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Integrating ecological networks modelling in a participatory approach for assessing impacts of planning scenarios on landscape connectivity

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Abstract

This research aims at integrating ecological networks modelling in a participatory approach in order to assess impacts of land-use planning scenarios on landscape connectivity. This approach was applied to the metropolitan area of Bordeaux, a highly dynamic territory that has been modified by several decades of rapid urbanization. Whilst ecological network modelling is widely used in the academic spheres, the concept of ecological network itself also rose within operational stakeholders acting in land-use planning. However, exchanges between scientists and stakeholders about this concept and its modelling and decision-making applications remain rare and generally relate to discussions about results of analyzes carried out by scientists on their own. To our knowledge, no studies to date have involved stakeholders throughout the whole modelling process. In this purpose, we developed an adapted companion modelling approach bringing together scientists and stakeholders for co-constructing (1) a multi-species approach based on ecological functional groups, (2) a conceptual model of the territory's social-ecological functioning and (3) five land-use planning scenarios over a 15-years horizon. Together with this participatory approach, we used a landscape graphs approach for modelling ecological networks of functional groups, computing local and global connectivity metrics and estimating scenarios' impacts on multi-species connectivity. The results globally showed negative impacts of dystopian scenarios or anticipated trends in planning on landscape connectivity (from -20.5% to -8.1% on average, respectively), and in a lesser extent positive impacts of utopian or transformative scenarios (+1.5% and 4.5% on average, respectively). Scenarios' impacts also varied among functional groups, with some groups showing similar or antagonistic effects. These results served as a support of debates between stakeholders on the consequences of policy decisions and actions on connectivity, and on the possibilities of translating connectivity modelling in land-use planning and biodiversity conservation in an urban context.

Highlights

- Ecological network modelling has been integrated in a participatory approach
- Ecological networks are modelled from multi-species landscape graphs
- Scientists and stakeholders co-constructed qualitative land-use planning scenarios
- Impacts of scenarios on multi-species landscape connectivity are estimated
- Results support a critical feedback on policy decisions and actions

1. Introduction

One of the most severe impacts of urbanization on natural systems is a decline in biodiversity (Balfors et al., 2016), which is expected to accelerate in the coming decades with a predicted unprecedented expansion of urban areas (Seto et al., 2012). Biodiversity decline in urban environments is mainly due to the rapid loss and fragmentation of natural habitats (Ewers & Didham, 2005; Fahrig, 2003; Maxwell et al., 2016; Solé & Bascompte, 2006), resulting from the combined development of urban artificial structures and associated transport networks (Antrop, 2004; Tannier et al., 2016). Due to densification within cities and sprawl in their fringes, natural habitats are shrinked and fragmented, leading to severe alterations of natural ecosystems, including biotic homogenization and biodiversity erosion (McKinney, 2006, 2008).

From an ecological conservation point of view, it is widely recognized that adopting initiatives for improving connections among habitats will favor species movements in fragmented urban systems, therefore contributing to preserve some functional assets of urban biodiversity (Goddard et al., 2010). Considering landscape connectivity, i.e. the degree to which the landscape facilitates the movement of species (Taylor et al., 1993), is thus of crucial importance. Landscape structure indeed mediates species movements at multiple scales from short- to long-range connectivity (Rayfield et al., 2016), affecting ecological processes such as feeding, mating, dispersal or migrations (Hanski & Gaggiotti, 2004; Iwamura et al., 2013). Connectivity conservation, which has become central in conservation planning in the last decades (Gonzalez et al., 2017), is therefore an appropriate strategy to mitigate biodiversity losses, ensuring viability of populations by their movements through fragmented landscapes (Chisholm et al., 2011; Clauzel et al., 2018; Crooks & Sanjayan, 2006). Even if it is admitted that urban development increases habitat fragmentation in urban regions (Irwin & Bockstael, 2007), its impact on connectivity can vary depending on urban structures and considered species (Alberti, 2005; Tannier et al., 2016). Integrating landscape connectivity into urban planning may however drive land-use changes of urban areas for preserving key habitats and corridors (Huang et al., 2018).

Multi-species approaches are needed in order to assess landscape connectivity at regional scales for pursuing biodiversity conservation objectives (Brodie et al., 2015). The efficiency of a regional biodiversity conservation strategy based upon the preservation of corridors allowing for species movements will indeed depend of its capacity to support simultaneously the movements of multiple species rather than those of single species (Beier et al., 2008). Such multi-species approaches therefore rely on existing knowledge of regional species diversity and species ecological requirements and needs in terms of habitats and mobility, in order to characterize their sensitivity to habitat fragmentation (Albert et al., 2017; Meurant et al., 2018; Sahraoui et al., 2017).

By offering a relevant compromise between its ability to represent ecological flows at a large spatial scale and the amount of input data required (Calabrese & Fagan, 2004), landscape graphs are increasingly used for supporting decisions in land-use planning (Foltête et al., 2014). Among the different existing methods for modelling connectivity (see Kool et al., 2013), landscape graph modelling is recognized as a relevant approach to model habitat networks and representing movements for numerous species (Urban & Keitt, 2001; Urban et al., 2009). In landscape graphs, nodes usually represent habitat patches used by the studied species, and links represent the species potential for movements between those habitat patches (Galpern et al., 2011; Urban et al., 2009). This formalism allows delineating patches and links contributing the most to connectivity (Rayfield et al., 2011; Saura & Pascual-Hortal, 2007). Applications include for example the provision of operational recommendations for

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prioritization in spatial planning (e.g. Saura et al., 2011), prioritizing possible actions for improving the potential functionality of connectivity networks (Clauzel et al., 2015; Zetterberg et al., 2010), or advices for the implementation of mitigation strategies (Bergès et al., 2020; Tarabon et al., 2019). Landscape graphs also permit the comparative assessment of potential impacts of different planning scenarios, such as transport infrastructure developments (e.g. Clauzel et al., 2015; Fu et al., 2010), urban development strategies (e.g. Huang et al., 2018; Tannier et al., 2016), or arbitration between urban development versus regional conservation strategies (Lechner et al., 2015). Such scenarios can be constructed from planning documents provided by local administrations (Mörtberg et al., 2007; Scolozzi & Geneletti, 2012) or by simulation methods (He et al., 2017; Tannier et al., 2016). In all of the latter examples, variations in the levels of landscape connectivity are being used to compare alternatives according to their respective positive or negative expected impacts. Such results could constitute an operational decision support in land use planning or biodiversity conservation.

Despite this demonstrated efficiency for the arbitration of operational decisions, the production of shared knowledge on ecological networks between scientists and other sources of expertise remains challenging (Vimal et al., 2012). This can be explained by a historically difficult accession by political and decision-making stakeholders to approaches involving connectivity and conservation planning at the landscape level, and by an existing gap between scientists and practitioners with regard to the implementation of ecological networks (Gippoliti & Battisti, 2017). Indeed, as for many conservation arenas, the level of understanding and perception of landscape connectivity issues is very different between scientist, NGO and policy-makers, and the question of how to improve the inter-relationships between these stakeholders remains a crucial issue (Berger & Cain, 2014). However, raising awareness among local communities, public institutions or private actors with relevant skills for the definition of ecological networks is particularly critical (Brodie et al., 2016).

In addition to their aforementioned potential in drawing a realistic picture of ecological networks, landscape graphs have a real potential for use at the science and policy interface through their balanced position between ecological reliability and ease of implementation for operational decisions. Through a practionner's perspective, Bergsten & Zetterberg (2013) showed that environmental managers recognize the operational relevance of graph-based methods, and that their reluctance facing this model are more linked to the difficulty of choosing focal species and acquiring spatial and ecological data. The fact remains that

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ecological networks modelling by landscape graphs is not an easy task for practitioners. This can be due to (1) their limited technical and human resources for acquiring specialized skills, as well as historically challenging relationships with scientists (Foltête, 2019) and (2) the reluctance to work together with different expertise, which is a real lock to operationalize methods coming from research, especially in an operational field such as urban landscape ecology requiring very varied knowledge and skills. However, we assume that some existing modelling approaches built with and for stakeholders (see Voinov et al., 2016; Voinov & Bousquet, 2010 for an overview) can overcome such limitations. Such approaches allow engaging stakeholders in the design of the modelling process itself, raising the potential for more collaborative exchanges on the decision-making support tool and therefore leading to higher chance of eventual implementation (Beier et al., 2011). The geoprospective approach (Houet et al., 2017; Houet & Gourmelon, 2014; Voiron-Canicio, 2012) allows in particular to explore in a spatially explicit prospective manner the environmental changes at the interface between spatial modeling, scenarios, and stakeholder participation. Among the fields of research that have marked its development, Companion Modelling (Barreteau et al., 2003) is an iterative approach consisting in learning on environmental systems or support collective decision processes in these systems by increasing knowledge both for scientists and stakeholders through an interaction between them mediated by modelling processes. It is particularly relevant both for sharing and increasing knowledge and for supporting collective decisions by clarifying impacts of actions or decisions to a given problem (Voinov & Bousquet, 2010). These approaches are widely orientated towards dynamic systems or individual-based simulations. But to answer particular questions on environmental systems, it is however possible to adapt them through their articulation with other existing models (e.g. Basco-Carrera et al., 2018). Similarly, landscape graphs could benefit from the involvement of non-scientific stakeholders through knowledge sharing and as a collective decision support (Foltête, 2019).

This study aims at the development of a modelling approach involving stakeholders to assess the impacts of land-use planning scenarios on multi-species landscape connectivity. This participatory approach, mobilizing landscape graphs at the interface between science and practice, and inspired by Companion Modelling, lasted two full years. It was carried out at the scale of the metropolitan area of Bordeaux, from which institutional decision-making spheres display the wish to reconcile its urban development with the preservation of biodiversity through landscape connectivity and habitat conservation. Based on this ambition, the

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scientists and stakeholders involved in this approach participated in the co-construction of the research question, of an appropriate multi-species approach to set up the graph-based modelling of landscape connectivity, and of land-use planning scenarios to estimate their potential impacts on multi-species connectivity. We hypothesize that land-use planning scenarios can have differentiated effects according to (1) trajectories and magnitude of change in urban development schemes and/or actions in favor of the preservation of landscape connectivity, and (2) species examined according to their habitats and dispersal capacities.

2. Materials and methods

2.1. Study area and context

The metropolitan area of Bordeaux (named Bordeaux Métropole), located in southwestern France (**Figure 1a**), includes 28 municipalities which cover 578.3 km² inhabited by approximately 750.000 people. Bordeaux Métropole is located at the North-East of the Landes forest, the largest maritime-pine forest in Europe, and on the banks of the Garonne river flowing further downstream into the Gironde estuary. Bordeaux Métropole is composed of a large variety of land-use types: large artificialized areas, open areas with agricultural use and vineyards, forests, multiple lentic and lotic aquatic areas and wetlands (**Figure 1b**).

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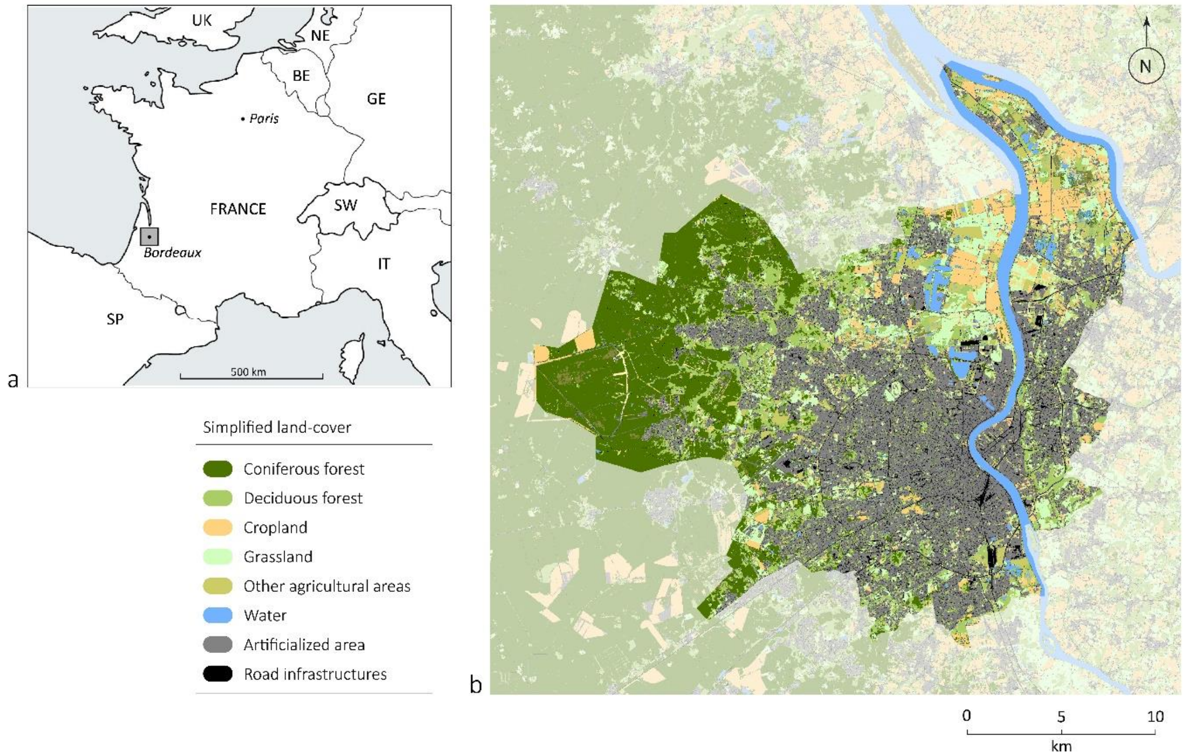

***Figure 1**. Location of the study area in the southwest of France (a) and its land-cover in 2016 (b). The dark-colored area corresponds to the metropolitan area of Bordeaux. Land-cover is simplified into eight classes for reading clarity.*

Bordeaux Métropole is currently concerned with important land use planning issues, with a political leadership assuming the ambition to reach a population of one million inhabitants by 2030. To reach this objective, the Metropolis launched in 2009 a prospective approach presented in a policy document entitled “5 Senses for a Metropolitan Bordeaux” which articulates a vision for the city to the year 2030 (Bordeaux Métropole, 2011). This policy in favor of territorial attractiveness has led to significant urbanization dynamics over the last decade, resulting in both a densification of the city-centre and an urban sprawl at the fringes of the metropolis. It is accompanied by the construction of transportation infrastructures, the improvement of the public transport offer, and a project for the construction of 50,000 collective housing around public transport infrastructures (Bordeaux Métropole, 2013a). In this context, biodiversity preservation is a pressing challenge. For example, Bordeaux Métropole territory includes several Natura 2000 areas and the Bruges National Natural Reserve (265 ha), and 17.5% of lands are concerned by a classification as Natural Areas of Ecological, Wildlife, and Floristic Interest (ZNIEFF). These challenges in biodiversity conservation have led the metropolitan area leaders to engage in knowledge and conservation actions, starting with the "55,000 ha for Nature" initiative for preserving and enhancing its

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natural heritage as major challenges to be met for sustainable development of the metropolis and for its attractiveness (Bordeaux Métropole, 2013b). The 55,000 ha for Nature was the counterpart of the 50,000 collective dwellings. This initiative was based on the consultation of multidisciplinary teams, bringing together expertise in ecology, landscape and urban planning, territorial development and agronomy. It was accompanied by the creation of an atlas of metropolitan biodiversity (Bordeaux Métropole, 2016a).

This ambition to conciliate territorial attractiveness leading to urban growth and nature preservation translated to some extent in local planning instruments defining land-use prospects over the next 15 years. In this context, the Nature Direction of Bordeaux Métropole has focused on identifying an ecological network to limit landscape fragmentation facing urban development projects by the implementation of a "strategy for biodiversity and wetlands" in 2016, from which this work was part.

2.2. Design of the participatory approach

The actors involved in the participatory approach were selected as representatives of the various structures acting in the fields of land use planning and nature conservation (local authorities, government departments, environmental NGO, research laboratories, consulting firms, etc.), and whose area of competency covers all or part of the metropolitan territory.

The methodology adopted was based on participatory workshops involving stakeholders, including researchers, with workshops following successive advancement steps of the spatial modelling work, and discussions based on step by step modelling results (**Figure 2**). The group of stakeholders was mobilized before each modelling step, and was involved for every step validation, with the aim of facilitating results' appropriation by all. This methodology is presented here in three parts: description of landscape connectivity modelling from a multi-species approach including terrestrial and semi-aquatic animal species (2.3), description of an adapted Companion Modelling dedicated to the involvement of stakeholders in the co-construction of scenarios (2.4), estimation of scenarios' impacts on landscape connectivity from land-use changes simulations (2.5).

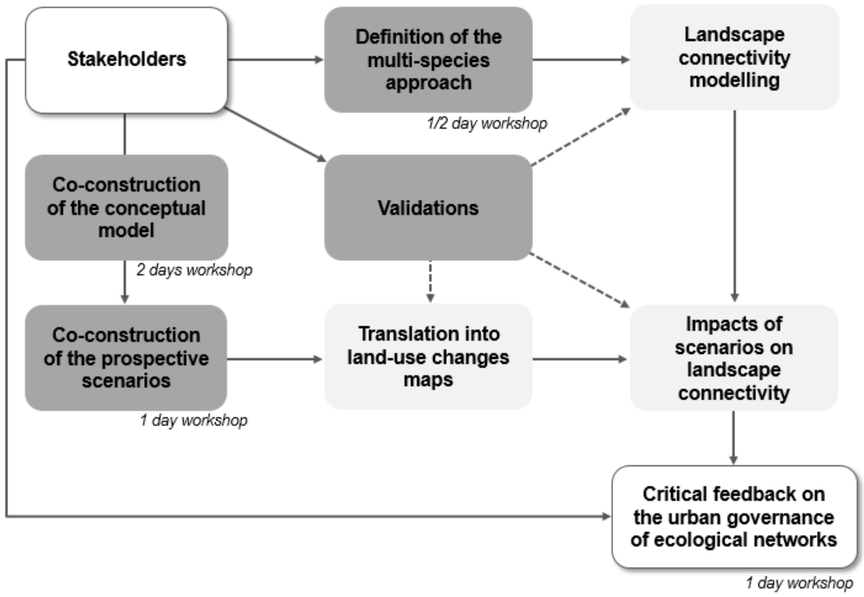

Figure 2*. Design of the participatory approach. The dark grey boxes correspond to the involvement of stakeholders and the light grey boxes correspond to the spatial modelling working phases.*

2.3. Landscape graph analysis

2.3.1. Spatial data

Several land-cover data were necessary for measuring landscape metrics. These data were mainly obtained by combining three databases for the year 2016 with ArcGIS 10:

(1) An existing 10-m resolution map of land cover data 2016 of France constructed from Sentinel-2 images and providing multi-spectral high-resolution optical observations (Inglada et al., 2017) allowed identifying landscape elements including artificialized areas, water surfaces, forests (coniferous and deciduous), croplands, grasslands, moors, sands, orchards and vineyards (see http://osr-cesbio.ups-tlse.fr/~oso/).

(2) The vector BD Topo databasis provided by the French National Geographical Institute (IGN, 2016) was used to characterize urban woods, buildings, transport infrastructures, watercourses and water surfaces in addition to the previous source (see https://geoservices.ign.fr/). Main transport infrastructures (highways and high-speed railway lines) were distinguished from secondary roads due to their differentiated barrier effect on the movement of species. Similarly, the Garonne River was distinguished from the other

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watercourses due to its larger size, considered as an unfavorable habitat and a limitation for the movements of terrestrial and semi-aquatic animal species considered in the study area.

(3) Specific spatial vector data from (Bordeaux Métropole, 2016b) were additionally used for mapping wastelands and some missing aquatic elements (see https://opendata.bordeaux-metropole.fr).

All those data were combined into a 5 m-resolution raster layer covering the entire study area and its wider environment so as to avoid the edge effects of the landscape analysis.

2.3.2. Multi-species approach

The multi-species approach was driven by an expert elicitation (Lechner et al., 2017). Among the stakeholders involved in the participatory approach, a panel of stakeholders with ecological expertise (naturalist experts and researchers) was mobilized throughout this working phase. All of them have a good knowledge of the study area and the species potentially present within it, through their involvement in field-based research or conservation activities, or in management and conservation actions at regional or metropolitan levels. This sub-group of experts was composed of six researchers in ecology and landscape ecology, eight field specialists from non-governmental biodiversity conservation organizations or environmental management agencies, and six members of governmental or local authorities' organisms in charge of nature conservation or landscape planning. This phase of multi-species approach design was conducted within a 1/2-day workshop with the aim to choose and design an appropriate species selection and grouping method from some possibilities presented by the researchers conducting the workshop.

The approach chosen by the experts is similar to ecoprofiles (Opdam et al., 2008; Vos et al., 2001) and followed three steps: (1) selection of an initial list of target species, (2) definition of their ecological needs and (3) construction of ecoprofiles. Experts were involved in the choice of the multi-species approach, the definition of the initial list of species and the definition of ecoprofiles. The ecological requirements of single-species and their arrangements into ecoprofiles were then carried out by the researchers present at the workshop, before a validation and adaptation through individual experts' feedbacks.

From the selection of target species (see **Appendix A**), modelling ecological networks in a realistic way implies to characterize potential habitat patches, movement paths of species and their movement capacity, here the dispersal distance. This information was identified for mammals, birds, amphibians and reptiles in the same way as Sahraoui et al. (2017), completed for birds by scientific literature and regional atlases (Billerman et al., 2020; Grafius et al., 2017; Shimazaki et al., 2016; Svensson et al., 2010; Theillout, 2015; Tremblay & St. Clair, 2009), for insects by scientific literature (**Appendix B** for the full list of references) and for all completed by expert knowledge. For modelling movements' paths, we used least-cost distances by characterizing the capacity of each land-cover category to facilitate or impede species movements. The values of resistance to movement were defined using a logarithmic scale following Clauzel et al. (2015). The selected species were then arranged into 16 ecoprofiles in the same way as Mimet et al. (2016) and Sahraoui et al. (2017), not by selecting a species composing each group and serving as ecoprofile but by averaging values of dispersal capacities and movement costs among species composing each group (see Appendix C for an example movement costs representation).

2.3.3. Measuring local and global connectivity

Minimal planar landscape graphs (Fall et al., 2007) were first generated for each ecoprofile from the 2016 land-cover map. The nodes of these graphs were defined by extracting habitat patches from the land-cover categories corresponding to species' habitats. According to the experts' opinion, a minimum area of 0.5 ha and 1 ha, respectively, were defined for species associated to open areas and forests, so that patches are retained as habitats patches in the graphs. Species associated to aquatic habitats (e.g. Odonata) live in direct proximity to the banks. Considering their ecological requirements, the nodes were therefore defined from a complementary analysis distinguishing the inside edges of water surfaces (20 meters thick) from remaining surfaces. In each case, the links correspond to the least-cost paths between habitat patches considering the landscape matrix resistance.

Among the variety of existing global connectivity metrics, we used the equivalent connectivity (*EC*) (Saura et al., 2011) characterizing the connectivity potential across the entire ecological network and measured as follows:

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

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 maximum probability of potential paths between i and j. p_{ij} was calculated with an exponential function such that:

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

where d_{ij} is the least-cost distance between i and j, and α ($0 < \alpha < 1$) reflects the intensity of decreasing probability of dispersion resulting from the exponential function. Dispersal distance values in metric units were converted into cost units using a linear regression between link topological distance and link cost distance for all the links of the graphs associated to species groups. The value of α was determined such that p_{ij} = 0.5 when d_{ij} corresponds to the median or mean dispersal distance of species.

To quantify connectivity at the patch scale, we chose the local metric interaction flux (IF) (Foltête et al., 2014; Sahraoui et al., 2017), which is the local contribution of each patch to global connectivity. 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.

With the aim of identifying ecological continuities conducive to the dispersion of individuals, the identification of least-cost paths is too restrictive. In addition to the previous analyses, dispersion corridors have been modeled. These corridors represent the space which can be crossed between two habitat patches, i.e. the space which represents all of the possible paths connecting two patches and having a distance lesser than the dispersal capacity of the ecoprofiles. These corridors being modelled by pairs of spots are then superposed (addition) and the result gives, for each pixel, the number of corridors passing through it.

All these landscape graphs analyses (metrics computation and corridor modelling) were performed with Graphab 2.2 software (Foltête et al., 2012) (see https://sourcesup.renater.fr/www/graphab/).

2.3.4. Mapping local connectivity

The spatial representation of local connectivity analysis from the graphs 'elements, the IF metric and corridors, were all discussed with the stakeholders. The objective was to obtain a cartographic atlas of connectivity for all ecoprofiles, understandable by these stakeholders and by managers, elected politicians and the public. Thus, in addition to a classic representation in the form of nodes and links of the graph at the metropolitan scale, more localized representations of the IF values at the patches' scale, least-cost paths and corridors were preferred, and superimposed on orthoimages. Beyond having served as a basis for discussion between stakeholders, the corridors were used for certain scenarios' GIS construction (see section 2.5 and **Appendix D**).

2.4. Adapted Companion Modelling approach

2.4.1. Principles of the adapted Companion Modelling

The co-construction of land-use planning scenarios was based on an adapted Companion Modelling approach. Among the different forms of participatory modelling, Companion Modelling was identified as the most appropriate in our non-cooperative context. Indeed, its primary aim is to enhance cooperation between stakeholders by the development of a common knowledge base. To do this, Companion Modelling puts stakeholders at the heart of the process by including them at all stages: co-construction of a conceptual model, choice or construction of indicators, and development of scenarios. The process is generally based on computer-supported role-playing and simulations (e.g. multi-agent simulations) (e.g. Barreteau et al., 2003; Becu et al., 2008; Dupont et al., 2016). This approach allows visualizing the resources' dynamics, and interactions between stakeholders and resources within the studied area, comparing the viewpoints of the actors, proposing scenarios and finally observing the consequences of decisions in this area as a discussion basis (Bousquet et al., 2014). As in Basco-Carrera et al. (2018), our adapted approach of Companion Modelling is conceptualized as a participatory modelling approach that follows some of its principles and key features. In our case, while the first step (co-construction of the conceptual model) was similar (2.4.2), our adaptation took two forms: the development of scenarios with an original and more qualitative approach (2.4.3) and the use of landscape graphs for estimating impacts of these scenarios on multi-species landscape connectivity considered as indicators (2.5). This adaptation was required to get in tune with the requirements of the planning and management processes that require using the graph-based modelling for better understanding the complexity associated to urban landscape connectivity

2.4.2. Actors, Ressources, Dynamics and Interactions

In Companion Modelling, the ARDI method (Etienne et al., 2011) is used to co-construct the social-ecological system by listing the Actors of the system (e.g. planners, citizens, owners), the Resources they use (e.g. land, water, biodiversity) their Dynamics, and the Interactions among actors and resources. This step required bringing stakeholders together during a two days workshop. The resulting model was as exhaustive as possible, both considering the multiplicity of actors and the issues of land use planning, environmental management and nature conservation at the scale of the metropolitan area. Its synthesis was finalized by the researchers from the several contents (recorded discussions, note taking and graphical diagrams) of the workshops, and then presented to the stakeholders for correction and validation. This model mainly aimed to share the representations of the stakeholders in the participatory approach and to provide a common framework for understanding the functioning of the territory, a prerequisite for the co-construction of territorial development. It also initiated discussions about the governance of the territory and the spatial and temporal scales of its impacts.

2.4.3. Co-construction of prospective scenarios

The realization of scenarios is a way to integrate a multiplicity of ideas and thoughts in holistic images giving a meaning to possible futures (Rasmussen, 2008). In the Companion Modelling approach, the co-construction of scenarios is a crucial step which does not aim to predict the future, but rather to estimate the possible impacts of developments from such a multiplicity of actors' point of view (Etienne et al., 2011). The scenarios were developed during a full day workshop. Their co-construction was based on the graphic definition of scenaristic trajectories, accompanied by narratives and maps of land use changes and anthropogenic pressures.

Based on the ARDI model and the content of the participants’ debates during the first workshop, the scientists facilitating this workshop established a support for the graphic definition of scenaristic trajectories and attempted to bring participants to build scenarios based on this model (Sahraoui et al., 2019). This support first proposed two trajectory axes, following both spatial and temporal patterns and opposing antagonistic modes of governance. In a spatial dimension, governance of the metropolitan area based on its dense urban-center is opposed to governance based on urban fringes, defined as areas where town meets countryside (Scott et al., 2013). In a temporal dimension, adaptive governance (Folke, 2007; Folke et al., 2005) is defined as adaptive response strategies to address uncertain environmental crisis needing a flexibility of responses. It is opposed to anticipatory governance (Boyd et al., 2015) which considers multiple strategies given the range of possible futures with the aim to change short-term strategies and decisions to a longer-term policy vision. From these axes, three components were to be positioned, relating to urban development (structures and dynamics of artificialized urban spaces), landscape ecological configurations (structures and dynamics of natural and semi-natural habitats) and urban and regional planning governance (through policy instruments). Considering the spatio-temporal imprint of management actions, the aforementioned components were positioned by level of importance depending on whether they are structuring (first level of importance), a support (second level of importance) or contingent (third level of importance), in an order that may be different.

In addition to filling the graphical support, facilitators asked participants to put in words narratives for the scenarios. These narratives are qualitative descriptions of the proposed scenarios integrating all of the key variables of interest involving spatial and temporal changes (Mahmoud et al., 2009), herein constituted by the three components of the scenaristic trajectories described above. Through this process, participants described the final state of the scenarios as well as the processes or changes leading to this final state (de Godoy Leski et al., 2018), component by component, and according to the defined trajectory. The contribution of those narratives is to focus on the way people mobilize systems rather than abstract descriptions (Rasmussen, 2008), which enriches ‘skeleton’ scenarios (here the script trajectories defined by the components) by ‘flesh and blood’, i.e. lively, detailed and coherent narratives. As recommended by Schwartz & Ogilvy (1998) and Rasmussen (2008), the narratives were written to communicate convincingly the future alternatives and allow participants to memorize them.

The ‘skeleton’ trajectories and ‘flesh and blood’ narrations were supplemented by the co-construction of maps to spatialize the changes implied by each scenario in the metropolis. Starting from the mapping of the initial 2016 land use (cf. 2.3.1) printed in very large format, participants were invited to spatially represent the land use changes (e.g. urban development or restoration of natural habitats) or anthropogenic pressures on natural habitats (e.g. frequentation of urban parks and peri-urban forests).

The facilitators proposed the participants to build one after the other:

(1) A strategic (realistic) scenario intended to explore the changes in the metropolitan area in the case of “business as usual” governance strategies and territorial dynamics (Iwaniec et al., 2020);

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(2) Several dystopian and utopian scenarios around this strategic scenario, considering both utopian and dystopian thought in visions of the future (Hjerpe & Linnér, 2009) intended to look at (realistically or not) negative and positive dynamics in terms of landscape ecological changes;

(3) A transformative (ideal-realistic) scenario in reaction to the state of the previous scenarios and intended to explore desirable outcomes from a sustainability visioning (Iwaniec et al., 2020; Wiek & Iwaniec, 2014).

It was decided by the participants to project scenarios over a period of 15 years, this period corresponding, according to them, to a time long enough to concretely visualize changes, while remaining comprehensive for an appropriation of actors involved in planning decisions.

2.5. Estimating impacts of scenarios on landscape connectivity

Estimating the impacts of scenarios on landscape connectivity requires their transposition into new land-cover maps. The modifications were mainly based on the tracings made by the stakeholders directly on the 2016 background land cover maps, and including the administrative divisions, and were supported by the narratives. Other sources of GIS data have been mobilized to fulfill these scenarios' mapping exercise: the urban planning documents locating urbanization projects, and the constructed connectivity maps (see 2.3.3). For some scenarios and several ecoprofiles, the capacity of habitat patches and costs attributed to the landscape matrix have also been modified (see Appendix D for more details on the GIS construction of the scenarios).

In order to assess the impacts of scenarios on landscape connectivity, graphs were constructed for the 16 ecoprofiles of species in their initial state (2016) and for each scenario. From this, global connectivity (EC) was measured at each step to estimate the positive or negative impacts of the scenarios. The impact I of a given scenario s on each ecoprofile ep was assessed by computing the EC variation such that:

$$I_{ep_s} = \frac{\left(EC_{ep_s} - EC_{ep}\right) \times 100}{EC_{ep}}$$

where EC is the initial global connectivity level and EC_s is the global connectivity level considering the scenario s.

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The impacts of these scenarios served as a basis for a critical feedback on the urban policies of *Bordeaux Metropole* and the identification of ecological networks at the scale of the metropolitan area from the actors involved in the process.

3. Results

3.1. Local connectivity analysis

In total, 88 species were included in this study: 15 mammals, 15 amphibians, 11 reptiles, 37 birds, 10 insects (rhopalocera and odonata only). The 88 selected species were arranged into 16 ecoprofiles with identical profiles according to their main habitat type, dispersal capacity and mobility behavior though the landscape matrix. Among the 16 resulting groups, 2 groups were composed of single-species, 14 groups from 2 to 9 species and 2 groups including 10 or more species. All ecoprofiles had contrasted habitat requirements and mobility capacities (**Appendix E**).

Local landscape connectivity analysis was performed for each of the 16 ecoprofiles. An example for the natural open areas species with low dispersal capacities is shown, illustrating the different levels of local connectivity at the metropolitan scale, with the highest connectivity of the habitat network outside the urban-center (**Figure 3**). At several localized scale of representation, the levels of connectivity can also widely vary for both habitats and corridors.

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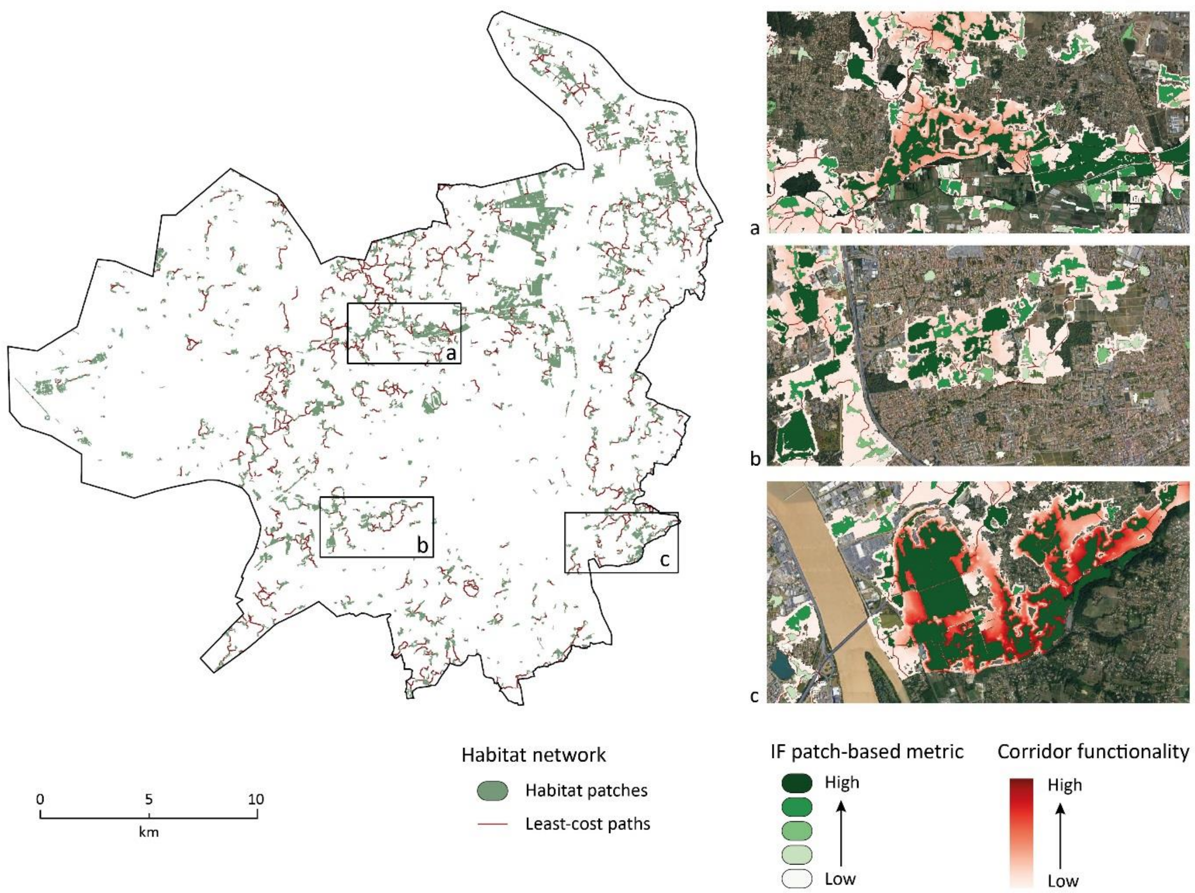

Figure 3. *Example of landscape connectivity analysis for the ecoprofile corresponding to species occupying natural open areas and characterized by low dispersal capacities.*

3.2. ARDI results

The resulting ARDI model (**Figure 4**) considers the multiplicity of actors and resources and the issues of land use planning, environmental management and nature conservation at the scale of the metropolitan area.

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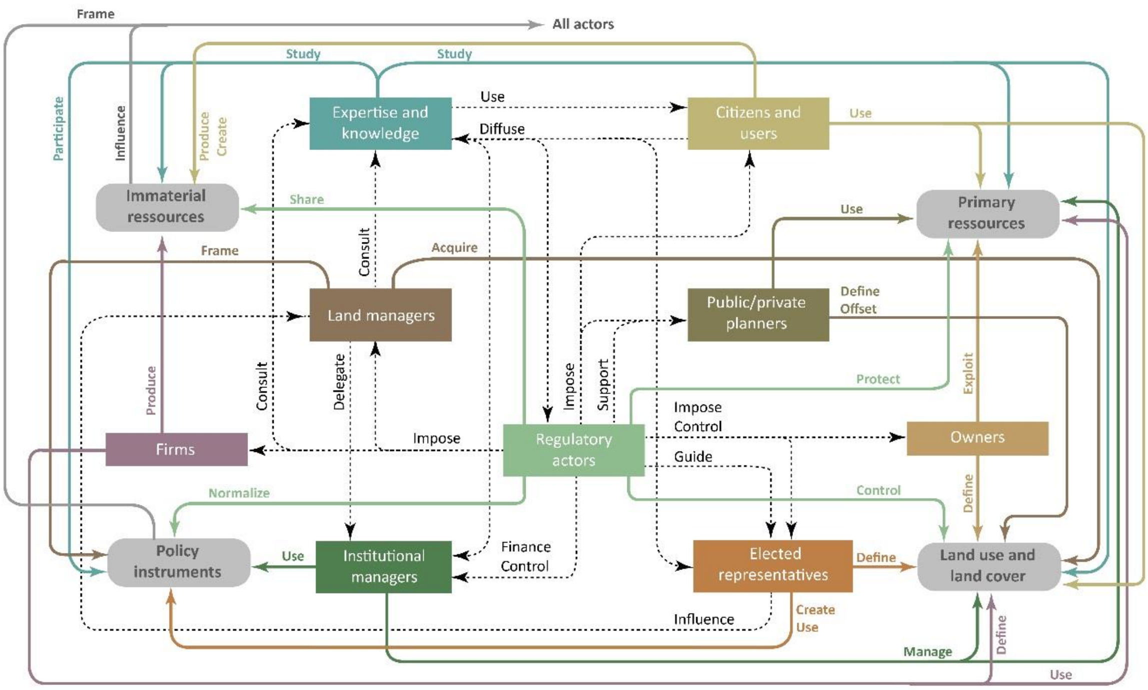

__Figure 4__. ARDI model at the scale of the metropolitan area of Bordeaux. Colored rectangular boxes represent groups of actors; grey rounded boxes represent groups of resources; black dashed arrows correspond to relationships among actors; and colored arrows correspond to interactions between actors and resources.

The territory's resources were grouped into four main categories: (1) resources related to land cover and land use which include all land use categories defined on land use maps (2.3.1.), (2) primary resources such as air, water, soil, deep aquifers, fauna and flora, (3) policy instruments such as documents and zoning maps for urban planning and development, preservation of biodiversity, environmental and risks management, ecological offsetting systems and areas, and financial instruments (e.g. taxes), and (4) immaterial resources such as quality of life, territorial attractiveness, collective intelligence, big data, education and training.

The identified actors were grouped into 9 main categories: (1) land managers, (2) regulatory actors (e.g. deconcentrated State services, *Bordeaux Métropole*), (3) expertise and knowledge actors (e.g. researchers, naturalist associations, biodiversity observatories, urban planning agency), (4) land owners (e.g. foresters, wine growers. farmers), (5) citizens and users (e.g. inhabitants, tourists, associations and citizen collectives, neighborhood committees), (6) firms, (7) public and private planners (e.g. public works companies), (8) elected representatives and (9) institutional managers (e.g. public forest managers).

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The relationships linking actors and their interactions with resources were then qualified. For example, elected representatives interact with land-use and land-cover by defining their status and trajectory. In contrast to the usual ARDI approaches, resources can also act indirectly on the actors, here through an influence exerted by immaterial resources and a regulatory framework imposed by the policy instruments.

3.3. Scenarios

In total, 5 scenarios were co-constructed (**Figure 5**) (see **appendix F** for narrations and **appendix G** for the resulting scenario maps): one strategic scenario, two dystopian scenarios, one utopian scenario, and one transformative scenario in reaction to the state of the four first scenarios. Scenarios trajectories showed the utopian scenario directed in the opposite direction to that of the strategic scenario. The transformative scenario was orthogonal and therefore intermediate to the utopian and strategic scenarios. Its direction was positioned at the opposite of dystopian scenarios and the order of its components was similar to that of the utopian scenario.

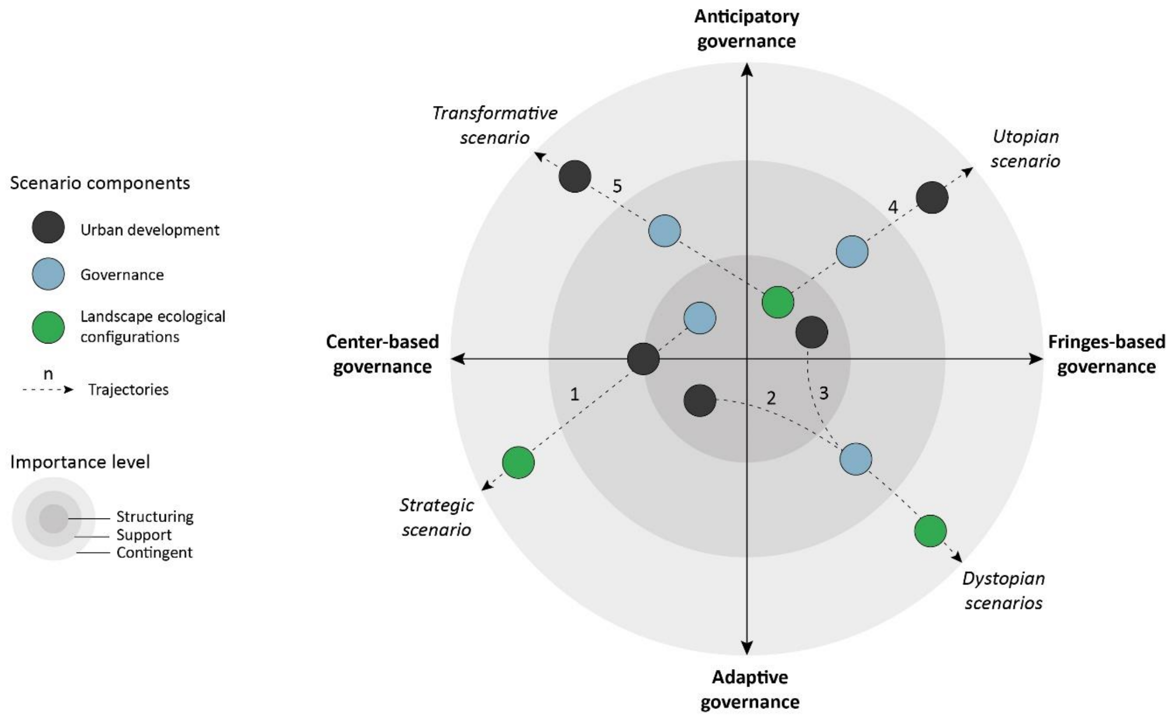

***Figure 2**. Scenario trajectories co-constructed by participants. The scenarios are read from the center of the matrix to its edges and the order of components is not necessarily the same. Example for the utopian scenario: the scenario begins with the landscape ecological configurations as a structuring component going in the direction of an anticipatory and fringes-based governance. Governance comes as a support component, and then urban*

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development as a contingent component always along the same axes directions (adaptive governance and fringes-based governance).

3.4. Impacts of scenarios on global connectivity

The impacts were different among ecoprofiles according to the scenarios (**Table 1**). The general trend for species from ecoprofiles associated to aquatic habitats (e.g., Odonata, amphibians) was most negatively impacted by the dystopian scenario 2, and to a lesser extent by the dystopian scenario 3 and the strategic scenario. The impacts of utopian and transformative scenarios had positive impacts for some ecoprofiles but slightly negative for others. The ecoprofiles associated with forest environments seemed to be more significantly and negatively affected by the strategic scenario than other ecoprofiles, and to a lesser extent by the two dystopian scenarios. The utopian and transformative scenarios had slightly negative impacts for all ecoprofiles, except for those associated exclusively with deciduous forests, for which utopian scenario was very positive (almost + 30% in EC metric). For ecoprofiles associated with open areas, strategic and dystopian scenarios had a consistently negative impact. Utopian and transformative scenarios had only marginal impacts, which could be positive or negative depending on the groups.

The impacts resumed by scenario (**Figure 6**) showed consistently negative impacts of the strategic and dystopian scenarios, with variable ranges of values. On average, the dystopian scenarios were respectively more (-20.5% for scenario 2) or less (-8.1% for scenario 3) impacting than the strategic scenario (-13.2%). If the utopian and transformative scenarios seemed to positively affect multi-species connectivity, these impacts appeared more moderate than for strategic and dystopian scenarios. On average, the utopian scenario was slightly more favorable (+4.6%) than the transformative scenario (+1.5%).

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Table 1. *Impacts of scenarios on equivalent connectivity metric (EC) calculated from current vs. scenaristic land use maps for each ecoprofile (see section 2.5).*

	EC variation (in %)				
Ecoprofiles	**S1 Strategic**	**S2 Dystopian**	**S3 Dystopian**	**S4 Utopian**	**S5 Transfor-mative**
Water courses species with medium dispersal capacities	-3.57	-18.83	-3.99	2.18	10.19
Water bodies species with low dispersal capacities	-1.62	-36.21	-2.03	-0.07	-0.13
Water bodies species with high dispersal capacities	-8.77	-40.50	-8.79	0.02	0.00
Water bodies and courses species with low dispersal capacities	-0.89	-21.80	-0.86	6.28	7.48
Water bodies and courses species with medium dispersal capacities	-6.85	-29.86	-7.60	2.17	7.19
Water bodies and courses species with high dispersal capacities	-3.96	-14.85	-6.59	4.97	8.19
Deciduous forests species with medium dispersal capacities	-26.92	-17.59	-13.76	29.99	-0.50
Mixed forests species with high medium capacities	-29.61	-14.50	-3.33	-0.73	-0.22
Deciduous forests species with high dispersal capacities	-25.98	-26.98	-19.26	28.96	-0.66
Mixed forests species with high dispersal capacities	-32.39	-13.86	-2.64	-1.85	-0.20
Mixed open areas species with low dispersal capacities	-5.64	-9.15	-3.66	-3.23	-0.07
Mixed open areas species with medium dispersal capacities	-8.57	-17.67	-5.77	-0.41	-0.16
Mixed open areas species with high dispersal capacities	-12.76	-22.80	-12.25	0.48	0.32
Natural open areas species with low dispersal capacities	-2.48	-5.24	-2.27	0.10	-0.02
Natural open areas species with medium dispersal capacities	-11.30	-14.83	-9.56	0.47	0.18
Natural open areas species with high dispersal capacities	-20.27	-21.45	-23.24	1.37	1.30

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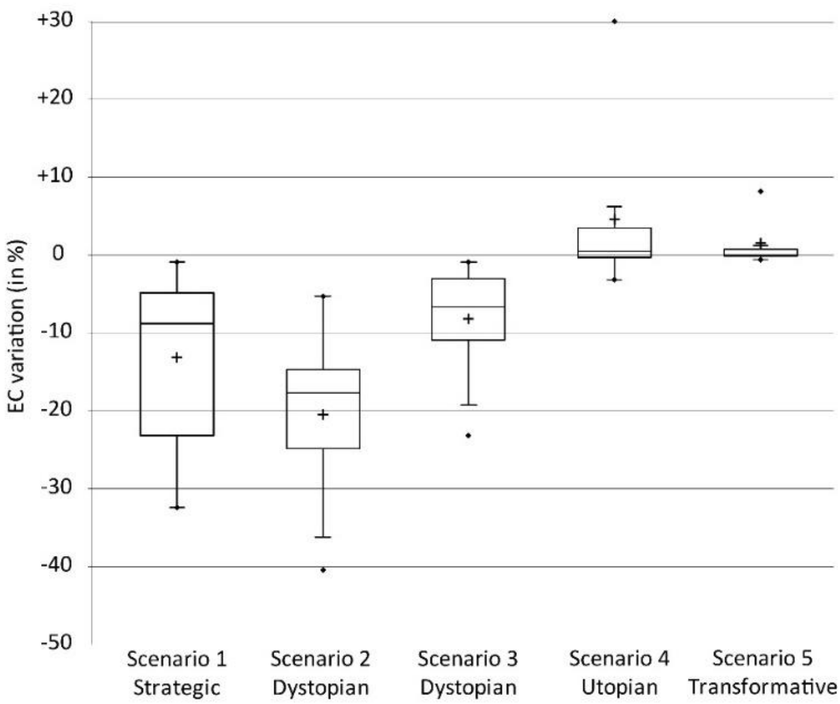

Figure 6. *Descriptive statistics of scenarios' impacts on multi-species landscape connectivity from EC variation (see section 2.5). The crosses and central horizontal bars correspond to means and medians, respectively. The lower and upper limits of the boxes correspond to the first and third quartiles, respectively, and the horizontal bars outside the boxes are standard error bars. The points are EC range values (min-max).*

4. Discussion

4.1. Feedback on the scenarios' impacts

We hypothesized that land-use planning scenarios could have differentiated effects according to the scenaristic trajectories and the species' ecoprofiles examined. Globally, the strategic and dystopian scenarios induced relatively important losses in the EC values, while the impacts of the utopian and transformative scenarios resulted in gains that were much more moderate. Therefore, the impacts on connectivity were indeed very different according to scenarios, with important losses in connectivity in the worst cases, but with limited gains in the best cases. On the other hand, the impacts of the scenarios largely varied among ecoprofiles. We have highlighted the consistently negative impacts of strategic and dystopian scenarios. However, if the dystopian scenario 2 seemed to be the most severe in negatively impacting connectivity metrics, it is especially the case for the groups of aquatic and open habitats, while the strategic scenario 1 was affecting most the groups associated with forest habitats. Indeed, the urban projects planned in the fringes of the metropolitan area directly

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affected forested habitats, in particular by impeding species ability to move among habitat patches. The dystopian scenario 3, favoring a more diffuse urbanization and the preservation of ecological corridors in urban interstices seemed less impacting for all ecoprofiles. Regarding the most positive average impacts of the utopian scenario 4, it seemed to have a really positive effect (greater than + 2%) for only 6 ecoprofiles, 4 having water courses as habitat and 2 having deciduous forests as habitat. For these latter, the positive impacts even reach almost +30%. Thus, the effect of the voluntarist actions of ecological restoration of the deciduous forests and the rivers concerned only the ecoprofiles directly associated with these habitats, having an almost null or slightly negative effect for the other ecoprofiles. Likewise, transformative scenario 5 seemed to have a really positive effect for groups associated with rivers only, while not degrading connectivity for the others. For the utopian and transformative scenarios, we observe therefore that none lead to overall positive benefits to connectivity for all ecoprofiles. This may mainly due to (1) the choice of ecological restoration of these scenarios which cannot meet species with different ecological needs, especially in terms of movements, and also to (2) the state of connectivity in a highly anthropized study area, already degraded with low opportunities in terms of ecological restoration for a strong increase.

Some studies showed that the negative impacts of urbanization tend to decrease with the dispersal capacities of species (e.g. Fu et al., 2010; Liu et al., 2014). Looking at the ecoprofiles associated with open habitats and with water bodies only, we observed the opposite, with a regular loss in the EC variation values with increased dispersal capacities for the scenarios 1, 2 and 3. In this highly anthropized context, this can be explained by the fact that the most connected ecological networks are more vulnerable than less connected networks facing new pressures due to urban development. However, for the scenarios 4 and 5 and for these same groups, the EC variation increased with increasing dispersion capacities. For the other groups, the relations were not linear and depended on the scenarios. The scenarios 1, 2 and 3 have for example impacted more the groups associated with the habitats of both ponds and rivers in the case of medium dispersal capacities than of low or high dispersal capacities. These results are therefore similar to other studies showing the complex and not necessarily correlated relationships between species' dispersal capacities and land use and climate change scenarios' impacts on their connectivity (Albert et al., 2017; Mazaris et al., 2013). Note here that beyond the differences in species' dispersal capacities with a similar habitat, the resistance of the landscape matrix may be different between species as well.

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While this adaptation in the model parameterization allowed considering mobility behaviors of ecoprofiles though the landscape matrix, making analyzes more ecologically relevant, it resulted in complexifying comparisons among groups with similar habitats according to their dispersal capacities.

In this work, we assessed the impacts of the scenarios on global connectivity only. However, the modelling of ecological networks by landscape graphs can also estimate local impacts, by measuring variations in local connectivity metrics at the scale of habitat patches and/or by visualizing changes in the networks' structure. In this aim, Tannier et al. (2016) studied the impacts of simulated urbanization scenarios on species' ecoprofile with a similar habitat (forests), while Lechner et al. (2015) relied on scenarios constructed using participatory GIS modelling to estimate both positive and negative impacts of vegetation evolution, with an approach based on land-facets. Our approach, based on the construction of 16 ecoprofiles of species living in different environments, explains our choice not to focus on local impacts. Indeed, our objective was to obtain elements of general trend as a basis for discussion between the actors on the future of the metropolis. This choice of a fairly large number of ecoprofiles seemed important for highlighting the possible differentiated and contradictory results of the planning scenarios (Albert et al., 2017; Allen et al., 2016; Nor et al., 2017; Schaffer-Smith et al., 2016; Tarabon et al., 2019). However, decoupling the results of the impacts of the 5 scenarios on the 16 ecoprofiles (i.e. 80 local impact analyses) would have contributed to blur the communication and debates with the stakeholders during the workshop dedicated to the restitution of the results. Thus, we argue that studying the multiple local impacts of development scenarios requires a compromise between considering a large number of species or groups with varied ecological traits (habitat, behavior through the landscape matrix and dispersal capacities, etc.) and the possibility to communicate results with an imprint relevant to urban management action.

Finally, while the only indicators evaluating the scenarios were multi-species connectivity indicators, it would be interesting to supplement them with indicators relating to the other two components of the scenarios, such as the quality of governance and the response of urbanization to the population's housing needs.

4.2. Promoting participation for operationalizing landscape graphs

Gippoliti & Battisti (2017) reported several limits to the mobilization of ecological networks in planning and conservation, among which (1) the semantic ambiguity of the term 'ecological

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network' (in an ecological or planning definition) and (2) its possible misuse in landscaping in a logic of biodiversity conservation. Many arguments have already been proposed to show how ecological networks could benefit from landscape graphs to overcome these limits (Foltête, 2019). Complementary, we address here these two important points from the perspective of the participatory experience presented herein.

Avoiding ambiguity by sharing knowledge

First, an ambiguity of the term ‘ecological network’ was indeed noted during this study. By involving scientists from different disciplines (ecology, geography, sociology) and professionals with different competencies (urban planning, landscape planning, naturalist associations and conservationists, local or governmental authorities), it appeared certain that everyone came up with an idea of the meaning of this term, relating to its field of scientific or professional competency. These differences in meaning are in many cases a source of difficulties for bringing together scientists from various disciplines, and other sources of expertise on ecological networks (Vimal et al., 2012). However, the advantage of a participatory modelling approach such as the one implemented herein was to meet the opportunity to clarify this concept by continuous exchanges and debates during several successive workshops. Vigilance has therefore been possible in the use of terms and their meaning between (1) the notion of ecological networks as modeled by landscape graphs in this work, and (2) the possibilities of their operational translation into landscape and urban planning in the French *Trame Verte et Bleue* plans (Green and Blue Infrastructures). We presumed at the start of this work that the involvement of stakeholders in this whole process, from the formulation of the research question to the interpretation of results, can clarify their understanding of the results, towards an operational translation of connectivity in planning. This involvement accompanied by a continuous communication was in our opinion a good way to avoid the ambiguities linked to the notion of ecological networks between science and practice. This approach therefore validates in a certain way the idea that trans-disciplinary methodologies allow for a better understanding of socio-environmental issues (Horlick-Jones & Sime, 2004; Petts et al., 2008) by considering the multiple perspectives and knowledge of stakeholders (Forrester et al., 2015). Thus, we think like Wyborn et al. (2012) that promoting participation around the challenges of connectivity conservation at the landscape scale allow as much connecting landscapes as people. However, the stakeholders here involved were not elected policy-makers, but were rather practitioners of policy tools. The key institutions make responsibility dependent on “knowledge practice” (Adam & Groves, 2007) but temporal

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boundaries of political mandates induce uncertainty and indeterminacy on long-term policies. The main limitation is not so much to bridge the gap between the scientists and the other professionals, but to create a common knowledge between policy-makers for an effective consideration of the results and proposals, specifically in an urban planning with multiple challenges (economic development in particular).

Ecological networks for landscape planning AND biodiversity conservation?

While ecological network is important to consider for landscape and urban planning, it appears that it is very little considered among the biodiversity conservation tools (Gippoliti & Battisti, 2017). However, we believe that our approach can help operationalize the modelling of ecological networks by landscape graphs for landscape and urban planning, and for biodiversity conservation. In addition to the impacts of the scenarios on global connectivity, the maps of ecological networks in their initial state (example in **Figure 3**) served as a support for debates on their relevance to meet this dual challenge of operational translation. In a planning goal, and to avoid impacts such as those of strategic and dystopian scenarios, this type of representation allowed stakeholders to anticipate operational translation perspectives aiming at the preservation of habitats and corridors, considered in urban planning documents or mobilized in impact assessments. The representation of multifunctional corridors in addition to the structure of the landscape graph (habitat patches and least-cost paths only) allowed to avoid the neglected effect of the landscape matrix in the movement of organisms mentioned by Battisti (2013) in the context of a project of urban development. In order to avoid connectivity losses as for utopian and transformative scenarios, it should however be accompanied by additional graph-based analyzes for guiding ecological restoration operations. This would consist in determining the most relevant sites for the reconnection of landscape graphs as proposed by Clauzel et al. (2015) and Tarabon et al. (2019) while meeting the challenges of a multi-species approach.

For a biodiversity conservation goal, a limit of the modelling and its spatial representation is its difficulty in highlighting certain areas recognized as biodiversity hotspots by the stakeholders according to their field knowledge. Faced with this limit, they expressed a need of including empirical data (occurrence or abundance) to the analysis for a better understanding of ecological processes. In parallel to this work, field protocols carried out by naturalists will allow to both identify certain biodiversity hotspots at the metropolitan scale, and to couple these protocoled data with the modelling of landscape graphs in a network design' operational approach (Foltête et al., 2020). Here we join the idea that connectivity modelling is one method among others to fulfill the goal of biodiversity conservation (Boitani et al., 2007) but very complementary to other approaches at this scale. To complement this, the quantification of habitat quality, by means of various environmental variables or constructing landscape graphs from habitat suitability models (Clauzel & Godet, 2020; Duflot et al., 2018; Godet & Clauzel, 2020) would be a means of improving our modeling approach.

5. Conclusion

Our objective was to integrate landscape graphs modelling into a participatory approach for studying potential impacts of land-use planning scenarios on multi-species landscape connectivity in a metropolitan area. We applied an adapted Companion Modelling for bringing together scientists and stakeholders on the co-construction of the multi-species approach based on ecoprofiles, a model of the territory functioning through interactions between actors and resources, and land-use planning scenarios as a performative knowledge. The results of this geoprospective co-constructed approach showed differentiated impacts on landscape connectivity depending on scenarios and species ecoprofiles. These results highlighted the negative consequences of dystopian scenarios or current trends in planning, compared to the possibility of improving connectivity with the implementation of voluntary actions for ecological restoration. In this way, we produced useful insights about the influence of policy decisions or actions at the scale of a metropolitan area. While, as expected, the dystopian scenarios produce significant negative impacts on connectivity, the continuation of current trends also leads to such impacts. This therefore means that immobility in terms of action or public policies is also negative. However, we showed that with a strong limitation of urban development accompanied by measures to restore natural habitats, connectivity is barely preserved compared to the negative consequences. This can be explained in part by the current state of the Bordeaux metropolitan area, urbanized for many years without real consideration of the ecological networks, reinforced by the global context of the erosion of biodiversity (Borges et al., 2009). Thus, an improvement in multi-species ecological connectivity requires a strong and assumed multi-actors' governance in favor of the preservation of natural habitats facing past and future anthropogenic pressures. As a conclusion to the participatory approach undertaken, the stakeholders expressed a better understanding of the challenges of reconciling urban development and preservation of connectivity, and the importance of collaboration in responding to them. They also expressed their willingness to defend the transformative scenario, which means not respecting certain

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planned urban developments. This could be reflected in public policies for the coming years, questioning in another way the trade-offs between urban development and the preservation of biodiversity. Therefore, we argue that this approach permitted to fill a gap in the use of ecological network approaches in the spheres of science and policy interdependencies, with the aim of a stronger consideration of biodiversity conservation issues in metropolitan governance.

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Table 2. *Impacts of scenarios on equivalent connectivity metric (EC) calculated from current vs. scenaristic land use maps for each ecoprofile (see section 2.5).*

	EC variation (in %)				
Ecoprofiles	**S1 Strategic**	**S2 Dystopian**	**S3 Dystopian**	**S4 Utopian**	**S5 Transfor-mative**
Water courses species with medium dispersal capacities	-3.57	-18.83	-3.99	2.18	10.19
Water bodies species with low dispersal capacities	-1.62	-36.21	-2.03	-0.07	-0.13
Water bodies species with high dispersal capacities	-8.77	-40.50	-8.79	0.02	0.00
Water bodies and courses species with low dispersal capacities	-0.89	-21.80	-0.86	6.28	7.48
Water bodies and courses species with medium dispersal capacities	-6.85	-29.86	-7.60	2.17	7.19
Water bodies and courses species with high dispersal capacities	-3.96	-14.85	-6.59	4.97	8.19
Deciduous forests species with medium dispersal capacities	-26.92	-17.59	-13.76	29.99	-0.50
Mixed forests species with high medium capacities	-29.61	-14.50	-3.33	-0.73	-0.22
Deciduous forests species with high dispersal capacities	-25.98	-26.98	-19.26	28.96	-0.66
Mixed forests species with high dispersal capacities	-32.39	-13.86	-2.64	-1.85	-0.20
Mixed open areas species with low dispersal capacities	-5.64	-9.15	-3.66	-3.23	-0.07
Mixed open areas species with medium dispersal capacities	-8.57	-17.67	-5.77	-0.41	-0.16
Mixed open areas species with high dispersal capacities	-12.76	-22.80	-12.25	0.48	0.32
Natural open areas species with low dispersal capacities	-2.48	-5.24	-2.27	0.10	-0.02
Natural open areas species with medium dispersal capacities	-11.30	-14.83	-9.56	0.47	0.18
Natural open areas species with high dispersal capacities	-20.27	-21.45	-23.24	1.37	1.30

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Figure 3. Location of the study area in the southwest of France (a) and its land-cover in 2016 (b).

Figure 2. Design of the participatory approach.

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Appendix A. Selection of target species

The selection of target species was based on the regional information system on wildlife (http://si-faune.oafs.fr/), which made it possible to select the species present in the study area with three filters: (1) All selected species to be included within functional groups were terrestrial or semi-aquatic species (i.e. species displaying only part of their life cycles within aquatic habitats). Indeed, strictly aquatic species (i.e. fishes) were excluded due to i) methodological constraints associated with the mapping and modelling of favorable habitats and mobility pathways for those species, which rely upon dynamic and diffuse environmental parameters that the selected modelling method cannot take into account at a landscape scale, ii) the lack of up-to-date reliable data on the presence and localization of obstacles to fish movements within aquatic systems included in the targeted territory. (2) Species were restricted to mammals, amphibians, reptiles, birds and insects sensitive to human disturbances, and concerned by national, European or international protection legislations. For insects, however, experts advised to select only species concerned by local conservation issues. (3) Several species were further excluded due to technical constraints related to the modelling of their ecological networks by landscape graphs: generalist species with multiple habitats, species whose habitat is difficult to characterize from land use data, species for which little knowledge exists about their ecological needs, and finally species whose dispersal distance is too great (i.e. greater than 20 km) relative to the area of study.

Appendix B. Full list of references for the definition of species' habitat, movement paths and dispersal distance.

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Watts, P.C., Saccheri, I.J., Kemp, S.J., Thompson, D.J., 2006. Population structure and the impact of regional and local habitat isolation upon levels of genetic diversity of the endangered damselfly Coenagrion mercuriale (Odonata: Zygoptera). Freshwater Biology, 51, 193–205.

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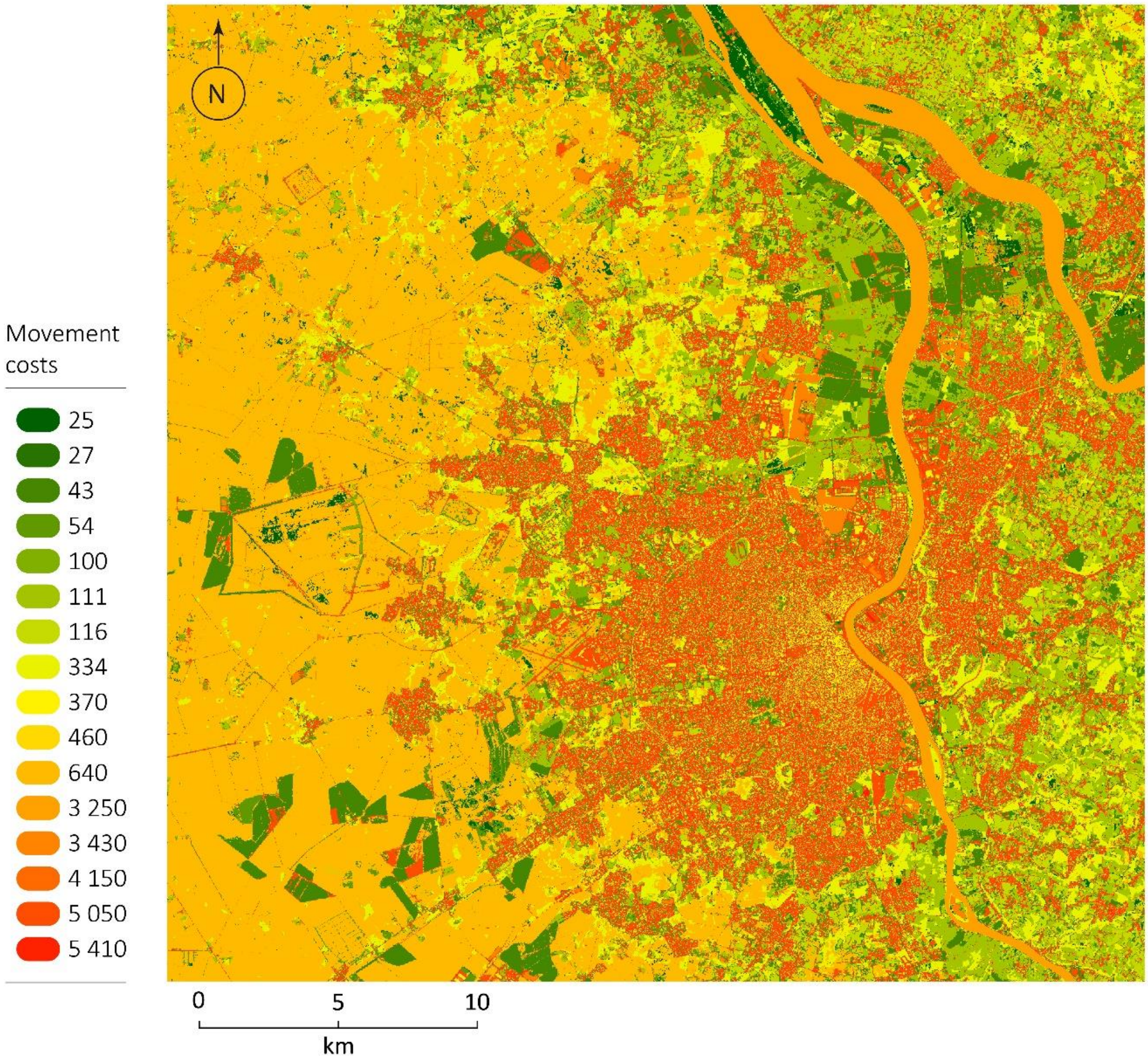
Appendix C. Example of movement costs representation for mixed open areas species with medium dispersal capacities



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Appendix D. Characteristics of ecoprofiles.

The table cannot be inserted but is in the repository.

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Appendix E. Scenarios' description and their GIS construction

Scenario	**Description of changes implied by co-constructed scenarios**	**GIS processing in land-use changes and graph parameterization**
Scenario 1 : Strategic	Urbanization within urban areas and in urban fringes. Preservation of protected area**s** (Natura 2000 and ZNIEFF) from their delimitations. Anthropogenic pressure on forests for recreation.	***[Land-use changes]*** 1. Application of all planned artificialized areas already equiped or not with infrastructure, identified from local development plans (PLUi, Bordeaux Métropole, 2016) excepted on protected areas identified from their delimitation (INPN, 2016). 2. Creation of 50m buffer zones around urban fringes, excepted on protected areas. ***[Graph parameterization]*** Decrease of 10% in capacity of forests and urban woods patches for forested species for computing connectivity metrics.
Scenario 2 : Dystopian	Urbanization by densification, verticalization, and urban sprawl not exceeding the limits of the main urban patch of the metropolitan area.	***[Land-use changes]*** 1. Application of planned artificialized areas already equiped or not with infrastructure identified from local development plans (PLUi, Bordeaux Métropole, 2016). 2. Manual filling of some small open-areas and urban woods by artificialized areas the urban center. 3. Buffer zones of 50m around artificialized areas within the main urban patch. ***[Graph parameterization]*** Increase of 50% for movements' resistance for all species on artificialized areas of the city-center of Bordeaux, only within the main urban patch.
Scenario 3 : Dystopian	Urbanization by densification, verticalization, and urban sprawl exclusively beyond the limits of the main urban patch of the metropolitan area, around the municipalities located along the main transport axes.	***[Land-use changes]*** 1. Application of planned artificialized areas already equipped with infrastructure or not identified from local development plans (PLUi, Bordeaux Métropole, 2016) 2. Manual filling of some small open-areas and urban woods by artificialized areas the urban center. 3. Buffer zones of 50m around artificialized areas of the concerned municipalities. ***[Graph parameterization]*** Increase of 50% for movements' resistance for all species on artificialized areas of the city-center of Bordeaux, only within the main urban patch.

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Scenario 4 : Utopian	Urbanization only within urban areas. Preservation of protected area**s** (Natura 2000 and ZNIEFF Type 1) and of existing landscape connectivity Restoration of forested and aquatic landscape connectivity by the reopening of old rivers, the (re)creation of flood expansion zones and replacement of coniferous forests into deciduous forests.	***[Land-use changes]*** 1. Application of planned artificialized areas (only those within urban areas and already equipped with infrastructure) identified from local development plans (PLUi, Bordeaux Métropole, 2016) excepted on protected areas identified from their delimitation (INPN, 2016) and on corridors identified in this study for all species. 2. Addition of the old rivers identified both from data (IGN, 2016) and expert elicitation. 3. Buffer zone of 50m along these added rivers and other major rivers, only within urban areas. 4. Application of a buffer zone of 100m around decideous forests on coniferous forests for their replacements. ***[Graph parameterization]*** Increase of 10% in capacity of water courses patches capacity for aquatic species.
Scenario 5 : Transformative	Urbanization only within urban areas. Preservation of protected area**s** (Natura 2000 and ZNIEFF Type 1) and of existing landscape connectivity Restoration of aquatic landscape connectivity by the reopening of old rivers and the (re)creation of flood expansion zones.	***[Land-use changes]*** 1. Application of planned artificialized areas (only those within urban areas and already equipped with infrastructure) identified from local development plans (PLUi, Bordeaux Métropole, 2016) excepted on protected areas identified from their delimitation (INPN, 2016) and on corridors identified in this study for all species. 2. Addition of the old rivers identified both from data (IGN, 2016) and expert elicitation. 3. Buffer zone of 50m along these added rivers and other major rivers, only within urban areas. ***[Graph parameterization]*** Increase of 10% in water courses patches capacity for aquatic species for computing connectivity metrics.

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Appendix F. Scenarios' narratives

Strategic scenario (S1)

In terms of governance, the metropolis has a regional, national and international dimension. Its anticipatory governance is based on the implementation of public policies aimed at territorial attractiveness and population growth, with the support of major urban development projects. These developments take the form of an urban densification both in the hyper-center and in the urban fringes. This urban development is done according to the existing urban plans, although natural and agricultural spaces preserved from urbanization in urban fringes are seen as constraints. The ecological configurations of the landscape are a contingent component. The challenges of preserving natural spaces and ecological continuities are only taken into account if there are strong regulatory constraints for urban development plans. In addition, these landscape ecological configurations are perceived as important only for their anthropocentric dimension as amenities for the inhabitants. Faced with urban densification, peripheral natural spaces as well as urban squares, parks and gardens are subject to anthropogenic degradation (e.g. over frequentation, pollution, trampling of plants).

Dystopian scenarios (S2 and S3)

Urban development is a structuring component and takes a hyper-densification form of the city center by verticalization of the buildings and a filling of remnant open spaces (scenario 2), or by an urban sprawl in the fringes or along the principal transportation axes outside the limits of the metropolitan area (scenario 3). Governance (similar for scenarios 2 and 3) supports and implements regulations opposing the infra-metropolitan space intended to be urbanized by overcoming urban plans, and the extra-metropolitan space to remain natural. The establishment of an ecological offsets system for infra-metropolitan urban projects allows the restoration of surrounding natural ecosystems and their accessibility for leisure activities. The landscape ecological configurations maintain a peripheral green belt allowing the preservation of the ecological functionalities of the surrounding (semi-)natural landscapes (scenario 2), or (semi-)natural corridors and areas in the urban interstices, also favoring landscape amenities (scenario 3).

Utopian scenario (S4)

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Landscape ecological configurations constitute the structuring component of the scenarios, resulting in the preservation of all existing and remnant corridors and habitats, even if they are isolated. Restoration of aquatic ecosystems results in the depollution of existing rivers, the reopening of old underground and dammed rivers and the restoration of flood expansion zones, herbaceous zones which can also be intended to be grazed meadows or recreational areas. Restoring the ecological functionality of the forests of the *Landes plateau* (west and south fringes of Bordeaux) requires the gradual replacement of coniferous forests into deciduous forests. Governance constitutes a supporting component and takes the form of a participatory democracy integrating citizens into decision-making. It is based on a new institution with a perimeter of action beyond the scale of the metropolitan area for the planning of major ecological projects. Urban development is adapted to the landscape ecological configurations, with (1) a deconstruction of artificial spaces for the reopening of old underground or dammed rivers and the restoration of river banks and (2) urbanization according to existing urban plans but only outside existing ecological corridors and natural spaces. These new constructions are accompanied by ecological engineering (e.g. constructions on stilts, green roofs, minimizing their ecological impact).

Transformative scenario (S5)

The landscape ecological configurations are a structuring component allowing the preservation of an ecological network on a larger scale, integrated in urban planning. A reopening of underground and dammed rivers is accompanied by solutions of depollution and sanitation of the existing aquatic network. A better understanding of natural spaces and their connectivity is encouraged to improve ecological restoration actions. Metropolitan governance extends to peripheral territories, and promotes an overall vision of the territory which involves more transversal and sustainable policies over the long term. The establishment of an incentive tax system encourages municipalities to protect natural habitats and species, and the preservation of the ecological network is included in urban planning documents. An ecological offset system is set up with a concerted governance between the metropolitan area and its peripheral territories. Urban development now depends on the landscape ecological configurations. Population growth is no longer a priority. The city center (Bordeaux), is however becoming denser through constructions according to urban plans, but only outside of ecological corridors.

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Appendix G. Resulting land-cover maps of scenarios.