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*Indicateur de biodiversité potentielle : exemple dans une matrice paysagère
anthropisée et fragmentée*

*Indicador de biodiversidad potencial: ejemplo de una matriz de paisaje
antropizado y fragmentado*

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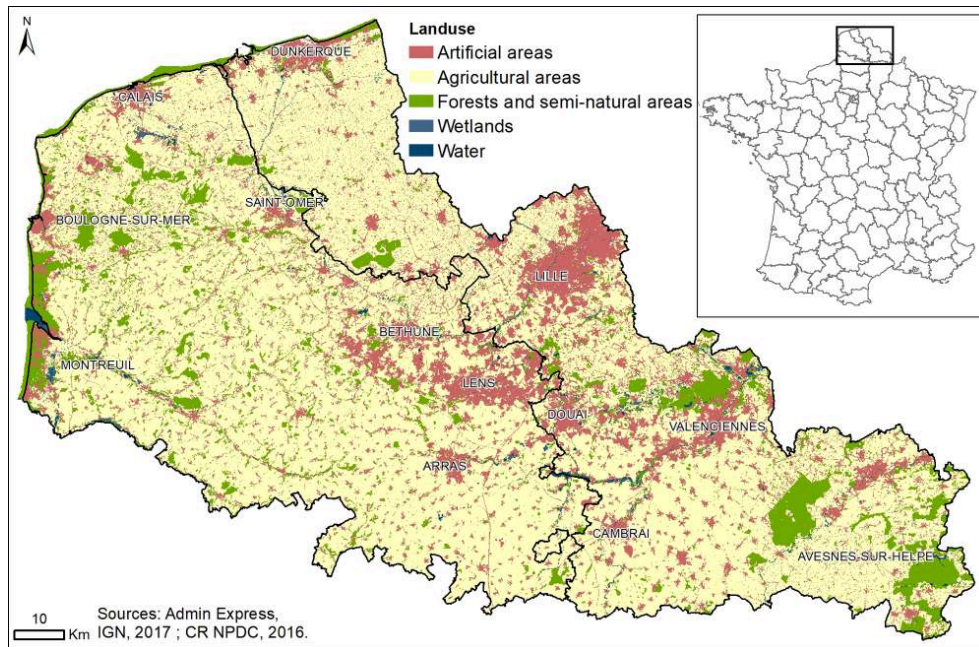
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Introduction

- 1 Promoting biodiversity has become an essential element in urban planning (Fischer et al., 2018). The Convention on Biological Diversity (1992, art. 2) defines biodiversity as “the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems”. Therefore, biodiversity covers three levels of genetic diversity, species diversity, ecosystem diversity and landscape diversity. At the global scale, the main factors contributing to the loss of biodiversity include the following:
 - habitat modification, fragmentation and destruction, especially through the growth of built-up areas and transport infrastructure,
 - introduction of invasive species,
 - pollution of ecosystems,
 - over-consumption of natural resources and,
 - climate change (Secretariat of the Convention on Biological Diversity, 2014).

- 2 Sustainable urban planning involves reducing the effects of these main factors, but also strengthening and creating green infrastructure, such as greenways (Walmsley, 2006). Urban planners need biodiversity indices to identify effective planning solutions for both biodiversity and development in anthropised areas (Hermy, Cornelis, 2006; Bekessy *et al.*, 2012). According to Walz and Syrbe (2010), biodiversity indices fall into two categories: those relating to species richness based on fauna and flora inventories and those relating to ecosystem characteristics on the basis of land use. The former indicators are heterogeneous and insufficiently adapted to the needs of urban planners (in terms of perimeter and spatial resolution). Moreover, urban planners generally have little training in ecology¹ (Alphandéry, Fortier, 2015). The latter indices have been more widely used, especially since the advent of landscape ecology (O'Neill *et al.*, 1988). The landscape can be a link between scientific knowledge on fauna and flora and urban planning (Mander, Uuemaa, 2010), because the organisation of the landscape matrix influences biodiversity according to biophysical conditions and land-use patterns. Landscape metrics can describe the variety of the landscape matrix, and also have connections with species diversity and abundance (McGarigal, 2002).
- 3 Landscape metrics are numerous and require a detailed knowledge of ecological processes (Walz, 2015). Landscape metrics for estimating the biodiversity potential of habitats have been the subject of numerous investigations and creation of synthetic indices (Kujala *et al.*, 2015; Tarabon *et al.*, 2020). In this article, we focus on the most widely used indices found in the literature and that can be used in a geographic information system (GIS), the preferred urban-planning tool (Vimal, Mathevet, 2011). The study area is highly anthropised and the landscapes are very fragmented. The urban planning documents for this area endeavour to strengthen connectivity by introducing a greenway (Franchomme *et al.*, 2013), therefore drawing heavily on indices of connectivity and habitat permeability. Thus, this article focuses on biodiversity-related indices to model an anthropised and fragmented landscape matrix.
- 4 In the first part, the construction of a composite index is detailed, because it is more easily appropriated by planners than several indices. With planners in mind, we also favour the vector format within a GIS² in the various calculations of landscape metrics (Yu *et al.*, 2019). This method is based on spatial analysis tools and the use of knowledge of experts in ecology, law, urban planning and geography. The results and contributions of the index are presented in the second part, focusing on the possibilities of monitoring the biodiversity potential in the initial phases of urban planning projects.
- 5 The study area comprises two intermediate French administrative divisions (known as *départements*, hereafter referred to in English as 'departments'): Nord and Pas-de-Calais (12 485 km²), with a population of 4,077,866 at the last population census. Natural areas are rare in this region, having the lowest surface area among all French departments, either in absolute or relative terms (Schmitt, 2009).

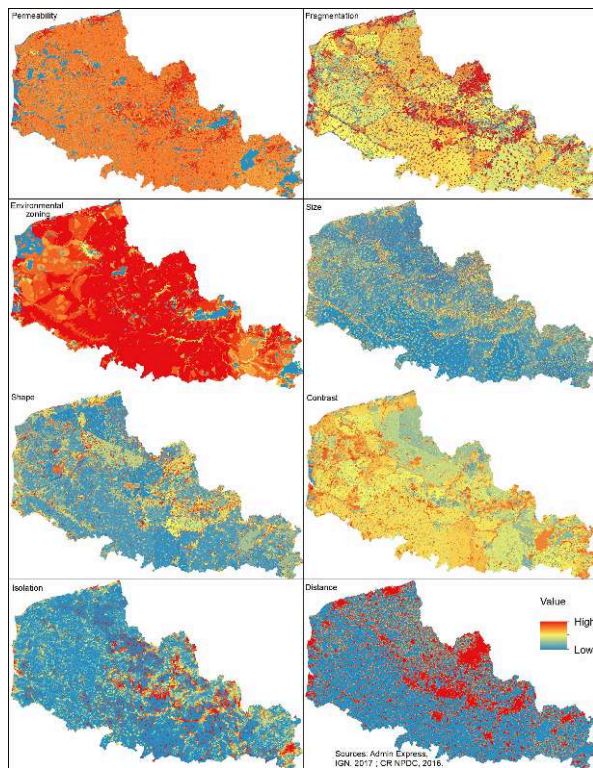
Figure 1: Map of the study area and its land uses



Method: modeling the landscape matrix

- 6 We developed a composite biodiversity potential index (CBPI) to model the landscape matrix of the study area. This index was constructed using eight indices³ of spatial quality, pattern and structure borrowed from landscape ecology (Riitters *et al.*, 1995; Aguejdad, Hubert-Moy, 2016) and supplemented with expert consultations during the whole modeling process (Dale *et al.*, 2019). The choice of indices considers structural connectivity (Taylor *et al.*, 2006). It corresponds to the organisation of the landscape patches that make up the landscape mosaic. Landscape structure affects the movement of species and is a component of biodiversity (Renetzeder *et al.*, 2010). In addition, functional connectivity is also assessed from a generic species profile (medium-sized mammals) to integrate the processes of supplementation and complementation in a fragmented landscape matrix (Ouin *et al.*, 2004). The first process is related to the movement of a species to obtain the necessary resources in a fragmented matrix for small habitats. The second process is linked to the life cycle of the species (reproduction, migration, etc.). Figure 2 illustrates the eight indices that are component of the CBPI in the study area. It is possible to distinguish the discriminatory potential of each index. The eight indices are presented in the following sections.

Figure 2: The eight indices composing the composite biodiversity potential index (CBPI)



Quality indices characterising the biodiversity of the landscape

- 7 Three quality indices were used in this study, and involve land use, fragmentation and environmental management of each entity in the landscape matrix.

Permeability index

- 8 The first index was developed from the latest available land-use map for Nord and Pas-de-Calais. The map is based on two sets of aerial photographs taken in 2009 at a spatial resolution of 20 cm in the visible and near-infrared regions of the electromagnetic spectrum. The map uses European Corine Land Cover (CLC) nomenclature with three nested levels and also includes a fourth level, giving a total of 54 categories to refine the distinctions within each of the following areas:
- artificial surfaces, varying with building density and use intensity (11 categories in the CLC vs 26 in the database we used),
 - agricultural areas, varying with crop assortment and cultivation practices (4 categories vs 6),
 - natural areas, with for example a distinction between forested areas according to planting or harvest date (13 categories vs 22).
- 9 With a recommended working scale of 1:25,000, a source scale of 1:15,000 and an observed minimum mapping unit of less than 100 m², the represented landscape matrix is complex and is composed of some 125,000 objects. Using a previously tested method, the various categories were grouped into six levels of increasing permeability for movements of medium-sized mammals⁴ common in northern France by distinguishing between areas that are difficult to cross, areas to be avoided, areas of occasional passage, substitute habitats, habitats amenable to reproduction and habitats ensuring

high reproduction and survival rates (Mimet *et al.*, 2017; Schmitt *et al.*, 2014). This species profile was based on a generalist medium-sized mammal for several reasons. Medium-sized mammals have an ecological profile corresponding to the landscape matrix in terms of habitat size, dispersal capacity and ecosystem (Opdam *et al.*, 2008). Their profile corresponds to a landscape species approach (Sanderson *et al.*, 2002). These mammals are studied by managers and developers because they are sensitive to management plans and actions to promote connectivity (Calenge *et al.*, 2015), which is the main objective of conservation planning (SRCE, Schéma Régional de Cohérence Écologique) in the study area (Weber, Allen, 2010). The regional wildlife organisation of the study area reports the presence of 41 mammal species including 22 considered 'threatened' according to the International Union for Conservation of Nature (IUCN). The average distance of 5 km between the biodiversity reservoirs identified in the regional land-use and conservation planning scheme (SRCE) is consistent with the movements of a medium-sized mammal (Minor, Lokkingbill, 2010).

- 10 This typology was compared with the expert knowledge of three ecologists on three test areas where they had conducted surveys (Table 1). Ten levels of permeability to movement were selected with a wider range between levels, particularly for areas to be avoided (Kinldmann, Burel, 2008):
- areas that are very difficult to cross (8 land-use categories, score 100),
 - areas that are difficult to cross (9 land-use categories, score 95),
 - areas to be avoided (1 land-use categorie, score 80),
 - areas of occasional passage (6 land-use categories, score 75),
 - substitute habitats (2 land-use categories, score 70),
 - better substitute habitats (2 land-use categories, score 60),
 - habitats amenable to reproduction (4 land-use categories, score 50),
 - habitats very amenable to reproduction (2 land-use categories, score 40),
 - habitats ensuring high survival rate (4 land-use categories, score 20),
 - habitats ensuring high reproduction and survival rates (12 land-use categories, score 1).
- 11 Table 1 also contains the change in the number of polygons in the initial land cover database after its modification following the scoring of the eight indices. The number of polygons increased from 125,000 to nearly 520,000, providing a finer estimate of biodiversity potential. Table 1 also contains the mean, median and standard deviation of CBPI for all land-use categories. The highest scores correspond to the least favourable habitats and the lowest values to the most favourable habitats. Variations in CBPI for the same habitat type or land-use category are explained by spatial variations in quality, shape and configuration indices.
- 12 Then, the indices of quality, shape and configuration were normalised from 0 to 100 to make them easier to weight (Liénard, Clergeau, 2011).

Table 1: The permeability index and the change in the composition of the landscape matrix after scoring the quality, shape and configuration indices

Permeability of land-use (value)	Permeability of land use (habitat)	Land-use category	Initial number of entities	Number of entities after scoring of the 8 indices of CBPI	Change (%)	Average CBPI	Median CBPI	Standard deviation CBPI
1	habitats ensuring high reproduction and survival rates	Broad-leaved forest	12689	65313	414.72	35.05	37.24	9.81
		Broad-leaved forest on sand dunes	437	3168	624.94	26.59	24.78	10.36
		Bushes, shrubs and herbaceous plants on sand dunes	666	3265	390.24	24.58	23.32	10.73
		Coniferous forest	936	3186	240.38	27.58	26.88	11.21
		Coniferous forest on sand dunes	203	805	297.04	25.12	23.89	11.73
		Dunes, beaches	27	844	3025.93	29.63	28.75	8.31
		Grey dunes	950	3399	257.79	23.69	21.73	10.56
		Inland marshes	1319	8791	566.49	30.13	30.9	10.11
		Natural grassland	195	1043	434.87	31.49	34.83	10.33
		Rock outcrops, cliffs	8	251	2787.5	29.02	28.15	8.29
		Salt marshes	18	124	588.89	31.49	34.83	10.32
		White dunes	762	2088	174.02	22.19	19.46	10.00
		20	habitats ensuring high survival rate	Estuaries	7	90	1185.71	23.89
Forest clear-cuts	1862			7166	284.85	35.91	36.65	10.45
Recent reforestation	1933			6410	231.61	40.34	41.56	9.53
Water bodies	5707			16071	181.6	32.09	33.44	10.79
Water courses	180			4102	2178.89	36.07	37.13	7.25
40	habitats very amenable to reproduction	Poplar forests	5024	23203	361.84	49.6	50.74	9.46
		Recent poplar forests	386	1855	380.57	47.27	48.44	10.21
50	habitats amenable to reproduction	Fruit trees and berry plantations	772	3203	314.9	58.05	58.24	6.98
		Green urban areas	1102	2621	137.84	60.72	61.25	9.12
		Mine dump sites	178	936	425.84	53.5	53.14	7.51
60	better substitute habitats	Quarry pits	77	387	400.6	53.87	55.17	7.43
		Complex cultivation patterns	177	1034	484.18	52.43	53.14	9.9
70	substitute habitats	Market gardening, greenhouses	1506	6553	335.42	61.88	62.78	7.68
		Abandoned (fallow) land	5891	24929	323.17	61.12	62.11	9.12
75	areas of occasional passage	Pasture	23800	133306	460.11	60.8	61.54	7.96
		Abandoned industrial areas	607	1547	154.86	67.9	68.86	7.75
		Areas of sport compounds	2517	5209	106.95	67.92	68.7	7.51
		Camping, caravanning	504	1980	292.86	64.68	65.35	8.08
		Cemeteries	1935	3153	62.95	71.02	71.41	7.04
		Golf	22	130	490.91	63.85	64.13	4.65
80	areas to be avoided	Working-class gardens	829	1564	88.66	68.43	69.18	7.5
		Permanent crops	7409	66331	795.28	60.88	61.66	7.67
95	areas that are difficult to cross	Airports	19	84	242.11	71.89	73.42	3.86
		Commercial units	650	1052	61.85	75.6	76.64	6.02
		Hospital units	231	428	85.28	75.02	75.44	6.24
		Industrial units	5771	11921	106.57	75.23	75.72	6.52
		Isolated housing	19780	42793	116.34	77.29	78.76	5.4
		Medium-density residential areas	10049	43656	328.46	75.76	76.52	6.78
		Mining housing	464	1216	161.07	77.28	77.94	7.39
		Other public units	1766	3223	82.5	75.14	75.28	7.2
		Scholar units	2318	3041	31.19	74.15	73.95	5.9
100	areas that are very difficult to cross	Construction sites	1198	2142	78.8	78.88	79.13	6.69
		Continuous and dense urban fabric	187	462	114.97	75.85	76.92	7.18
		Dump sites	1018	1930	98.59	78.67	79.08	7.67
		High-rise collective housing	1060	1300	22.64	79.63	79.76	5.4
		Major railway axes and associated spaces	192	672	250.00	74.9	75.26	6.21
		Major roads and associated areas	378	2154	469.84	77.75	78.21	7.44
		Port areas	63	199	215.87	80.6	81.02	5.73
		Storage area	22	39	77.27	79.24	81.18	5.49
Total			125800	519690	313.11			

Habitat fragmentation index

- 13 The second quality index corresponds to an assessment of the fragmentation of each occupied patch. This index was used for a practical reason: land-use maps do not show all roads (only roads exceeding 25 m in width were inventoried). Also, from a landscape ecology point of view, roads are known to have effects – in terms of road kill or noise pollution – on species diversity and richness (Forman, Alexander, 1998). The density (linear metres per km²) of all passable roads were thus calculated for each patch by weighting them by their number of lanes, their administrative classification and their width, when this information was available in large-scale reference maps (IGN). This quality index also constitutes an index of exposure to human activity (Bernier, Théau, 2013 – Figure 3). This index is easily updated, because it uses standardised, open data.

Figure 3: Illustration of the habitat fragmentation index



Environmental management index

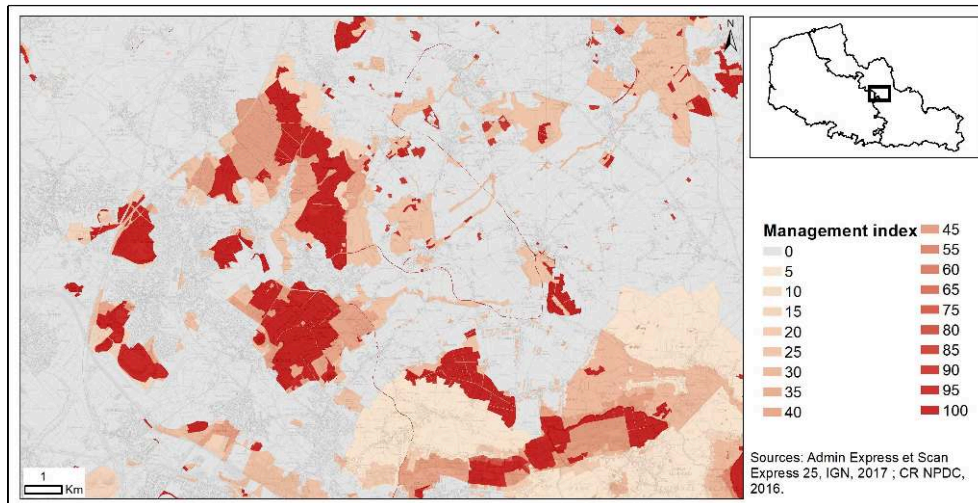
- 14 The third quality index involves the estimation of biodiversity. We originally planned to use fauna and flora inventories, but their great heterogeneity, their temporal and spatial anisotropy and their scarcity led us to choose a different approach (Alphandéry, Fortier, 2015). Thus, the environmental management index was estimated using different zoning categories used for inventory and for protected areas (Dudley, 2008). In the study area, there are 19 coexisting zoning categories or zones, which can overlap. For example, up to eight zones overlapped in the Audomarais marshes near Saint-Omer. These different zones can be defined by international law (biosphere reserves part of the Man and Biosphere programme, MAB), European law (Special Protection Areas, SPAs), national law (biological reserves), be part of regional policies (regional natural reserves) or formulated locally ('natural areas') identified in local land-use plans (PLU, *Plan local d'urbanisme*). These zones do not all have the same regulatory scope (more or less restrictive measures) and sometimes involve specific environment management methods (Natura 2000 reference documents), more or less strict zoning rules regarding constructability (natural areas and classified wooded areas in local land-use plans) or are simply areas delimited for inventories (Natural Areas of Ecological, Faunistic and Floristic Value, ZNIEFF). Therefore, the use of these zones as an environmental management index was cross-checked with experts in land-use planning, environment, geography and ecology, who sit on the scientific boards of regional natural parks or MAB reserves.
- 15 More specifically, we first produced a map of these zones and then showed this map individually to five experts to confer with them about what these zones actually meant. These interviews showed that the number of zones for a given patch was not a sufficiently significant variable. Although an area covered by high number of zones likely indicates an area with high environmental value or stakes, zones also reflect work on land-use planning in the interest of keeping urbanisation in check or to promote tourism (Lorant-Plantier, 2014). Moreover, not all zones benefit from the same degree of conservation. For example, acquisition of public land (i.e. coastal or lakeside areas) or the investment of public funds are the manifestations of a desire to preserve the environment or of the presence of remarkable or high biodiversity (Table 2).

Table 2: The different denominated zones found in the study area and their weights based on consultation with experts for the development of a composite biodiversity potential index

Coastal Conservatory lands	100
Departmental Sensistive Natural Areas	
Regional Nature Conservatory lands	
Natural Regional Reserves	
National Nature Reserves	
Biotope decrees	
Classified wooded areas identified in local land-use plans	90
Special Protection Areas defined in the Birds Directive of 2 April 1979	60
Special Areas of Conservation defined in the Habitats Directive of 21 May 1991	
Proposed Sites of Community Importance	
Hunting and wildlife reserves	45
National and (local) Forest Biological Reserves	
Biosphere reserves part of the UNESCO Man and Biosphere program	35
Ramsar list wetlands	
Natural (no-build) areas identified in local land-se plans	25
Important Bird Areas	20
Natural Areas of Ecological, Faunistic and Floristic Interest (ZNIEFF 1)	15
Natural Areas of Ecological, Faunistic and Floristic Interest (ZNIEFF 2)	10
Regional Natural Park	5

- 16 After interviews with experts, we organised a group meeting during which each expert proposed a ranking of zones according to his/her field of knowledge. During the group meeting, IUCN's Protected Area Categories System was not satisfactory. Indeed, some areas classified with the IUCN system as high level had a lower biodiversity potential according to experts than other areas managed by the department (classified in the IUCN system with a lower level of protection). The confrontation of the different rankings helped establish a score for each zone. In the case of disagreements amidst experts, the land use was used as the final decision criterion. For example, ZNIEFF 1 (score 15) is composed equally of artificial areas, forest and semi-natural areas. ZNIEFF 2 (score 10) has one-third less forest and semi-natural areas, and more agricultural and artificial areas. Within the two inventory areas, parcels often have higher scores if they are included in national or regional reserves (Figure 4). The zoning categories of "natural regional reserves", "national nature reserves" and "biotope decrees" were the most difficult to classify; in these areas, the consensus among experts was frequently more difficult to reach. Ultimately, the choice was made to apply the maximum score identified. This zone scoring system was used to assign each occupied patch a score from 0 to 100 according to whether it belonged to an inventory zone or to an environmental conservation zone.

Figure 4: Illustration of the environmental management index



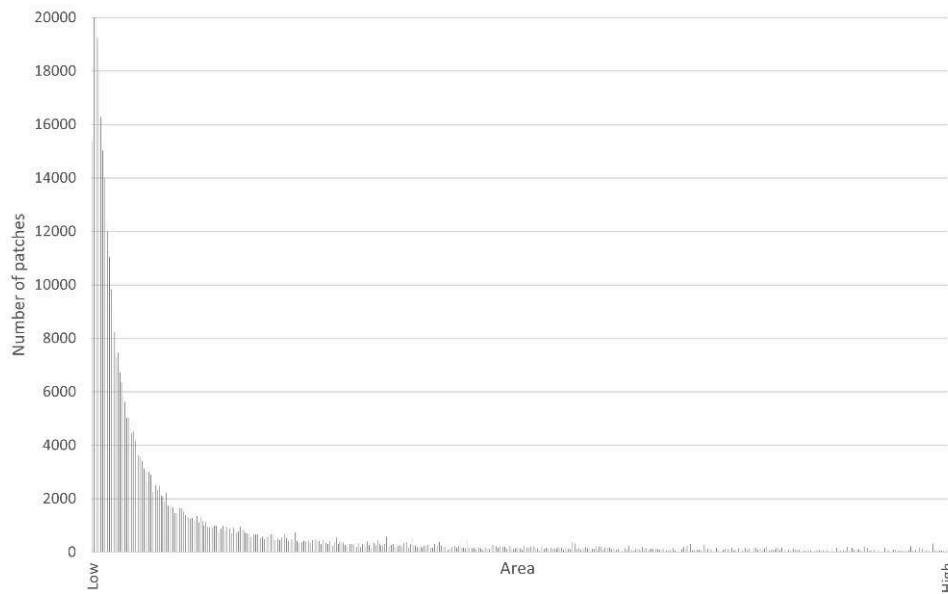
Shape indices characterise fragmentation and landscape connectivity

- 17 Indices of patch shape are frequently employed – and often amended – in landscape ecology to study landscape fragmentation and connectivity (Turner *et al.*, 2015). Patch shape effectively influences mammal movements (Hardt, Forman, 1989). Indices are generally strongly inter-correlated and depend on patch size (Hargis *et al.*, 1998).

Size index

- 18 For each patch in the study area, we successively calculated the perimeter-to-area ratio, the shape index and the fractal dimension index (McGarigal *et al.*, 2002). In particularly fragmented landscapes such as those found in northern France, the choice of a given patch shape index was based on the complementarity with the area index (Figure 5).

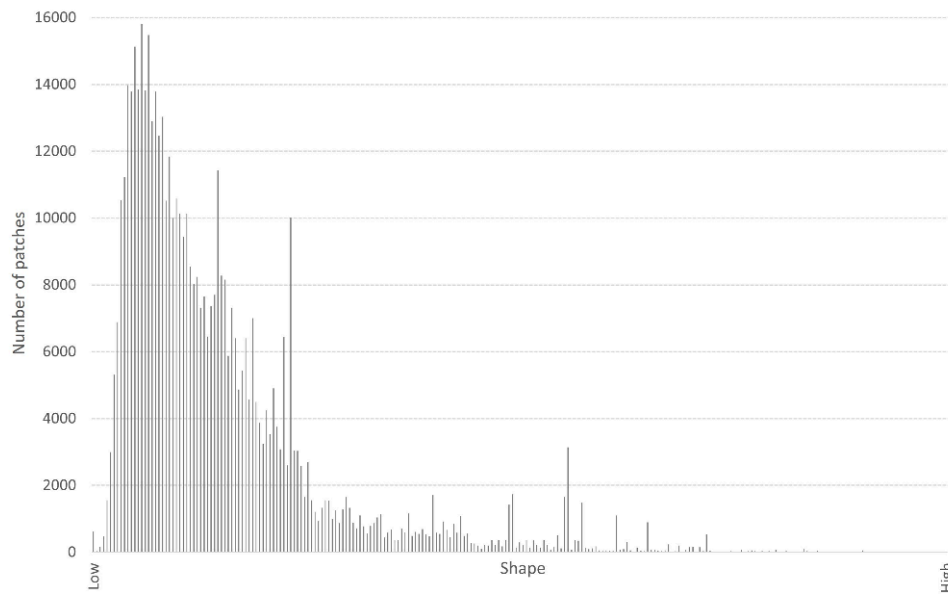
Figure 5: Illustration of size index in the study area: most patches have a low surface area



Shape index

- 19 Shape indices are particularly used to describe natural habitats (forest, wetlands, etc.). The relationship between population or building density and biodiversity is well documented (Tratalos et al., 2007). The relationship between biodiversity and the shape of urban areas, or more generally habitats less favourable to biodiversity, is less frequently investigated (Flégeau et al., 2021). Urban structures have an influence on the biodiversity of nearby spaces (Tannier et al., 2012). The presence of mammals varies within urban areas and they are often more numerous in the suburban areas or where there is a significant presence of parks (Parsons et al., 2018). Considering the configuration of urban areas (private gardens on the periphery, decreasing density with distance from the centre, etc.) and the low proportion of natural areas in the study area (Figure 1), we created a shape index for the habitats defined by the permeability index. We measured the internal complexity of habitats encompassing several categories of land cover/use. The index is particularly discriminating for occasional or avoidable habitats (see Figure 10). In practice, we calculated the ratio between the number of vertices and the line length of the land-use polygons comprising these habitats (Moser et al., 2002). This index also provides a measure of edge effects between patches on species movements in relation to the quality indices and configuration indices (Figure 6).

Figure 6: Illustration of the shape index



Configuration indices reveal the pattern of habitat distribution

- 20 We used three different configuration indices. They depict the connectivity potential of each patch with respect to its environment according to patch contiguity or proximity (Haines-Young et al., 1996).

Contrast index

- 21 The first index involves topological contiguity and the level of contrast between adjacent patches (McGarigal et al., 2002). It measures the degree of isolation, for example a forest in an urban area or, at the other extreme, a high degree of similarity with adjacent patches. An urban area with many borders on quality habitats will have a more favourable contrast index than an urban area surrounded by agricultural land. It was calculated in vector mode in GIS⁵ by subdividing the perimeter of each patch according to its contiguity at different degrees of permeability defined above. Subdivisions of each patch are then weighted according to the length of the shared edge and summed to give a single contrast index (Figure 7).

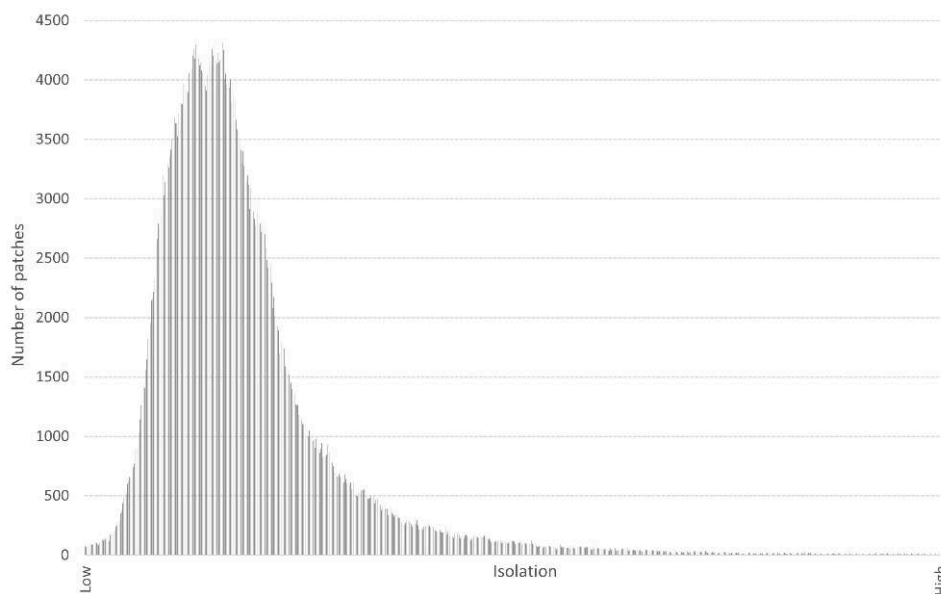
Figure 7: Illustration of the contrast index



Isolation index

- 22 The second index is related to the isolation of each patch and can be used to compare the degree of isolation of patches (Bender *et al.*, 2003). Within a radius of 5 km corresponding to the average travelling distance for a medium-sized mammal, we calculated the number and distance of 'habitats ensuring high reproduction and survival rates' defined in the permeability index for each polygon (Figure 8). The average distance to the best habitats is the most discriminating variable and there is a positive correlation between proximity to biodiversity hotspots and biodiversity potential at the regional scale (Rüdissler *et al.*, 2012).

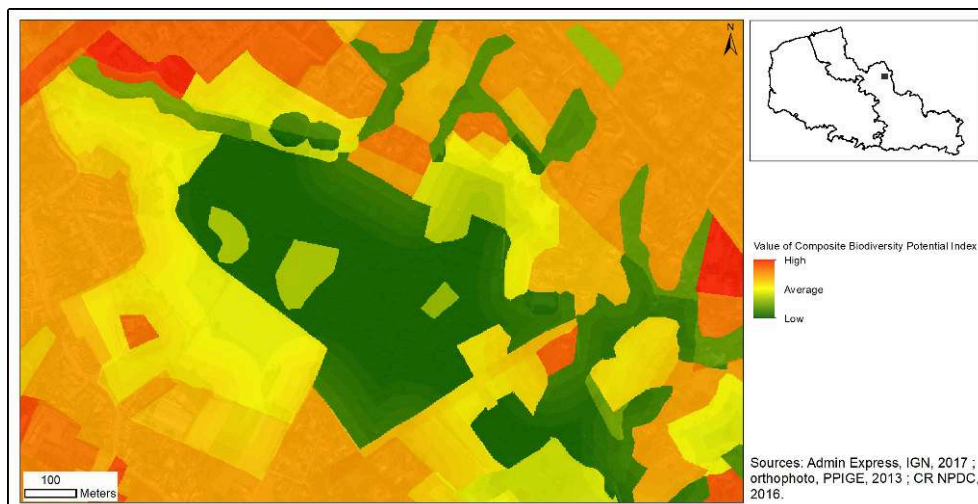
Figure 8: Illustration of the isolation index



Distance index

- 23 The third index measures the distance from built-up areas defined from the land-use map. Proximity to built-up areas seems to generate avoidance behaviour in medium-sized mammals (Crocchi *et al.*, 2008; Jolivet *et al.*, 2015). In Nord and Pas-de-Calais, the impervious surfaces inventoried in the 2009 map cover 15.8%. We applied successive buffer zones to built-up areas, using a step size of 25 m, and a threshold of 100 m. With this buffer zone, the influence of built-up areas extends to 22.2% of the study area. With increasing distance from built-up areas, the distance index decreases with a threshold effect (Figure 9).

Figure 9: Illustration of influence of the distance index on the composite biodiversity potential index



Weighting the indices to construct a composite biodiversity potential index

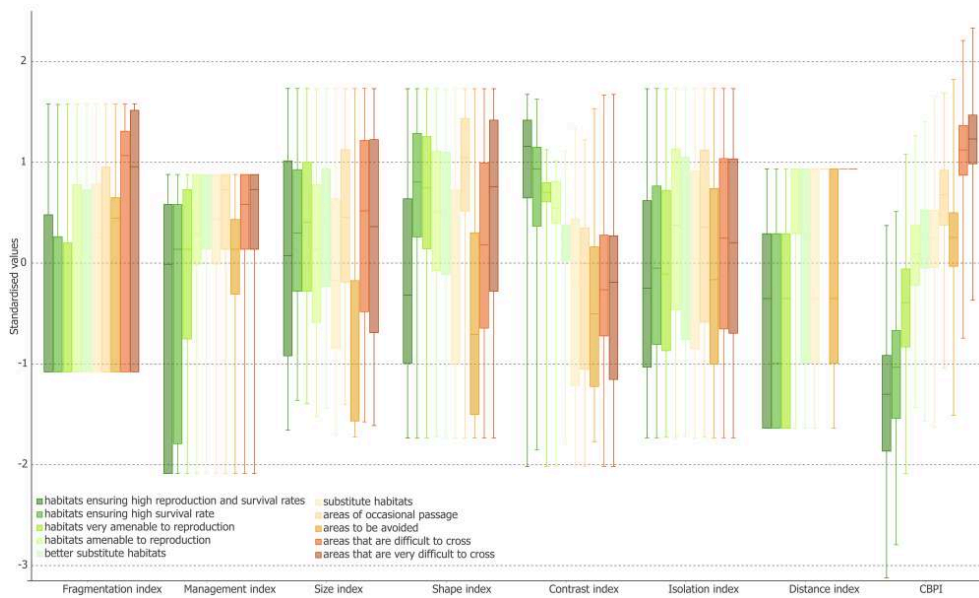
- 24 After this initial preparatory phase, the landscape matrix was composed of 520,000 patches and the weight of each index was determined after consultations with ecologists, geographers and legal experts to produce a composite index of biodiversity potential (CBPI). We adopted a multidimensional index construction method based on the same principles of the permeability index and based on Dobbie and Dail (2013): use of common indices, standardisation, statistical progressiveness of weighting and aggregation, statistical testing and local studies. Compared with other multi-criterion analysis methods, this approach has the advantage of having been used on the permeability index with experts who knew the study area. Here, the weighting of the eight indices was done by the same experts who defined the permeability and environmental management index (Table 3). The same iterative method was used (individual weighting, then group meeting). However, this method is more time-consuming, because each index was gradually adjusted on a map during the group meeting and local examples (shown in Figures 3, 4, 7 and 9) were based on the experts' knowledge of the area. In practice, the regional level of the landscape (permeability, environmental management) is favoured in the prioritisation of indices (Noss, 1990).

Table 3: Weighting of the quality, shape and configuration (exposure) indices to construct a composite biodiversity potential index (CBPI), scaled from 0 to 100.

Index category	Criteria used	Variables used	Adjustment of data distribution	Weight of the index in %	
Quality indicator	Permeability of land-use	Land-use in 54 categories	10 levels from 0 to 100	35	composite potential biodiversity index (CBPI) from 0 to 100.
	Habitat fragmentation	Density of roads per km ²	Scaled from 0 to 100	10	
	Environmental management	Environmental zoning	Scaled from 0 to 100	20	
Shape indicator	Size	Area in ha	Scaled from 0 to 100	5	
	Shape	Complexity of the habitat shape (vertices and lines)	Scaled from 0 to 100	5	
Configuration indicator	Contrast	Edge indicator	Scaled from 0 to 100	10	
	Isolation	Proximity to and number of the best habitats	Scaled from 0 to 100	10	
	Distance from built-up areas	Threshold of "pressure"	Scaled from 0 to 100	5	

- 25 The variations of the indices composing the CBPI according to the degrees of permeability thus illustrate the heterogeneity of the landscape matrix (Figure 10). The fragmentation index is highest for the least favourable habitats. It distinguishes the most suitable habitats according to the density of the road network. The management index refined the CBPI for the most suitable habitats. In addition, it gave a positive value to artificialised areas with a biodiversity protection system (quarry pit with the presence of endangered animals, etc.). The size index (5% of the CBPI) scores the largest habitats in relation to the smallest, in particular for the "better substitute habitats". The shape index complements the size index. It is highest for habitats containing urban spaces and quite clearly separates the most suitable habitats according to their shape. The contrast index reduces the CBPI of the most suitable habitats with many boundaries with the least favourable habitats. Conversely, the potential of occasional habitats is enhanced when there are adjacent forests, for example. The isolation index distinguishes among the most favourable habitats according to their respective spacing. In contrast, and especially for the least favourable small habitats, the CBPI is enhanced according to the number and distance to the habitats of better quality. The distance index provides nuances in the description of the potential of habitat edges. The CBPI has an increasing average score from 'habitats ensuring high reproduction and survival rates' to 'areas that are very difficult to cross', with the exception of 'areas to be avoided' which correspond solely to 'permanent crops'. The high average size of 'permanent crops' and the evolution of the number of polygons (+ 800% - Table 1) explain the score and deviations of the CBPI. More generally, the differences in CBPI illustrate its ability to estimate the biodiversity potential of a patch according to its qualities, shape and configuration.

Figure 10: Index statistics according to the level of permeability



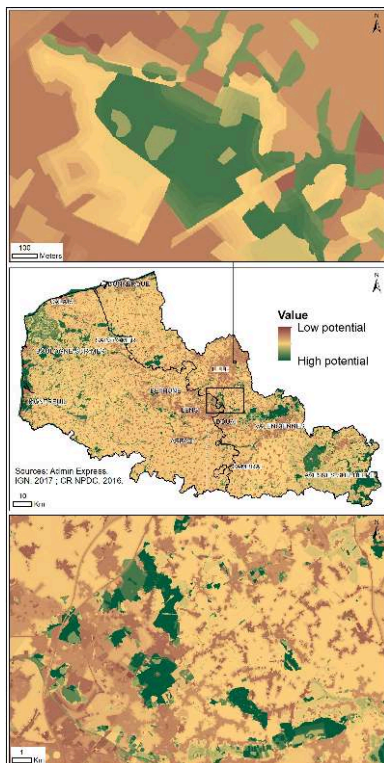
Results and discussion

- 26 The CBPI describes the low biodiversity potential of the Nord and Pas de Calais departments (Figure 11). The low values correspond to the urban framework (port area of Dunkerque, Lille metropolitan area, conurbation between Béthune and Valenciennes). The intermediate values correspond to agricultural areas of permanent crops, as in the example of the south of Arras, with a significant difference between popiculture and grassland areas in the south-east of the department of Nord. Areas of high potential correspond to non-industrialised coastlines (estuary, etc.), large forests (Desvres Forest, Saint-Amand and Mormal), as well as relict wetlands (between Douai and Cambrai in the Sensée Valley). The high density of the transport infrastructure network is particularly visible (motorways and railways between Lille and Paris) and separates areas of medium and low potential (coastal motorway south of Boulogne-sur-Mer). At a finer scale, there are many juxtapositions of high and low potential patches, particularly between urban agglomerations (between Lille and Lens), but also in the natural areas mentioned above.
- 27 The CBPI is part of a line of biodiversity potential indices and in particular that developed by Larrieu and Gonin (2012) and used in Clevenot *et al.* (2017) on a forested area in the Greater Paris region. By definition, this index is multifactorial in its assessment of habitat biodiversity in terms of abundance, richness and functionality. It also integrates relatively different management practices and uses, and does not depend on any initial reference state. It is different from previous indices insofar as it neglects vegetation stratification and age⁶, is not based on field surveys and it can be extended to types of habitat other than forest areas. It describes the biodiversity potential of environments that are particularly fragmented and overlap with dense urban areas such as parks and gardens (Pellissier *et al.*, 2014). It can also illustrate different types of habitat by focusing in particular on the potential connectivity and

biodiversity of each element of the landscape matrix. Each patch of the landscape matrix is a combined function of:

- its shape and size, thus avoiding the spread of homogeneous values over the entire study area (for example, not all grasslands have the same connectivity or biodiversity potential),
- factors related to structural connectivity (a forest enclosed by artificial areas has a low biodiversity potential unless it is likely to be an effective biodiversity reservoir),
- environmental management factors (a classified and closed wetland has a high biodiversity potential) and
- more functional factors by using a landscape species profile in the determination of permeability scores (index with the greatest impact on the CBPI).

Figure 11: Illustration of the composite biodiversity potential index (CBPI)

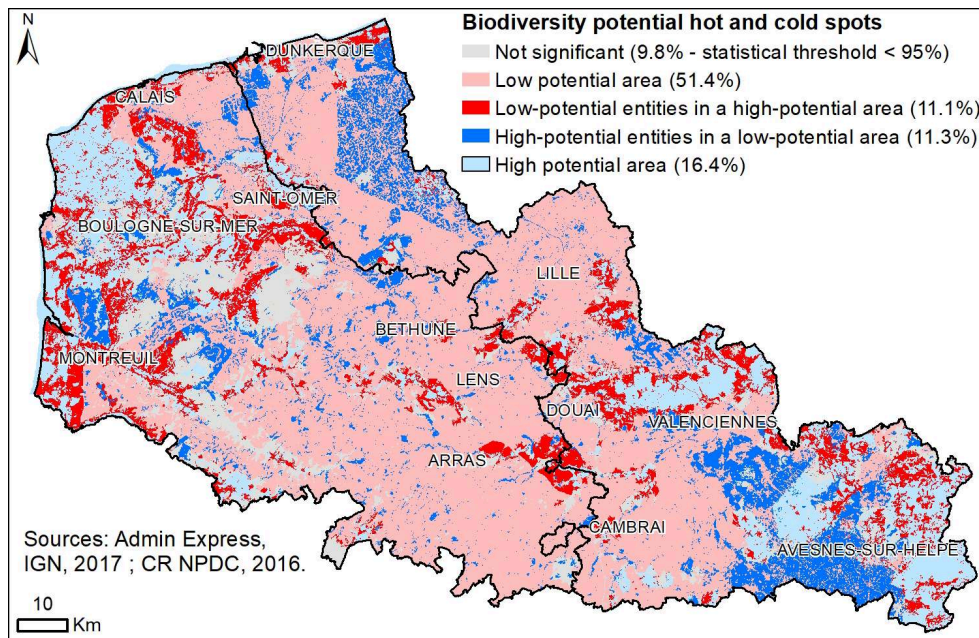


- 28 The contributions and limitations of CBPI involve either the biodiversity aspect of the indices or are of a technical nature.
- 29 By using indices that convey structural information and functional connectivity with respect to a generalist mammal species, the CBPI is a generic index of biodiversity potential in particularly fragmented and anthropised spaces. It provides a general overview of biodiversity potentials as a complement to naturalist inventories, which are generally scattered and specific to a few species. It assigns biodiversity potential to a habitat type that varies according to the configuration, environmental management, quality and shape of each ecological patch. The CBPI thus combines the 'habitat' and 'species' approaches classically used in ecological connectivity studies (Locquet, Clauzel, 2018) with a 'locality' approach that integrates proximity relationships within the landscape matrix. It can be used at the beginning of the initial diagnosis of the environment in urban planning schemes. It can also be used as a map-based mediation

tool between the different local stakeholders: ecologists, mayors, planners and citizens (MacEachren, 2004).

- 30 On a technical level, CBPI was carried out in vector mode within a GIS. Local authority agencies use this tool and this format more frequently used than the raster format (classically used in landscape ecology) (Vimal, Mathevet, 2011). Production methods and techniques are thus more easily adopted. Nevertheless, and despite substantial literature, the various calculations can be long to implement, especially when using complex databases. It is often a question of finding a compromise between the degree of precision, the calculation time and the computational capacities (Foltête *et al.*, 2012). The spatial resolution of the landscape matrix in this study, however, allows analyses to be conducted from regional to local scales in a unified reference frame. This unification can help to limit misinterpretation and increase sharing between different administrative levels (Alphandéry, Fortier, 2015). CBPI also uses expert knowledge in a diagnostic approach shared between several disciplinary fields. This type of approach can be transposed during the development of urban planning tools. In terms of mediation between experts, the scoring method (e.g. value of 2 for a Natura 2000 site and value of 1 for a ZNIEFF) proved to be less efficient than the one used for CBPI with a finer scoring method (from 0 to 100).
- 31 Finally, CBPI mapping can be a tool for ecological monitoring from a land-use planning perspective. For instance, it can be applied in the GIS of institutions that oversee compliance with building regulations. The CBPI can contribute to enhancing ecological avoidance, reduction or compensation approaches generally based on habitat type along with a few proximity criteria (Müller *et al.*, 2007). For example, geostatistical tools make it possible to study proximity relationships. In his review of the literature on hotspots, Schröter (2015) identifies four commonly used methods: top richest cells, richness, intensity and spatial clustering. The latter is frequently employed in fragmented landscape matrices. The G_i^* statistic identifies high concentrations of polygons with high or low values within a specified distance (Getis, Ord, 1992). We followed a stepwise approach to determine the average distance to maximise the spatial correlation. The 5 km distance corresponds to the distance travelled by a medium-sized mammal and gives the highest z-score (Minor, Lookingbill, 2010). The statistical model was adjusted by increasing the control points⁷ and considering multiple tests and spatial dependence (Caldas de Castro, Singer, 2006). Figure 12 first distinguishes between areas with high (pale blue) and low (light red) biodiversity potential (Schröter, 2015). It also separates areas with high potential including entities with low potential (deep red) from areas with low potential including entities with high potential (deep blue). The impacts of urban planning projects on the landscape matrix can thus be further anticipated.

Figure 12: Biodiversity potential hot and cold spots



- 32 In areas of low potential (51.4% of the study area), ecological compensation actions may be preferred to strengthen ecological continuities or restore environments. In the 'low-potential entities in a high-potential area' category (11.1%), priority may be given to measures that mitigate and reduce negative effects on biodiversity. In low-potential areas containing high-potential entities (11.3%), spatial planning projects should also strive to preserve relictual natural areas, as in areas with high potential (16.4%) by avoiding damage to biodiversity.

Conclusion

- 33 The CBPI is a multifactorial index of biodiversity potential. It is composed of quality, shape and configuration indices from landscape ecology. It combines a structural and functional approach, focusing, in this article, on a generalist medium-sized mammal. It can be recalculated to (i) measure the effects of urban planning projects on biodiversity potential and (ii) provide a tool for monitoring biodiversity over time. It can also be a reference in the determination of roughness coefficients (cost of passage) in the identification of ecological corridors by spatial analysis (distance cost according to species and patches of the landscape matrix). Finally, it can be readily updated following the creation of new databases describing the coverage, use, morphology and characteristics of the landscape on a smaller scale⁸.

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NOTES

1. Modelling outputs are not always produced at the scale of political territories and their spatial resolution is not always compatible with spatial planning tools. Generally, they are applied in a 'project-by-project approach' (Bigard et al., 2020 - p. 8).
 2. Most of the indices have been calculated in Python language or use common spatial operators (overlap, join, etc.)
 3. Six indices were calculated on the land use/cover polygons in the database presented below. Two indices (shape and isolation) were calculated from the grouping of these polygons according to their adjacency and permeability index value or score.
 4. Mustelidae (weasels, European badgers, ermines).
 5. For technical reasons and to facilitate data processing and computation, all patch-related indices were calculated in vector mode.
 6. Some land-use categories involved forest age and monospecific stands.
 7. The value of the Local Moran's I index is calculated from 499 permutations. A 95% threshold is used to identify hot and cold spots.
 8. <https://land.copernicus.eu/eagle>.
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ABSTRACTS

Promoting biodiversity is a major issue in urban planning. Estimating the biodiversity potential of patches in the landscape matrix often uses the tools of spatial analysis and landscape ecology indices, especially in large study areas. In this paper, we present the construction of a composite biodiversity potential index (CBPI) based on structural and functional approaches of landscape ecology. The CBPI is composed of eight indices (quality: permeability, fragmentation, environmental management; shape: size, shape complexity; configuration: contrast between neighbouring patches, distance to the most favourable habitats, distance from built-up areas). The CBPI appears to be suitable for anthropised and fragmented landscape matrices. It can be used to identify ecological networks in an 'Avoid, Reduce, Compensate' approach and can be readily updated with new map databases.

La connaissance de la biodiversité est un enjeu majeur de la planification urbaine. L'estimation de la biodiversité potentielle des entités de la matrice paysagère mobilise souvent les outils de l'analyse spatiale et les indicateurs de l'écologie du paysage, notamment dans de vastes zones d'étude. Dans cet article, nous exposons la constitution d'un indice composite (CBPI) mobilisant les approches structurelle et fonctionnelle de l'écologie du paysage. Il est composé de 8 indicateurs (de qualité : perméabilité, fragmentation, gestion environnementale ; de forme : taille, complexité de la forme ; de configuration : contraste avec les polygones voisins, distance aux habitats les plus favorables, distance aux zones bâties). Le CBPI apparaît adapté aux matrices paysagères anthropisées et fragmentées. Il peut servir dans l'identification des réseaux écologiques, dans la démarche Eviter, Réduire, Compenser et il peut être actualisé avec de nouvelles bases de données cartographiques.

El conocimiento de la biodiversidad es un importante desafío en la planificación urbana. La estimación de la biodiversidad potencial de las entidades de la matriz del paisaje, involucra

frecuentemente herramientas del análisis espacial e indicadores de la ecología del paisaje, particularmente en amplias zonas de estudio. En este artículo, proponemos un índice compuesto (CBPI) que abarca los enfoques estructural y funcional de la ecología del paisaje. Está compuesto por 8 indicadores (calidad: permeabilidad, fragmentación, gestión ambiental; forma: tamaño, complejidad de la forma; configuración: contraste con los polígonos vecinos, distancia a los hábitats más favorables, distancia a zonas con superficie construida). El CBPI emerge adaptado a matrices de paisajes antropizados y fragmentados. Este puede ser utilizado en la identificación de redes ecológicas, en el enfoque de Evitar, Reducir, Compensar y puede ser actualizado con nuevas bases de datos cartográficas.

INDEX

Palabras claves: indicador de biodiversidad, SIG, conectividad, fragmentación, apoyo a la toma de decisiones

Keywords: biodiversity indicator, GIS, connectivity, fragmentation, decision support

Mots-clés: indicateur de biodiversité, SIG, connectivité, fragmentation, aide à la décision

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