Multiple habitat graphs: how connectivity brings forth landscape ecological processes
Supporting information

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In the following appendices, we provide details regarding the modeling choices made for our three case studies. We additionally provide the codes/scripts used for the two first case studies (in R and command lines, respectively).

The format we use for providing this information follows a common baseline and we encourage future users to follow it as well.

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Appendix S1: Case study 1: modeling details

Modeled ecological processes (e.g., dispersal, gene flow, foraging):
Dispersal and dispersal-driven gene flow among forested habitats across urban and peri-urban areas

Focal taxon/taxonomic group/generic ecological profile (provide the common and scientific name when the analysis focuses on a single species):
Urban tolerant species occupying forest habitats, and having intermediate dispersal distances (dispersal probability = 0.05 for a 5 km distance). This encompasses several vertebrate taxa, such as forest birds or mammals.

Objectives of the analyses:

- Modeling the urban and peri-urban habitat network supporting the life cycle of urban tolerant species occupying urban green spaces and (peri-)urban forests.
- Quantifying the respective contribution of urban green spaces and forest to habitat connectivity within and around urban areas.
- Locating the most important habitat patches for dispersal movements among urban green spaces and forests, and for each habitat type.

Graphab version: 3.0

If command lines/scripts are provided, please specify the language/environment:
R script, using the `graph4lg` package.

URL of command lines/scripts if available: `multihab_urban_R_code.R`, Available in Zenodo: https://doi.org/10.5281/zenodo.10576225

Land cover map:

Study area geographic coordinates (Lat., Lon. [WGS 84] of the study area centroid): 48°86'N, 2°72'E

Geographic data source(s): Institut Paris Région, MOS+ 2017

Total study area (km^2) (deducted from the raster study area): 822 km^2, Figures 2 and 3 in the main text cover a central area of about 100 km^2 within it.

Spatial resolution of the landscape map (m): 2 m

Number of land cover categories: 9

List of land cover categories and corresponding integer codes: Table S1 below

Code	Land cover category
1	Forest habitat
2	Urban green spaces
3	Open habitat (not agricultural, nor grasslands)
4	Grasslands
5	Crops
6	Highly modified open habitat
7	Water
8	Impervious areas
9	Built-up areas

Table S1: Land cover categories of the land cover map used for the first case study

Habitat patches and movement paths:

Habitat categories and associated land cover codes:

Habitat name (in Graphab project): habitat1
Type of habitat (e.g., breeding habitat, foraging habitat): Forest habitat
Land cover category (code): Forest habitat (1)
Neighborhood type for habitat patches (rook [4] or queen [8]): rook [4]
Minimal habitat patch area (ha): 0.25

Habitat name (in Graphab project): habitat2
Type of habitat (e.g., breeding habitat, foraging habitat): Urban green spaces
Land cover category (code): Urban green spaces (2)
Neighborhood type for habitat patches (rook [4] or queen [8]): rook [4]
Minimal habitat patch area (ha): 0.25

Link sets:

Link set name: lcp1
Type of movement assumed: Dispersal movements
Connected habitat categories (intra X, inter X and Y, all X and Y): among all habitat patches, irrespective of their category
Link distance type (cost distance or Euclidean): Cost distance
Link set topology (planar or complete): Planar
Cost scenario (if not Euclidean): See Table S2 below.

Land cover category (code)	**Cost**
Forest habitat (1)	1
Urban green spaces (2)	1
Open habitat (not agricultural, nor grasslands) (3)	5
Grasslands (4)	10
Crops (5)	50
Highly modified open habitat (6)	75
Water (7)	900
Impervious areas (8)	1000
Built-up areas (9)	900

Table S2: Cost scenario used for the first case study

Graph construction:

Graph name: g1
(List of) link set(s) used: lcp1
Type of nodes (deducted from link sets): all types of habitats
Type of links (e.g., intra-X, inter X-Y, intra-Y, deducted from link sets): all possible pairs
Graph topology (pruned or same as link set): Same as link set

Graph analysis:

Graph name: g1
Metric name: F
d: 25,000 cost units
p: 0.05
β: 1

The previous metric is computed by taking into account all different types of links among habitat types (1-1, 2-2, 1-2) and separately for each type of habitat patch.

Appendix S2: Case study 2: modeling details

Modeled ecological processes (e.g., dispersal, gene flow, foraging):
Foraging movements of natural enemies preying upon agricultural pests within agricultural landscapes

Focal taxon/taxonomic group/generic ecological profile (provide the common and scientific name when the analysis focuses on a single species):
Invertebrate natural enemies foraging in agricultural crops and breeding in semi-natural areas within agricultural landscapes. This includes for instance common staphylinid beetle species and carabid beetle species.

Objectives of the analyses:

- Modeling the movements among crops and semi-natural areas supporting biocontrol in agricultural landscapes.
- Quantifying temporal changes in connectivity due to changes in agricultural policies and practices.

Graphab version: 3.0

If command lines/scripts are provided, please specify the language/environment:
Command lines.

URL of command lines/scripts if available: `multihab_agri_command_lines`, Available in Zenodo: https://doi.org/10.5281/zenodo.10576225

Land cover map:

Study area geographic coordinates (Lat., Lon. [WGS 84] of the study area centroid): 48°08'N, 1°40'E

Geographic data source(s): Registre Parcellaire Graphique, years 2010 and 2020
Note that the same data and analyzes were used and performed at the two dates.

Total study area (km^2) (deducted from the raster study area): 1,387 km^2

Spatial resolution of the landscape map (m): 5 m

Number of land cover categories: 3

List of land cover categories and corresponding integer codes: Table S3 below

Code	Land cover category
0	Landscape matrix
1	Agricultural crops
2	Semi-natural areas

Table S3: Land cover categories of the land cover map used for the second case study

Habitat patches and movement paths:

Habitat categories and associated land cover codes:

Habitat name (in Graphab project): habitat1
Type of habitat (e.g., breeding habitat, foraging habitat): Agricultural crops, used for foraging
Land cover category (code): Agricultural crops (1)
Neighborhood type for habitat patches (rook [4] or queen [8]): rook [4]
Maximum habitat patch extent (m)[1]: 500 m

Habitat name (in Graphab project): habitat2
Type of habitat (e.g., breeding habitat, foraging habitat): Semi-natural areas, used for breeding and overwintering
Land cover category (code): Semi-natural areas (2)
Neighborhood type for habitat patches (rook [4] or queen [8]): rook [4]
Maximum habitat patch extent (m): 500 m

Link sets:

Link set name: jl_inter_euc
Type of movement assumed: Seasonal foraging movements
Connected habitat categories (intra X, inter X and Y, all X and Y): only among crops and semi-natural areas, excluding movement paths within them
Link distance type (cost distance or Euclidean): Euclidean
Link set topology (planar or complete): Complete, with a pruning distance criterion
Pruning distance threshold (if pruned topology at the link set creation step[2]): 1000 m

Graph construction:

Graph name: g_inter
(List of) link set(s) used: jl_inter_euc

[1]This parameter allows users to split habitat patches into several ones as soon as one side of the rectangular extent polygon of a patch exceeds the specified size.

[2]N.B.: The topology of a link set and that of the graph created from it can be different. For instance, a pruned graph can be built from a complete link set. However, the reverse is not true and a complete graph cannot be created from a pruned or planar topology.

Type of nodes (deducted from link sets): crops and semi-natural areas (habitat1, habitat2, respectively)
Type of links (e.g., intra-X, inter X-Y, intra-Y, deducted from link sets): among habitat1 and habitat2, provided the path is no longer than 1000 m.
Graph topology (pruned or same as link set): Pruned (1000 m threshold)

Graph analysis:

Graph name: g_inter
Metric name: EC
d: 1,000 m
p: 0.05
β: 1

Graph name: g_inter
Metric name: F
d: 1,000 m
p: 0.05
β: 1

Appendix S3: Case study 3: modeling details

Modeled ecological processes (e.g., dispersal, gene flow, foraging):
Migration between aquatic and terrestrial habitats. Dispersal between aquatic habitats, passing through one or more intermediate terrestrial habitats used over winter.

Focal taxon/taxonomic group/generic ecological profile (provide the common and scientific name when the analysis focuses on a single species):
Generalist amphibian group, with ponds as its aquatic habitat and a variety of forest and open land habitats as its terrestrial habitat. This includes for instance the Agile frog, the Common frog or the European tree frog.

Objectives of the analyses:

- Modeling the ecological network supporting the life cycle of amphibian species using both aquatic and terrestrial habitats.
- Locating the most important habitat patches for migration and/or dispersal movements among aquatic and terrestrial habitats, and for each habitat type.

Graphab version: 3.0

Land cover map:

Study area geographic coordinates (Lat., Lon. [WGS 84] of the study area centroid): 48°44'N, 2°17'E

Geographic data source(s): Institut Paris Région (2021), IGN 2021, BD TOPO, inventory of ponds from the National Society for the Protection of Nature (SNPN).

Total study area (km^2) (deducted from the raster study area): 168 km^2

Spatial resolution of the landscape map (m): 3 m

Number of land cover categories: 21

List of land cover categories and corresponding integer codes: Table S4 below

Habitat patches and movement paths:

Habitat categories and associated land cover codes:

Habitat name (in Graphab project): HT
Type of habitat (e.g., breeding habitat, foraging habitat): Terrestrial habitat

Code	Land cover category
1	Shrubland
2	Forest
3	Crop
4	Grassland
6	Urban green space
7	Other wetland
8	Wet grassland
9	Wet forest
10	Artificialized open spaces
11	Urbanized area
12	Hedge
13	Pathway
14	Tertiary road
15	Railway
16	Secondary road
17	Primary road
18	Small river
19	Small pond
20	Large pond
21	Large river

Table S4: Land cover categories of the land cover map used for the third case study

Land cover category (code): Forest (2), Wet grassland (8), Wet forest (9)
Neighborhood type for habitat patches (rook [4] or queen [8]): queen [8]
Minimal habitat patch area (ha): 0.01

Habitat name (in Graphab project): HR
Type of habitat (e.g., breeding habitat, foraging habitat): Aquatic habitat (reproduction)
Land cover category (code): Small pond (19)
Neighborhood type for habitat patches (rook [4] or queen [8]): queen [8]

Link sets:

Link set name: jl_inter_cost
Type of movement assumed: Migration between aquatic and terrestrial habitats
Connected habitat categories (intra X, inter X and Y, all X and Y): inter HT and HR
Link distance type (cost distance or Euclidean): Cost distance
Link set topology (planar or complete): Complete
Cost scenario (if not Euclidean): See Table S5 below.
Pruning distance threshold (if pruned topology at the link set creation step): 16,506 cost units

Land cover category (code)	Cost
Shrubland (1)	100
Forest (2)	1
Crop (3)	1000
Grassland (4)	10
Urban green space (6)	1000
Other wetland (7)	1
Wet grassland (8)	1
Wet forest (9)	1
Artificialized open spaces (10)	1000
Urbanized area (11)	10000
Hedge (12)	10
Pathway (13)	100
Tertiary road (14)	500
Railway (15)	500
Secondary road (16)	1000
Primary road (17)	1000
Small river (18)	10
Small pond (19)	1
Large pond (20)	10
Large river (21)	1000

Table S5: Cost scenario used for the third case study

Graph construction:

Graph name: g_hr_cost
(List of) link set(s) used: jl_inter_cost
Type of nodes (deducted from link sets): HR and HT
Type of links (e.g., intra-X, inter X-Y, intra-Y, deducted from link sets): inter HT and HR
Graph topology (pruned or same as link set): Pruned (1000 m)

Graph analysis:

Graph name: graph1000
Metric name: F
d: 2,000 cost units
p: 0.05
β: 1

Publication: See details in Clauzel, C., Godet, C., Tarabon, S., Eggert, C., Vuidel, G., Bailleul, M., and Miaud, C. (2024). From single to multiple habitat connectivity: The key role of composite ecological networks for amphibian conservation and habitat restoration. *Biological Conservation*, 289:110418.