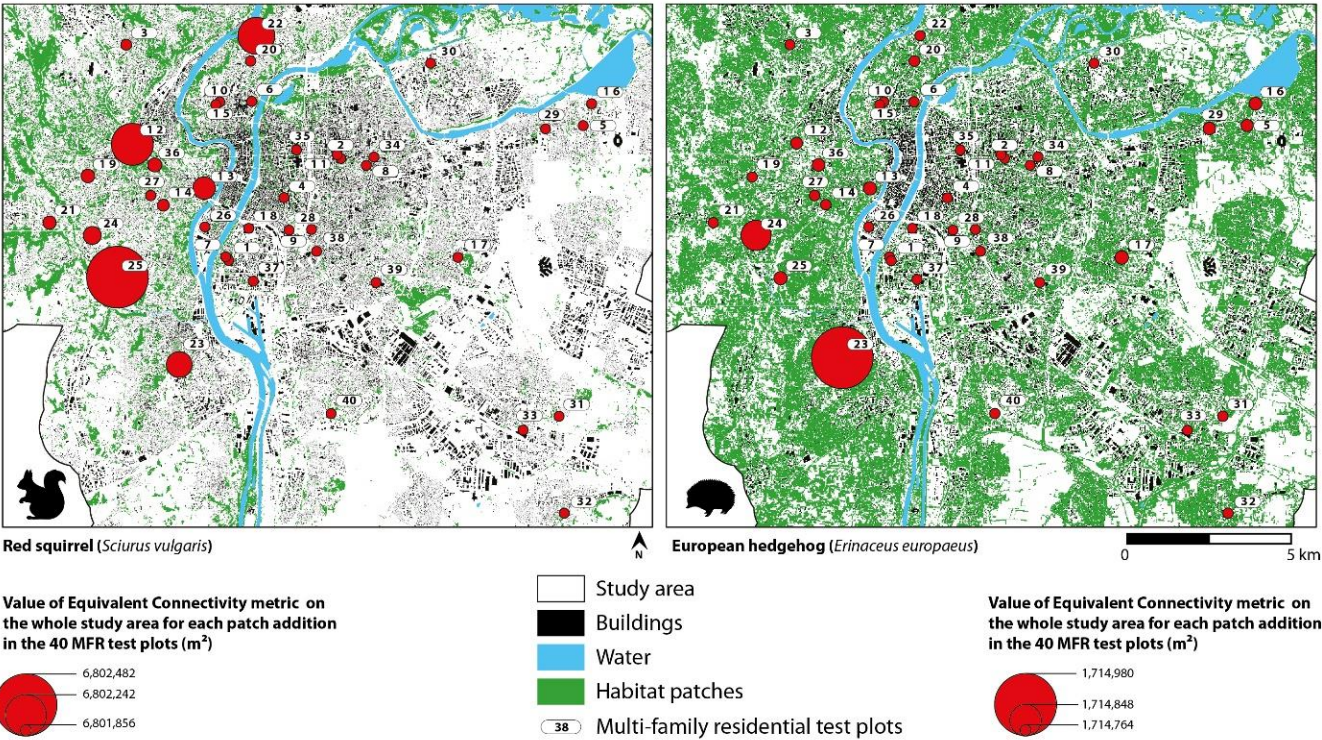


Figure 7: Contributions of each patch addition in 40 MFR test plots to the whole connectivity of the study area. The big red circles represent the MFR test plots where greening (with adding habitat patches) would be the most efficient for improving global connectivity.

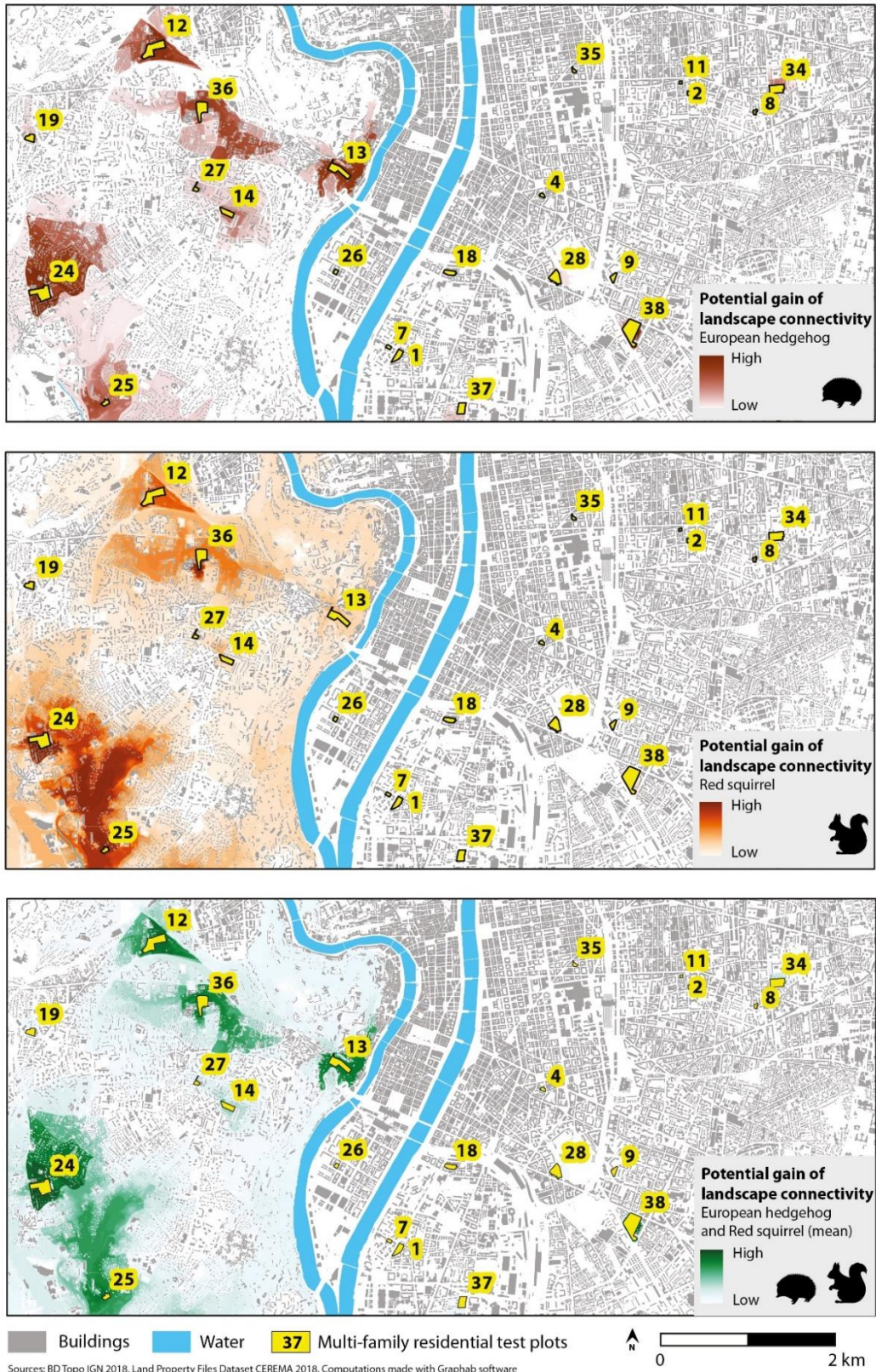


Figure 8: Spatial interpolations of the *IF* metric for each MFR test plot in scenario 5. The pixel values depend on the ecological network of each species (cost values, location and size of habitat patches and dispersal capacities). The green pixels show the mean value for each pixel for two species after normalization of values.

4. Discussion

4.1 The value of MFR plots for global connectivity

As urban areas are growing at a sustained pace, maintaining ecological connectivity is crucial to maintain biodiversity in the long term (Kong et al., 2010; Rudd et al., 2002; Saura et al., 2019). Several studies have already demonstrated the importance of small green spaces in urban areas for connectivity (Iojă et al., 2014; Luo et al., 2022; Mimet et al., 2020; Serret et al., 2014). Nonetheless, to our knowledge, none had focused on the importance of vegetation in MFR plots for the study of habitat connectivity, despite their strategic location in the urban matrix for ecological networks and human well-being. We expected results similar to previous studies on urban green space connectivity since MFR plots contribute more than 9 % of the overall vegetation in our study area. Accordingly, we showed that green spaces in MFR plots could substantially improve the functional connectivity of urban spaces. Indeed, when we removed all these green spaces (reference 2), we logically observed a loss of connectivity for all the studied taxa, as other studies simulating new urban areas realistically, replacing natural and agricultural spaces by new buildings (Sahraoui et al., 2021; Tannier et al., 2016; Tarabon et al., 2020). Our results show that MFR green spaces could be much improved to make them more hospitable to biodiversity.

In line with studies conducted on private gardens, our results highlight the importance of efficiently managing urban green spaces to maintain or increase global ecological connectivity (App et al., 2022; Mimet et al., 2020). Indeed, improving habitat quality (S3), or drastically increasing habitat areas in these patches (S5) led to connectivity gains twice higher than massive greening of sealed surfaces (up to 68.7% for squirrels in scenario 5). Other studies have demonstrated the importance of vacant and underused spaces (bare ground) within patches to biodiversity (Schilling and Logan, 2008; Zhang et al., 2019), but shifting management practices of condominium managers in that direction could be difficult and hamper progress.

Our results also showed that the potential for improving connectivity is much greater for terrestrial species than for flying species, which are less sensitive to urban matrix permeability between habitat fragments under our movement assumptions. Consequently, increasing the connectivity of urban green spaces for less mobile species cannot be limited to improving the quality of urban habitats. In contrast, when increasing the quantity of greened areas (*e.g.*, in scenario 4), connectivity is not or only slightly improved when the new green spaces are not suitable habitats for the focal taxa. Therefore, adding only one type of green spaces, with sub-optimal quality in cities also falls short in improving overall habitat connectivity. Our use of highly contrasted scenarios showed that achieving positive impacts on habitat connectivity for several taxa requires acting jointly at several levels. In other words, favouring one conservation measure and pushing it to its extreme falls short in reaching optimal conservation outcomes. For example, in the centre town, the scenario 3 does not improve significantly the connectivity because green spaces are lacking in the neighbourhood. Finally, we believe that the success of greening operations will depend on the targeted taxa, and on the location of the MFR plots in the ecological networks. In the city centre, there is a vital need to work on both the quantity and quality of green spaces, whereas in the suburbs the priority is rather to work on their quality.

4.2 Spatialising connectivity to guide landscape management policies

Spatialising connectivity metrics at the local scale identified the MFR plots for which connectivity gains (or losses) are most important. While this spatialisation provides useful mapping information for management, it must be remembered that it assumes all land cover changes are made at the same time, in all patches, which is impossible in reality. This is why targeting on 40 study sites,

we illustrate how urban planning could actually orient conservation measures at realistic scales. Our methodology of adding habitat patches one by one in each of the focal plots allowed us to rank these 40 MFR plots according to their contribution to the global connectivity of the ecological network. This type of classification can be used to prioritise landscape management policies depending on financial resources and political goals. In reality, all four taxa considered should be studied simultaneously. Specific measures for four taxa can be developed in a limited number of plots, chosen for example according to economic and social feasibility criteria. The selected measures can be optimised by working more specifically on the results obtained for each of the simulated scenarios.

In addition, mapping the connectivity gains achieved over the entire study area showed the impact that the management of a plot can have on the surrounding neighbourhood. This type of map may be questionable from an ecological point of view, as it highlights areas where species might move very rarely. However, it still deserves attention for raising awareness of the concept of ecological networks among citizens, planners and politicians (Bourgeois et al., 2022). Making people aware of each action that could favour biodiversity at the scale of their residential plot can have significant repercussions for the entire ecological network (Cameron et al., 2012).

4.3 Limitations and perspectives

Our approach modelled potential ecological networks without using biological data. While modelling ecological networks using least-cost paths has been shown to be relevant in other studies (Balbi et al., 2019; Zeller et al., 2012), we are aware of the limitations of this method since it is not possible to accurately predict all potential movements of individuals in the landscape. Not all fragmenting elements can be considered (*e.g.*, noise, light pollution, urban heat island). Furthermore, in a large study area such as ours, it was not possible to identify small fragmenting elements such as fences, which can hinder the movements of species, *e.g.* hedgehogs. Finally, the choice of four taxa with different ecological requirements is useful for perceiving the different impacts of our scenarios (Lechner et al., 2017), but complicates the interpretation of the results for applying concrete measures. This makes it possible to prioritise the locations of interventions but does not give practical instructions towards landscape management at the site scale which must be left to the appreciation of ecologists and landscapers. In addition, improving habitat connectivity for some target species might crucially improve connectivity for “unwanted” species (*e.g.*, alien or invasive species).

The potential connectivity improvements highlighted by our scenarios lead us to believe that by acting in accordance with the human and financial resources available, it is possible to improve global connectivity in a targeted and realistic way. We believe that our results can foster actions for biodiversity-friendly landscaping. For example, in our scenario 4, we show that simple greening is not enough to improve connectivity. In order to have a positive impact on biodiversity, landscaping must be carried out correctly by targeting native species, and their needs in terms of landscape composition and configuration (Goddard et al., 2013; Mimet et al., 2020; Muratet and Fontaine, 2015). However, the quality of these landscapes and their proper management can only be achieved through good coordination of gardeners throughout the territory and an evolution of their ecological practices (App et al., 2022; Gazzard et al., 2021; Goddard et al., 2010; Van Helden et al., 2020). Our results could also be useful for integrating habitat connectivity into planning tools to improve biodiversity indicators at the scale of urban development projects (*e.g.* Masson and Frascaria-Lacoste, 2020).

5. Conclusion

In this work, we targeted a particular type of urban green spaces, the green spaces included in multi-family residential (MFR) plots. We assessed the importance of these green spaces for the global connectivity of four animal species profiles (European hedgehog, red squirrel, forest-dwelling

passerines and grass-dwelling moths) based on the current state of land cover and on five scenarios of land cover changes (Maximum Theoretical Connectivity, Minimum Theoretical Connectivity, Improve quality of green spaces, Improve quantity of green spaces with sub-optimal quality, Maximum restoration). The different evolutions of the global connectivity values obtained for these five scenarios in comparison with the initial state showed that:

- Vegetation in the MFR plots is important for the global connectivity of the network. If they are all removed, there is a 4 to 5 % loss of global connectivity for all focal species
- The greening of these plots could lead to large potential connectivity gains, depending on the strategy (from 6% to 100% gains)
- Greening the plots without adding habitat patches does not improve connectivity.

Our results showed that in order to substantially increase connectivity, it is relevant to coordinate actions on a network of plots because the effects are non-cumulative and increase disproportionately the benefits of greening actions when they are carried out jointly on several plots. Moreover, as the initial state of the neighbourhood's ecological network has a great impact on the connectivity benefits observed for each individual plot, these results call for increased efforts in neighbourhoods lacking green spaces in order to improve their ecological condition.

The spatialisation of local connectivity metrics makes it possible to map these results and to target priority areas in landscape management. This will create a basis for the design of relevant landscaping practices, which would favour the maintenance of ecological connectivity and, consequently, the long-term biodiversity of these urban spaces. Finally, maps that clearly show the positive impacts of connectivity can be useful for a better inclusion of all citizens and stakeholders in decision making.

References

- App, M., Strohbach, M.W., Schneider, A.K., Schröder, B., 2022. Making the case for gardens: Estimating the contribution of urban gardens to habitat provision and connectivity based on hedgehogs (*Erinaceus europaeus*). *Landsc. Urban Plan.* 220. <https://doi.org/10.1016/j.landurbplan.2021.104347>
- Aronson, M.F.J., Lepczyk, C.A., Evans, K.L., Goddard, M.A., Lerman, S.B., MacIvor, J.S., Nilon, C.H., Vargo, T., 2017. Biodiversity in the city: key challenges for urban green space management. *Front. Ecol. Environ.* 15, 189–196. <https://doi.org/10.1002/fee.1480>
- Balbi, M., Croci, S., Petit, E.J., Butet, A., Georges, R., Madec, L., Caudal, J.P., Ernoult, A., 2021. Least-cost path analysis for urban greenways planning: A test with moths and birds across two habitats and two cities. *J. Appl. Ecol.* 58, 632–643. <https://doi.org/10.1111/1365-2664.13800>
- Balbi, M., Petit, E.J., Croci, S., Nabucet, J., Georges, R., Madec, L., Ernoult, A., 2019. Ecological relevance of least cost path analysis: An easy implementation method for landscape urban planning. *J. Environ. Manage.* 244, 61–68. <https://doi.org/10.1016/j.jenvman.2019.04.124>
- Bednář, M., Šarapatka, B., Mazalová, M., Kuras, T., 2020. Connectivity modelling with automatic determination of landscape resistance values. A new approach tested on butterflies and burnet moths. *Ecol. Indic.* 116. <https://doi.org/10.1016/j.ecolind.2020.106480>
- Bellec, A., 2018. Dynamiques spatiales, temporelles et écologiques de la Métropole de Lyon : 1984-2015. Université Lyon 3 Jean Moulin.
- Beninde, J., Veith, M., Hochkirch, A., 2015. Biodiversity in cities needs space: A meta-analysis of factors determining intra-urban biodiversity variation. *Ecol. Lett.* 18, 581–592. <https://doi.org/10.1111/ele.12427>
- Bolund, P., Hunhammar, S., 1999. Ecosystem services in urban areas. *Ecol. Econ.* 29, 293–301. <https://doi.org/10.1017/S174217051300046X>
- Bond, M.L., Bradley, C.M., Kiffner, C., Morrison, T.A., Lee, D.E., 2017. A multi-method approach to delineate and validate migratory corridors. *Landsc. Ecol.* 32, 1705–1721. <https://doi.org/10.1007/s10980-017-0537-4>
- Bourgeois, M., Sahraoui, Y., 2020. Modelling in the context of an environmental mobilisation: A Graph-based approach for assessing the landscape ecological impacts of a highway project. *Ekol. Bratislava* 39, 88–100. <https://doi.org/10.2478/eko-2020-0007>
- Bourgeois, M., Sahraoui, Y., Dietrich, J., 2022. The contributions of socio-environmental information maps in an environmental mobilisation: the case of a fight against a highway project in France. *Local Environ.* 27, 1102–1121. <https://doi.org/10.1080/13549839.2022.2100881>
- Braaker, S., Moretti, M., Boesch, R., Ghazoul, J., Obrist, M.K., Bontadina, F., 2014. Assessing habitat connectivity for ground-dwelling animals in an urban environment. *Ecol. Appl.* 24, 1583–1595. <https://doi.org/10.1890/13-1088.1>
- Cameron, R.W.F., Blanuša, T., Taylor, J.E., Salisbury, A., Halstead, A.J., Henricot, B., Thompson, K., 2012. The domestic garden - Its contribution to urban green infrastructure. *Urban For. Urban Green.* 11, 129–137. <https://doi.org/10.1016/j.ufug.2012.01.002>
- Carpenter, M., 2013. From “healthful exercise” to “nature on prescription”: The politics of urban green spaces and walking for health. *Landsc. Urban Plan.* 118, 120–127. <https://doi.org/10.1016/j.landurbplan.2013.02.009>
- Chiesura, A., 2004. The role of urban parks for the sustainable city. *Landsc. Urban Plan.* 68, 129–138.

<https://doi.org/10.1016/j.landurbplan.2003.08.003>

- Clauzel, C., Girardet, X., Foltête, J.-C., 2013. Impact assessment of a high-speed railway line on species distribution: application to the European tree frog (*Hyla arborea*) in Franche-Comté. *J. Environ. Manage.* 127, 125–34. <https://doi.org/10.1016/j.jenvman.2013.04.018>
- Delaville, D., Watkin, Y., Dugué, R., 2020. Un nouvel outil d'analyse des formes urbaines pour mieux anticiper le développement des territoires. Paris.
- Fahrig, L., 2019. Habitat fragmentation: A long and tangled tale. *Glob. Ecol. Biogeogr.* 28, 33–41. <https://doi.org/10.1111/geb.12839>
- Foltête, J.-C., Girardet, X., Clauzel, C., 2014. A methodological framework for the use of landscape graphs in land-use planning. *Landsc. Urban Plan.* 124, 140–150. <https://doi.org/10.1016/j.landurbplan.2013.12.012>
- Foltête, J.-C., Vuidel, G., Savary, P., Clauzel, C., Sahraoui, Y., Girardet, X., Bourgeois, M., 2021. Graphab: An application for modeling and managing ecological habitat networks. *Softw. Impacts* 8, 100065. <https://doi.org/10.1016/j.simpa.2021.100065>
- Gaston, K.J., Smith, R.M., Thompson, K., Warren, P.H., 2005. Urban domestic gardens (II): experimental tests of methods for increasing biodiversity. *Biodiversity* 14, 395–413.
- Gazzard, A., Boushall, A., Brand, E., Baker, P.J., 2021. An assessment of a conservation strategy to increase garden connectivity for hedgehogs that requires cooperation between immediate neighbours: A barrier too far? *PLoS One* 16, 1–22. <https://doi.org/10.1371/journal.pone.0259537>
- Geoghegan, J., 2002. The value of open spaces in residential land use. *Land use policy* 19, 91–98. [https://doi.org/10.1016/S0264-8377\(01\)00040-0](https://doi.org/10.1016/S0264-8377(01)00040-0)
- Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., 2007. Adapting cities for climate change: The role of the green infrastructure. *Built Environ.* 33, 115–133.
- Goddard, M.A., Dougill, A.J., Benton, T.G., 2013. Why garden for wildlife? Social and ecological drivers, Motivations and barriers for biodiversity management in residential landscapes. *Ecol. Econ.* 86, 258–273. <https://doi.org/10.1016/j.ecolecon.2012.07.016>
- Goddard, M.A., Dougill, A.J., Benton, T.G., 2010. Scaling up from gardens: biodiversity conservation in urban environments. *Trends Ecol. Evol.* 25, 90–98. <https://doi.org/10.1016/j.tree.2009.07.016>
- Inglada, J., Vincent, A., Arias, M., Tardy, B., Morin, D., Rodes, I., 2017. Operational High Resolution Land Cover Map Production at the Country Scale Using Satellite Image Time Series. *Remote Sens.* 9, 95. <https://doi.org/10.3390/rs9010095>
- Ioja, C.I., Grădinaru, S.R., Onose, D.A., Vânău, G.O., Tudor, A.C., 2014. The potential of school green areas to improve urban green connectivity and multifunctionality. *Urban For. Urban Green.* 13, 704–713. <https://doi.org/10.1016/j.ufug.2014.07.002>
- Irwin, E.G., 2002. The effects of open space on residential property values. *Land Econ.* 78, 465–480. <https://doi.org/10.2307/3146847>
- Jones, H.B.C., Lim, K.S., Bell, J.R., Hill, J.K., Chapman, J.W., 2016. Quantifying interspecific variation in dispersal ability of noctuid moths using an advanced tethered flight technique. *Ecol. Evol.* 6, 181–190. <https://doi.org/10.1002/ece3.1861>
- Kong, F., Yin, H., Nakagoshi, N., Zong, Y., 2010. Urban green space network development for biodiversity conservation: Identification based on graph theory and gravity modeling. *Landsc.*

- Urban Plan. 95, 16–27. <https://doi.org/10.1016/j.landurbplan.2009.11.001>
- LaPoint, S., Balkenhol, N., Hale, J., Sadler, J., van der Ree, R., 2015. Ecological connectivity research in urban areas. *Funct. Ecol.* 29, 868–878. <https://doi.org/10.1111/1365-2435.12489>
- Lechner, A.M., Sprod, D., Carter, O., Lefroy, E.C., 2017. Characterising landscape connectivity for conservation planning using a dispersal guild approach. *Landsc. Ecol.* 32, 99–113. <https://doi.org/10.1007/s10980-016-0431-5>
- Lepczyk, C.A., Aronson, M.F.J., Evans, K.L., Goddard, M.A., Lerman, S.B., Macivor, J.S., 2017. Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green Spaces for Biodiversity Conservation. *Bioscience* 67, 799–807. <https://doi.org/10.1093/biosci/bix079>
- Loram, A., Warren, P., Thompson, K., Gaston, K., 2011. Urban domestic gardens: The effects of human interventions on garden composition. *Environ. Manage.* 48, 808–824. <https://doi.org/10.1007/s00267-011-9723-3>
- Louis-Lucas, T., Clauzel, C., Mayrand, F., Clergeau, P., Machon, N., 2022. Role of green roofs in urban connectivity, an exploratory approach using landscape graphs in the city of Paris, France. *Urban For. Urban Green.* 78. <https://doi.org/10.1016/j.ufug.2022.127765>
- Luo, Y., Zhu, Z., Wu, J., Zhang, Y., Li, X., Zhao, W., Yuan, Y., Duanmu, Z., Li, M., 2022. Exploring habitat patch clusters based on network community detection to identify restored priority areas of ecological networks in urban areas. *Urban For. Urban Green.* 78, 127771. <https://doi.org/10.1016/j.ufug.2022.127771>
- Lynch, A.J., 2021. The role and potential of residential open space in a suburban green space network. *Urban For. Urban Green.* 58, 126971. <https://doi.org/10.1016/j.ufug.2020.126971>
- Masson, A., Frascaria-Lacoste, N., 2020. Biodi(V)strict. A Tool For Incorporating Biodiversity within Development., in: Peuportier, B., Leurent, F., Roger-Estrade, J. (Eds.), *Eco-Design of Buildings and Infrastructure: Developments in the Period 2016-2020*. CRC Press, London, p. 500.
- Melles, S., Glenn, S., Martin, K., 2003. Urban Bird Diversity and Landscape Complexity: Species–environment Associations Along a Multiscale Habitat Gradient. *Conserv. Ecol.* 7. <https://doi.org/https://doi.org/10.5751/ES-00478-070105>
- Mimet, A., Kerbiriou, C., Simon, L., Julien, J.F., Raymond, R., 2020. Contribution of private gardens to habitat availability, connectivity and conservation of the common pipistrelle in Paris. *Landsc. Urban Plan.* 193, 103671. <https://doi.org/10.1016/j.landurbplan.2019.103671>
- Muratet, A., Fontaine, B., 2015. Contrasting impacts of pesticides on butterflies and bumblebees in private gardens in France. *Biol. Conserv.* 182, 148–154. <https://doi.org/10.1016/j.biocon.2014.11.045>
- Paradis, E., Baillie, S.R., Sutherland, W.J., Gregory, R.D., 1998. Patterns of natal and breeding dispersal in birds. *J. Anim. Ecol.* 67, 518–536. <https://doi.org/10.1046/j.1365-2656.1998.00215.x>
- Penone, C., Machon, N., Julliard, R., Le Viol, I., 2012. Do railway edges provide functional connectivity for plant communities in an urban context? *Biol. Conserv.* 148, 126–133. <https://doi.org/10.1016/j.biocon.2012.01.041>
- Rasmussen, S.L., Berg, T.B., Dabelsteen, T., Jones, O.R., 2019. The ecology of suburban juvenile European hedgehogs (*Erinaceus europaeus*) in Denmark. *Ecol. Evol.* 9, 13174–13187. <https://doi.org/10.1002/ece3.5764>

- Ribeiro, M.P., de Mello, K., Valente, R.A., 2022. How can forest fragments support protected areas connectivity in an urban landscape in Brazil? *Urban For. Urban Green.* 74, 127683. <https://doi.org/10.1016/j.ufug.2022.127683>
- Rudd, H., Vala, J., Schaefer, V., 2002. Importance of backyard habitat in a comprehensive biodiversity conservation strategy: A connectivity analysis of urban green spaces. *Restor. Ecol.* 10, 368–375. <https://doi.org/10.1046/j.1526-100X.2002.02041.x>
- Sahraoui, Y., De Godoy Leski, C., Benot, M.L., Revers, F., Salles, D., van Halder, I., Barneix, M., Carassou, L., 2021. Integrating ecological networks modelling in a participatory approach for assessing impacts of planning scenarios on landscape connectivity. *Landsc. Urban Plan.* 209. <https://doi.org/10.1016/j.landurbplan.2021.104039>
- Sahraoui, Y., Foltête, J.-C., Clauzel, C., 2017. A multi-species approach for assessing the impact of land-cover changes on landscape connectivity. *Landsc. Ecol.* 32, 1819–1835. <https://doi.org/10.1007/s10980-017-0551-6>
- Sandström, U.G., Angelstam, P., Mikusiński, G., 2006. Ecological diversity of birds in relation to the structure of urban green space. *Landsc. Urban Plan.* 77, 39–53. <https://doi.org/10.1016/j.landurbplan.2005.01.004>
- Saura, S., Bertzky, B., Bastin, L., Battistella, L., Mandrici, A., Dubois, G., 2019. Global trends in protected area connectivity from 2010 to 2018. *Biol. Conserv.* 238, 108183. <https://doi.org/10.1016/j.biocon.2019.07.028>
- 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. <https://doi.org/10.1016/j.ecolind.2010.06.011>
- Schilling, J., Logan, J., 2008. Greening the Rust Belt: A Green Infrastructure Model for Right Sizing America's Shrinking Cities. *J. Am. Plan. Assoc.* 74, 451–166. <https://doi.org/https://doi.org/10.1080/01944360802354956>
- Schneider, A.K., Strohbach, M.W., App, M., Schröder, B., 2020. The “GartenApp”: Assessing and communicating the ecological potential of private gardens. *Sustainability* 12, 1–15. <https://doi.org/10.3390/SU12010095>
- Serret, H., Raymond, R., Foltête, J.C., Clergeau, P., Simon, L., Machon, N., 2014. Potential contributions of green spaces at business sites to the ecological network in an urban agglomeration: The case of the Ile-de-France region, France. *Landsc. Urban Plan.* 131, 27–35. <https://doi.org/10.1016/j.landurbplan.2014.07.003>
- Smith, R.M., Thompson, K., Hodgson, J.G., Warren, P.H., Gaston, K.J., 2006. Urban domestic gardens (IX): Composition and richness of the vascular plant flora, and implications for native biodiversity. *Biol. Conserv.* 129, 312–322. <https://doi.org/10.1016/j.biocon.2005.10.045>
- Tannier, C., Bourgeois, M., Houot, H., Foltête, J.-C., 2016. Impact of urban developments on the functional connectivity of forested habitats: A joint contribution of advanced urban models and landscape graphs. *Land use policy* 52, 76–91. <https://doi.org/10.1016/j.landusepol.2015.12.002>
- Tarabon, S., Bergès, L., Dutoit, T., Isselin-Nondedeu, F., 2019. Environmental impact assessment of development projects improved by merging species distribution and habitat connectivity modelling. *J. Environ. Manage.* 241, 439–449. <https://doi.org/10.1016/j.jenvman.2019.02.031>
- Tarabon, S., Calvet, C., Delbar, V., Dutoit, T., Isselin-Nondedeu, F., 2020. Integrating a landscape connectivity approach into mitigation hierarchy planning by anticipating urban dynamics. *Landsc. Urban Plan.* 202, 103871. <https://doi.org/10.1016/j.landurbplan.2020.103871>

- Teillac-Deschamps, P., Lorrillière, R., Servais, V., Delmas, V., Cadi, A., Prévot-Julliard, A.C., 2009. Management strategies in urban green spaces: Models based on an introduced exotic pet turtle. *Biol. Conserv.* 142, 2258–2269. <https://doi.org/10.1016/j.biocon.2009.05.004>
- Thompson, P.L., Gonzalez, A., 2017. Dispersal governs the reorganization of ecological networks under environmental change. *Nat. Ecol. Evol.* 1. <https://doi.org/https://doi.org/10.1038/s41559-017-0162>
- Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., James, P., 2007. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landsc. Urban Plan.* 81, 167–178. <https://doi.org/10.1016/j.landurbplan.2007.02.001>
- United Nations, 2018. *World Urbanization Prospects: The 2018 Revision*, Department of Economic & Social Affairs. New York.
- Urban, D., Keitt, T., 2001. Landscape Connectivity : A Graph-Theoretic Perspective. *Ecology* 82, 1205–1218.
- Van Helden, B.E., Close, P.G., Steven, R., 2020. Mammal conservation in a changing world: can urban gardens play a role? *Urban Ecosyst.* 23, 555–567. <https://doi.org/10.1007/s11252-020-00935-1>
- Vergnes, A., Viol, I. Le, Clergeau, P., 2012. Green corridors in urban landscapes affect the arthropod communities of domestic gardens. *Biol. Conserv.* 145, 171–178. <https://doi.org/10.1016/j.biocon.2011.11.002>
- Von Thaden, J., Badillo-Montaño, R., Lira-Noriega, A., García-Ramírez, A., Benítez, G., Equihua, M., Looker, N., Pérez-Maqueo, O., 2021. Contributions of green spaces and isolated trees to landscape connectivity in an urban landscape. *Urban For. Urban Green.* 64. <https://doi.org/10.1016/j.ufug.2021.127277>
- Wauters, L., Casale, P., Dhondt, A.A., 1994. Space use and dispersal of red squirrels in fragmented habitats. *Oikos* 69, 140–146.
- Wauters, L.A., Verbeylen, G., Preatoni, D., Martinoli, A., Matthysen, E., 2010. Dispersal and habitat cuing of Eurasian red squirrels in fragmented habitats. *Popul. Ecol.* 52, 527–536. <https://doi.org/10.1007/s10144-010-0203-z>
- Zeller, K.A., McGarigal, K., Whiteley, A.R., 2012. Estimating landscape resistance to movement: A review. *Landsc. Ecol.* 27, 777–797. <https://doi.org/10.1007/s10980-012-9737-0>
- Zhang, R., Zhang, L., Zhong, Q., Zhang, Q., Ji, Y., Song, P., Wang, Q., 2021. An optimized evaluation method of an urban ecological network: The case of the Minhang District of Shanghai. *Urban For. Urban Green.* 62, 127158. <https://doi.org/10.1016/j.ufug.2021.127158>
- Zhang, Z., Meerow, S., Newell, J.P., Lindquist, M., 2019. Enhancing landscape connectivity through multifunctional green infrastructure corridor modeling and design. *Urban For. Urban Green.* 38, 305–317. <https://doi.org/10.1016/j.ufug.2018.10.014>

Appendices

Appendix 1: Land cover classes, cost values and data sources used for each scenario for European hedgehog

See attached file

Appendix 2: Land cover classes, cost values and data sources used for each scenario for Red squirrel

See attached file

Appendix 3: Land cover classes, cost values and data sources used for each scenario for forest-dwelling passerines

See attached file

Appendix 4: Land cover classes, cost values and data sources used for each scenario for grassland-dwelling moths

See attached file

Appendix 5: Ranking of MFR test-plots with EC metric values for European hedgehog and Red squirrel.

See attached file