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European blue and green infrastructure network strategy vs. the common agricultural policy. Insights from an integrated case study (Couesnon, Brittany)

Houet Thomas [a,h,*], Palka Gaetan [a,h], Rigo Roberta [a,h], Boussard Hugues [b,h], Baudry Jacques [b,h], Poux Xavier [c], Narcy Jean-Baptiste [c], Alvarez Martinez José Manuel [d], Balbi Stefano [e], Mony Cendrine [f,h], Lecoq Lucie [f,h], Beganton Johanna [g], Barquin José [d]

[a] *CNRS – UMR LETG-Rennes, University of Rennes 2, France*
[b] *UMR 0980 BAGAP, INRAE-ESA-Institut Agro Rennes Angers, 65 Rue de Saint-Brieuc, 35042 Rennes Cedex, France*
[c] *AScA Paris, France*
[d] *IHCantabria – Instituto de Hidráulica Ambiental de la Universidad de Cantabria, Spain*
[e] *BC3 – Basque Centre for Climate Change, Spain*
[f] *UMR ECOBIO CNRS, University of Rennes 1, France*
[g] *UMR AMURE, University of Brest, France*
[h] *LTSER Zone Atelier Armorique, France*

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ABSTRACT

Urbanization and agricultural intensification are the main drivers of biodiversity losses through multiple stressors, especially habitat fragmentation, isolation and loss. Designing Blue and Green Infrastructure Networks (BGIN) has been recommended as a potential tool for land-use planning to increase ecosystem services while preserving biodiversity. All municipalities in France are required to perform BGIN planning. This article focuses on the Couesnon watershed (Brittany, France) and the participatory process used to define and analyze five possible pathways of future land-use and land-cover changes that included implementation of BGINs. Impacts on biodiversity were estimated by quantifying the change in landscape connectivity of woodlands, grasslands and wetlands. The effectiveness of BGIN policies was assessed by comparing current landscape connectivity (2018) to those in possible futures. Landscape connectivity referred to functional connectivity for three indicator species (*Abax parallelepipedus*, *Maniola jurtina* and *Arvicola sapidus*) across three landscape features: woodlands, grasslands and wetlands, respectively. Results allowed impacts of urban and agricultural land-use changes to be identified in terms of extent and quality. If BGIN policies were applied effectively to control the expansion of gray infrastructure, they would help increase the area and the quality of grassland and woodland connectivity by no more than 2%. Agricultural land-use and land-cover changes could have more impact on the extent of grassland (−82% to +38%) and wetland (−49% to +47%) connectivity. Current and future trends for hedgerows implied a decrease in woodland connectivity of 9.8–33.8%. Impacts on the quality of landscape connectivity is not proportional with the extent, as a decrease of the latter can have relatively more negative impacts on the former, and inversely. The study highlights that the BGIN strategy can preserve landscape connectivity effectively in urban ecosystems, where human density is higher, but can be threatened by agricultural intensification.

1. Introduction

After 1950s, rural landscapes in Europe experienced rapid changes in agriculture, urban sprawl and transport infrastructure (Anon, 2001; Lambin and Geist, 2006). Cities and their infrastructure have expanded since then, at the expense of farmland and nearby natural and semi-natural areas. Within this farming landscape, a variety of land-use and land-cover (LULC) trends have occurred in recent decades. Fields with steep slopes and poor soil have been abandoned, while most farmland has been turned into more homogeneous landscapes, with a

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* Corresponding author at: CNRS – UMR LETG-Rennes, University of Rennes 2, France.
E-mail address: thomas.houet@univ-rennes2.fr (H. Thomas).

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sharp decrease in semi-natural elements (e.g. hedgerows, permanent grassland) and crop diversity (Foley et al., 2005; Tscharntke et al., 2005). Conversely, landscape simplification through intensification of agricultural practices has resulted in major losses of biodiversity and many regulating ecosystem services (Matson et al., 1997; Tilman et al., 2001; Butler et al., 2007; Maron and Fitzsimons, 2007). To counteract biodiversity losses and subsequent impacts on ecosystem services, the European Commission continues to foster several policies, such as the "greening" of the Common Agricultural Policy (CAP), the Bird Habitat Directive, as well as other current initiatives within the European Green Deal, such as the development and implementation of Blue and Green Infrastructure Networks (BGINs) (European Commission, 2019a, 2019b).

BGINs are strategically planned networks of natural and semi-natural landscape elements that support, among other functions, the existence and dispersal of plant and animal species across fragmented landscapes. BGINs consist of a variety of landscape elements and structures, including individual tree rows to more comprehensive *green* ecosystems (e.g. hedgerows, shrublands, orchards, woodlands, riparian vegetation, permanent grasslands), as well as *blue* ecosystems (e.g. pools, ponds, wetlands, lakes, watercourses), that provide structural and functional connectivity across landscapes (European Environment Agency, 2011). The spatial arrangement of blue and green landscape elements, defined hereafter as BGINs, represents a spatial entity at a higher hierarchical level than independent nature-based solutions. They are promising tools for land-use planning that encompass the objective of enhancing ecosystem services while securing biodiversity. In this regard, they can contribute to sustainable food production, water quality improvement, climate mitigation and adaptation, social health and well-being, recreational services and environmental education (EU, 2012).

Application of BGINs at the national level in the EU shows different stages of progress. Some countries are still wo king to define BGINs and implement them locally (e.g. Spain, Portugal), while others have already integrated BGINs into regional and local territory planning schemes, such as France, where BGINs have limited and oriented land-planning strategies since the mid-2010 s. French regions have identified and defined main corridors in, namely, "Regional management plans for the sustainability and equality of territories". Because BGIN maps have been developed at a coarse scale (1:100 000), they are downscaled to a finer scale (1:5 000) to incorporate them into local management plans at the level of a municipality or group of municipalities, as in a "Coherent Land-management Scheme" (*Schéma de Cohérence Territoriaux* (SCoT)). A SCoT is intended to serve as a reference framework for sector-specific policies, particularly land and urban planning, housing, transportation, commercial development, and the environment, including biodiversity, energy and climate. SCoT must be set for 15–20 years and defined by elected representatives, which strongly constrains urban planning with recommendations of urban renewal, densities and norms. Due to the multiscale nature of BGINs, designing them can still be challenging since no single method has been defined. In France, their design includes protecting patterns of connectivity among biodiversity reservoirs and the biodiversity reservoirs themselves (e.g. Natura 2000 sites), as encouraged by the European Commission. Thus, when incorporated into land-planning policies, BGINs are a possible strategy for preserving biodiversity by counteracting negative effects of human development. This strategy appears relatively attractive and potentially effective for preserving landscape connectivity, its related biodiversity and ecosystem services over the medium-to-long term (Mazza et al., 2011).

This study evaluated the potential effectiveness of case-study-specific BGIN strategies by exploring the influence of multiple and contrasting pathways of land-use intensification at a fine scale. Its originality lies in assessing the BGIN strategy as a sustainable land-management tool. As Helming and Pérez-Soba (2011) highlighted, assessing impacts of future scenarios of landscape-level land-use change is particularly relevant for sustainable policymaking. In this study, intensification of agricultural land use was examined independently of that of urban land use, since they depend on different driving forces. Agricultural land use is driven mainly by economic factors related to the European Union (EU) CAP and individual farmer preferences (e.g. production system, crop rotations) (Houet et al., 2014). Urban land use is driven by socio-economic, demographic, transportation and many other multiscale factors and regulated by local (territorial) land-planning strategies (Meyfroidt et al., 2013). The latter are designed for natural/protected areas and areas that will support future urban development (i.e. "territorial development"). The case study was the Couesnon River watershed (Brittany, western France), which faces major ecological challenges. We made two hypotheses: (1) impacts on biodiversity can be assessed by analyzing functional connectivity of the landscape, as a proxy of biodiversity habitats and functioning (Bélisle, 2005; Vogt et al., 2009; Mimet et al., 2013) and (2) the CAP can greatly decrease the effectiveness of the BGIN strategy, even though two pillars of the CAP provide instruments for addressing sustainable management of natural resources and climate action (European Commission, 2012; European Commission, 2019a, 2019b).

2. Materials and methods

2.1. Overview of the methodology

The overall workflow of the study (Fig. 1) distinguished steps performed by scientists only from those made in collaboration with participants (e.g. local stakeholders, elected officials, technicians, NGOs). We first characterized the land-use and -cover change (LUCC) trajectory of the study site, and then we organized two participatory meetings that helped collect the information required to build narratives. Next, we developed the FORESCEM modeling framework and used it to simulate future LUCC based on the narratives. We combined results of LUCC simulations with the narratives to develop scenarios that were then validated during another participatory meeting. Once validated, the scenarios provided inputs for the CHLOE landscape metrics software, which predicted potential impacts of future LUCC on biodiversity through the lens of landscape connectivity. Finally, all results were analyzed and disseminated to all participants and a wider audience to raise awareness about the potential effectiveness and limitations of the study site's SCoT management plan, the local French application of the EU BGIN strategy.

2.2. Study area and LUCC trajectory

The case study focused on the Couesnon River watershed (1130 km^2) in the Armorican massif, in northwestern France (Fig. 2a). It flows into Mont-Saint-Michel Bay (a UNESCO World Heritage Site) and contains mainly intensive agriculture with mixed dairy/livestock production in the upstream part, while vegetables/cropping systems dominate in the polders, next to the sea. The agricultural landscape is dominated by grasslands (temporary and permanent), maize and other cereals/oilseeds (wheat/rapeseed/barley) (Table 1). Temporary grasslands are sown grasslands with mixed grazing and mowing. Permanent grasslands are mainly riparian grasslands in valley bottoms. The landscape has a hedgerow network of variable density and connectivity. Wooded areas are mainly post-agricultural woodlands that contain a mixture of oaks (*Quercus* sp.), chestnut (*Castanea sativa*) and beech (*Fagus sylvatica*). Except for two large forests, wooded patches are quite small in the agricultural matrix. A Natura 2000 floodplain, the Sougéal marsh (Fig. 2b), lies near the estuary and is a hotspot of bird biodiversity close to one of the most important and complex bays worldwide.

For this study, we first enlarged the watershed area by adding a 3 km buffer zone around it to remove edge effects. A generic approach was developed to analyze LUCC using maps with a 10 m resolution (Appendix 1). The area's agriculture intensified greatly after 1945, with the utilized agricultural area (UAA) shifting predominantly to maize (+39 964 ha) since the early 1990 s, which has decreased the area of

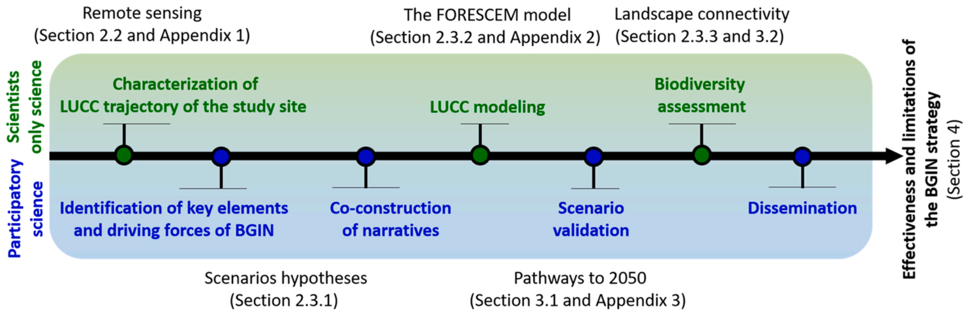

Fig. 1. The overall method used combined scientific studies and participatory science. Land-use and land-cover change (LUCC) scenarios built by combining narratives and simulations were used to estimate impacts of possible LUCC on landscape connectivity. Comparison of scenarios helped assess the effectiveness and limitations of the current European Union (EU) BGIN strategy in an intensive agricultural landscape. Green text identifies the main steps of scientist-only studies. Blue text identifies participatory studies and meetings (one for each blue dot). Each step (method and/or result) is detailed in the article in the sections mentioned.

Adapted from Houet et al. (2017)).

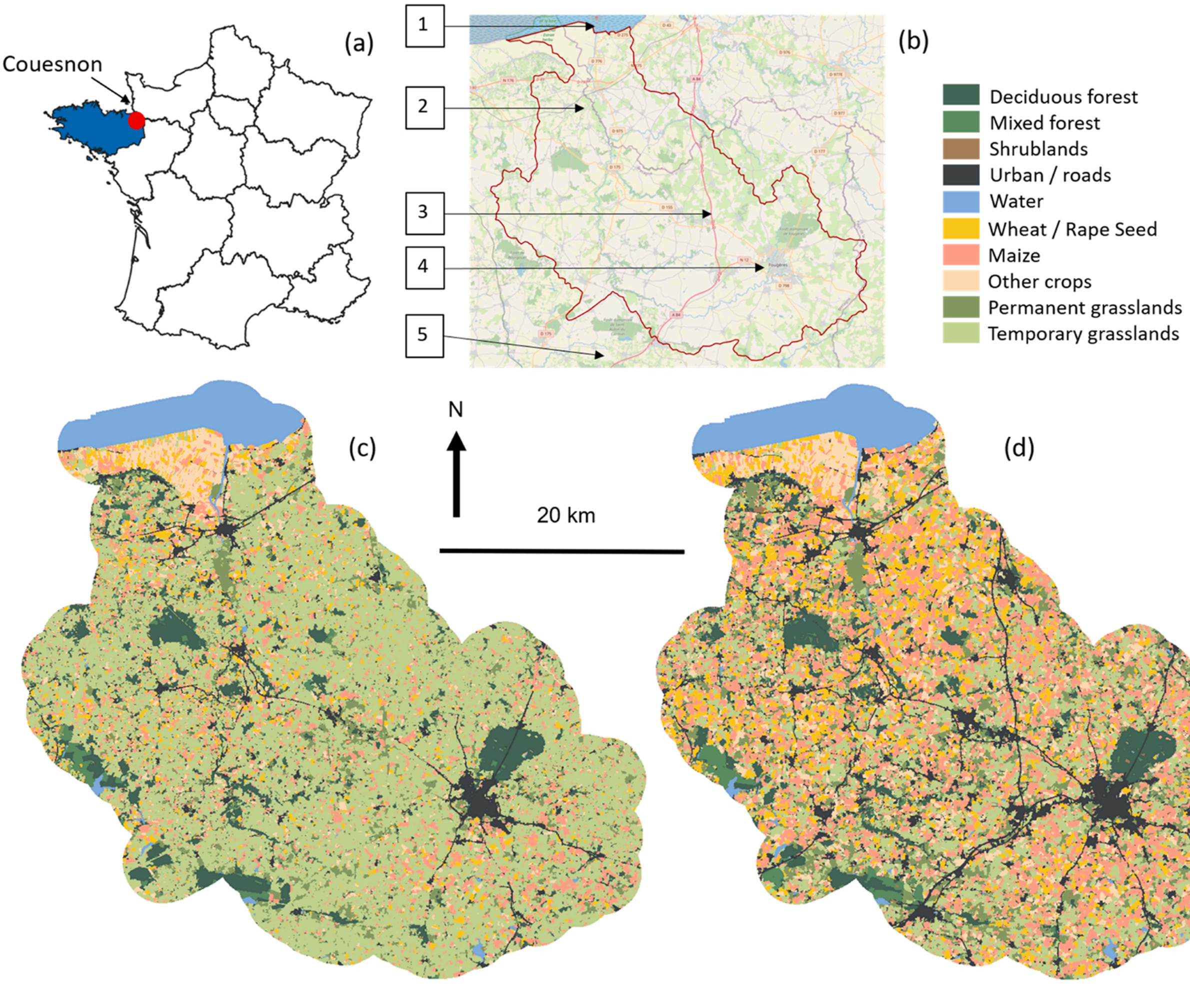

Fig. 2. Presentation of the study site: (a) Location of the Couesnon watershed in France; (b) Couesnon watershed (red outline) and key geographical features: 1 - Mont Saint Michel, 2 - Sougéal marsh Natura 2000 site, 3 - A84 highway, 4 - Fougères metropolitan area, and 5 - Rennes metropolitan area, 40 km from Fougères; land-cover maps in (c) 1990 and (e) 2018.

grasslands greatly (Fig. 2c and d; Table 1). In 2018, maize, grasslands and other cereals/oilseeds covered 41 201, 56 234 and 21 524 ha, respectively. Along with the loss of grasslands, agricultural fields have been abandoned due to problems of accessibility, size, forage production and flooding, especially in valley bottoms, which transitioned to shrublands and then forests, reaching 7 791 ha in 2018. During this period, urban land use also increased due to urban sprawl and construction of the A84 highway (+5 951 ha), reaching 12 844 ha in 2018.

The two main ecological concerns in the area are related to agricultural land use. Water quality and quantity are impacted by agricultural practices that emit large nutrient loads into the Couesnon River, which is the main source of drinking water for local populations, including the Rennes metropolitan area. Overall, 30% of the water pumped is exported and consumed by people located outside of the watershed. Agricultural intensification in valleys and on plateaus, land abandonment in valley bottoms, and urbanization and soil sealing have simplified the landscape matrix, decreased landscape connectivity and contributed to biodiversity losses (Kazemi et al., 2018).

Table 1
Cross-tabulation of land-use and land-cover changes from 1990 to 2018 (in ha, percentages indicate the change in area from 1990 to 2018).

		2018						Change analysis		
		Broadleaf Forest	Mixed Forest	Grasslands	Urban	Water	Crops	1990	2018	Delta
1990	Broadleaf Forest	8 989 (64.99%)	1 289 (9.32%)	1 166 (8.43%)	259 (1.87%)	16 (0.12%)	2 112 (15.27%)	13 831	15 197	+ 1 365 (+9.87%)
	Mixed Forest	1 153 (57.39%)	832 (41.41%)	16 (0.80%)	2 (0.10%)	1 (0.05%)	6 (0.30%)	2 009	2 261	+ 252 (+12.54%)
	Grasslands	4 220 (4.59%)	91 (0.10%)	40 330 (43.83%)	4 192 (4.56%)	45 (0.05%)	43 136 (46.88%)	92 014	52 050	-39 964 (−43.43%)
	Urban	0	0	0	7 079 (100%)	0	0	7 079	13 030	+ 5 951 (+84.07%)
	Water	241 (3.06%)	31 (0.39%)	0	2 (0.03%)	7 605 (96.50%)	3 (0.04%)	7 881	7 676	-206 (−2.61%)
	Crops	593 (1.23%)	19 (0.04%)	10 539 (21.86%)	1 496 (3.10%)	8 (0.02%)	35 561 (73.75%)	48 217	80 818	+ 32 601 (+67.61%)

2.3. *Defining future landscape changes and their impacts on biodiversity patterns*

Using scenarios to explore the future is particularly popular in the field of environmental management (Garb et al., 2008) as a tool to define land-management policies and make decisions based on scientific evidence (Kok et al., 2017). Three types of uses of scenarios can be distinguished: instrumental, conceptual and political (Dunlop, 2014; Lumbroso, 2019; McKenzie et al., 2014). In instrumental use, scenarios serve to inform decision makers and to make informed decisions. In conceptual use, they deepen understanding of a complex phenomenon, to shape the way of thinking and to allow new beliefs and values to arise. In political use, scenarios promote and support a policy option or a specific interest group, which legitimizes action. Thus, scenarios can be also considered as tools to assess policies, their potential effectiveness and future sustainability.

To explore possible pathways of future LUCC that include implementation of BGIN, we applied a framework similar to those defined by Houet et al., (2016, 2017) that combines participatory and modeling methods to design scenarios. These scenarios consist of contrasting narratives that are then illustrated by LULC maps using the LUCC model FORESCEM (Palka submitted, Houet et al., 2017). Potential impacts on biodiversity are estimated using a landscape-connectivity model.

2.3.1. *Scenario assumptions*

Systemic scenarios were defined by combining three independent and contrasting assumptions each about agriculture and territorial development (Table 1). Given a temporal horizon of 2050, agriculture could evolve in three directions. The first was the “cerealization” assumption, which favors producing cereals as biomass or biofuel. Due to a decrease in dairy and livestock production in Brittany in response to production in eastern and central European countries, EU Agricultural Energy Policy promotes agro-energy cropping systems in 2032. Large biogas plants are installed to transform these crops into energy. Locally, livestock production becomes a relict, dedicated to local markets, and less favorable farmland is abandoned. The second direction is the “dairy intensification” assumption. Reform of the CAP creates subsidies per ha that favor intensification of local dairy/livestock production. Excessive nutrient flows are treated in small biogas plants, while fertilization practices improve. The third direction is the “greening” assumption: the CAP is deeply transformed in 2025 to promote an agroecological transition and agrifood protection. Farmers receive subsidies as Payment for Ecosystem Services (PES) supported by the regional government. Dairy and livestock production diversify and are based mainly on grassland forage, organic farms increase in total area, and agricultural products are dedicated to local markets. In this scenario, agriculture improves in terms of the quality of food products and environmental preservation.

Territorial development respects local urban-management plans that are set at the municipal level according to local representatives’ strategies and national policies. It is also driven by the social demand from inhabitants for certain types and locations of housing. It could evolve in three directions. The first direction is the “business-as-usual” assumption, which follows past trends. Inhabitants prefer single-family houses with a small yard, and municipalities compete to attract future inhabitants (+31 600 in 2050; INSEE Bretagne, 2019a, INSEE Bretagne, 2019b; AUDIAR, 2018). The objective of “zero urbanization” defined by the French government’s “Biodiversity Plan” (France Stratégie and Fosse, 2019) cannot be attained in 2040, although the main BGINs are protected from urban sprawl. The second direction is the “energy transition” assumption, in which development is oriented in order to transition effectively. Commuting decreases due to the development of teleworking. High-energy performance of new buildings and renovated houses is the norm. The energy-oriented economy makes the Couesnon watershed attractive for people (+38 800 more inhabitants in 2050 than in 2018). Urban sprawl is controlled and concentrated in the main urban areas to decrease commuting and favor public transportation. Renovation of old buildings is encouraged to limit urban sprawl, thus meeting the zero-urbanization objective by 2045, and BGINs are strongly preserved. The third direction is the “ecological citizen” assumption. Development is driven by citizens’ preferences for a better quality of life (away from cities) and more food independence. Due to its location in Brittany and its well-preserved hedgerow landscape, the area is more attractive than other areas in Brittany, although the local economy is less dynamic than that in the “energy transition” assumption (+35 900 inhabitants). The countryside attracts and gains new inhabitants after decades of rural exodus. Although the main urban areas are still the most attractive and strictly control urban sprawl, the zero urbanization objective is not met. Rural villages still expand even though renovation is strongly encouraged. BGINs are strictly preserved, however, and local authorities favor ecological preservation and restoration.

Combining these 3 × 3 assumptions created eight potential scenarios, since one combination (“greening” agriculture with “business-as-usual” territorial development) was not internally consistent (Table 2). The five most contrasting scenarios were selected to explore the widest

Table 2
Combination of territorial and agricultural development assumptions. The five most contrasting scenarios (in bold) were selected to explore the widest diversity of possible futures.

		Territorial development		
		Business-as-usual	*Energy transition*	*Ecological citizen*
Agricultural development	*Cerealization*	**Desert of cereals**	**Energy performance**	Conflicts
	Dairy intensification	**Business-as-usual**	Diversified Biomass	**Double performance**
	Greening	Ø	Optimized BGINs	**Green attractiveness**

diversity of possible future landscape changes: (1) Business-as-usual, (2) Double performance, (3) Desert of cereals, (4) Energy performance and (5) Green attractiveness.

These assumptions were presented to, refined by and completed with stakeholders during the first participatory meeting. Since they remained quite general, the aim of the second participatory meeting was to specify them by considering local characteristics through narratives and participatory mapping to define the scenarios' parameters (Fig. 1). Narratives were then refined and quantitatively illustrated using simulated and estimated outcomes according to the method of Houet et al. (2017), which combines participatory meetings and modeling tools to create and downscale fine-scale LUCC scenarios.

2.3.2. *The FORESCEM model*

The FORecasting landscapE SCEnarios Model (FORESCEM) combines cellular automata and object-oriented approaches to spatially allocate future LUCC based on narratives, which were defined using participatory or expert-based approaches, and to predict combined effects of interactions among LUCC in human-managed territories (Palka et al., submitted; Houet et al., 2017). It was used to simulate LUCC from 2018 to 2050 at a fine scale, while preserving landscape patterns (fields). This framework makes as transparent and direct as possible the translation of narratives built with stakeholders into input parameters of the model. LUCC are defined as natural vegetation dynamics (e.g. from grassland to forest states) and agricultural or forest cover successions (e.g. crop rotations, maturing forest). LUCCs are also associated with any change due to human decisions (or lack thereof), such as urban planning or land abandonment. It allows a regulatory map of the BGINs, designed in the SCoT, to be considered as areas that are protected from future urbanization (Fig. 1 of Appendix 2). FORESCEM was detailed and validated by Palka et al., (submitted). See Appendix 2 for details on its functioning and input data.

2.3.3. *Evaluating landscape connectivity*

The simulated land-cover maps were used as input for a landscape-metrics spatially explicit model that estimated landscape connectivity for each of the five scenarios. Thus, the resulted maps differ from the one representing the BGIN land-planning strategy used as input for FORESCEM. Two broad categories of methods can be used to assess landscape connectivity: (1) landscape metrics that measure connectivity of the entire landscape (Kindlmann and Burel, 2008) and (2) connectivity maps. Making the latter first requires a land-cover map, in which some land-cover types assimilated here as habitats that are easy for certain species to move through, while others are more difficult (Knaapen et al., 1992). In permeability maps (Theobald et al., 2012), each land-cover type is assigned a cost of movement. The assumption is that the cumulative cost for an individual of a species to move through a landscape has a limit; once this limit is reached, movement stops. We distinguished two approaches to movement. The least-cost approach, which seeks pathways with the least cost (see Etherington, 2016 for a recent review), is used to create landscape graphs (Foltête et al., 2021; Saura and Pascual-Hortal, 2007) and circuits (McRae et al., 2008). In comparison, the accessibility-map approach maps all areas that a species can access in a landscape (Yu, 1996), from its habitats to the limits of its maximum dispersal distance. While the least-cost approach produces maps of corridors between suitable habitats, accessibility maps illustrate the parts of a landscape that a species can use. These maps, which are produced by the CHLOE landscape metrics software that we used, are useful for species that move short distances along at least part of a corridor. A third approach, which we did not consider, is to use an individual-based model, which simulates movements of each individual in a population (Delattre et al., 2018).

To represent a wide range of biodiversity, landscape connectivity was defined by modeling ecological functional connectivity for one "virtual" species (i.e. considering only dispersal ability) for each of three habitat types. We used dispersal data for the following species and habitat types: a carabid beetle (*Abax parallelepipedus*) (Charrier et al.; Loreau and Nolf, 1993) for woodlands, the meadow brown butterfly (*Maniola jurtina*) (Delattre et al., 2010) for grasslands and the south-western water vole (*Arvicola sapidus*) Koenig et al. (1996); Centeno-Cuadros et al. (2011)) for wetlands. One distinctive feature of our method is the permeability map, derived from the land-cover map, which assigns a movement cost to each type of landscape element for each species. We then add, by simulation, an herbaceous strip along woody landscape elements (i.e. woodlands, hedgerows). These strips are almost always present in a landscape but are rarely mapped because doing so require a high resolution. Butterflies move along these strips, but consider hedgerows as both a barrier and a corridor (Dover, 2019). We also considered that interactions among landscape elements modify the elements' ecological conditions. For instance, hedgerows and woodlands are windbreaks that change the climate in adjacent open elements, such as grasslands and crops. We used the landscape-grain metric (Betbeder et al., 2017) to estimate these windbreak effects. Fine-grained landscapes (i.e. strong interactions among hedgerows) increase the ability of hedgerows to harbor species that prefer a shady and moist forest environment. Inversely, when hedgerow networks are more open (coarse-grained) they do not provide suitable habitats. With these additions, the landscape permeability maps were much more informative than maps that consider only different types of land-cover patches.

To estimate woodland, grassland and wetland connectivities, CHLOE landscape metrics software (Boussard et al., 2020) was applied in three steps (Fig. 3): (1) potential habitats for each indicator species were characterized spatially (Boolean map), (2) a permeability (friction) map that describes the species' ability to move was created and (3) a functional distance map, which illustrates the species' potential biodiversity, from its potential habitats to a maximum dispersal distance based on the permeability, was created for the species. All maps were raster and had a resolution of 10 m. The characteristics used to create functional distance maps varied among the three indicator species (Table 3). Current and simulated land-cover maps were used to express both habitats and permeabilities of landscapes for each species in 2018 and 2050 (Fig. 3).

To estimate impacts of future LUCC on biodiversity in the Couesnon watershed, we used two indicators of landscape connectivity as proxies: extent and quality. Extent equaled the total area of connected habitats in the landscape (i.e. with positive mean landscape connectivity, which was defined as the mean of the three types of connectivity per pixel). Quality equaled the total sum of connectivity values over the study area for each species. Connectivity indicators were ultimately evaluated by comparing current (2018) indicators to those for the scenarios (2050).

3. Results

3.1. *Pathways of land-use intensification: narratives of 2050*

We describe the three most contrasting pathways: Business-as-usual, Green attractiveness and Energy performance. The Double performance and Desert of cereals scenarios had narratives that differed from those of Business-as-usual and Energy performance, respectively, but had similar landscape changes (Appendix 3). All simulated LUCC maps are available online (Houet and Palka, 2021a, 2021b).

3.1.1. *Business-as-usual scenario*

Following intensification of the dairy sector, agricultural identity follows the current trend, in which dairy farms in the Couesnon watershed contribute to the French industrial dairy sector. On plateaus, fields are enlarged and dominated by cereal crops, particularly maize. In 2050, maize covers 42.2% of the UAA (vs. 30.2% in 2018), which highlights the intensification of dairy/livestock production, and some less productive farmland in valley bottoms has been abandoned (+3 253 ha) (Fig. 4). While all hedgerows not protected by regulations disappear (−1 617 km), the availability of agricultural subsidies preserves those along roadsides and farm boundaries. Territorial development continues the

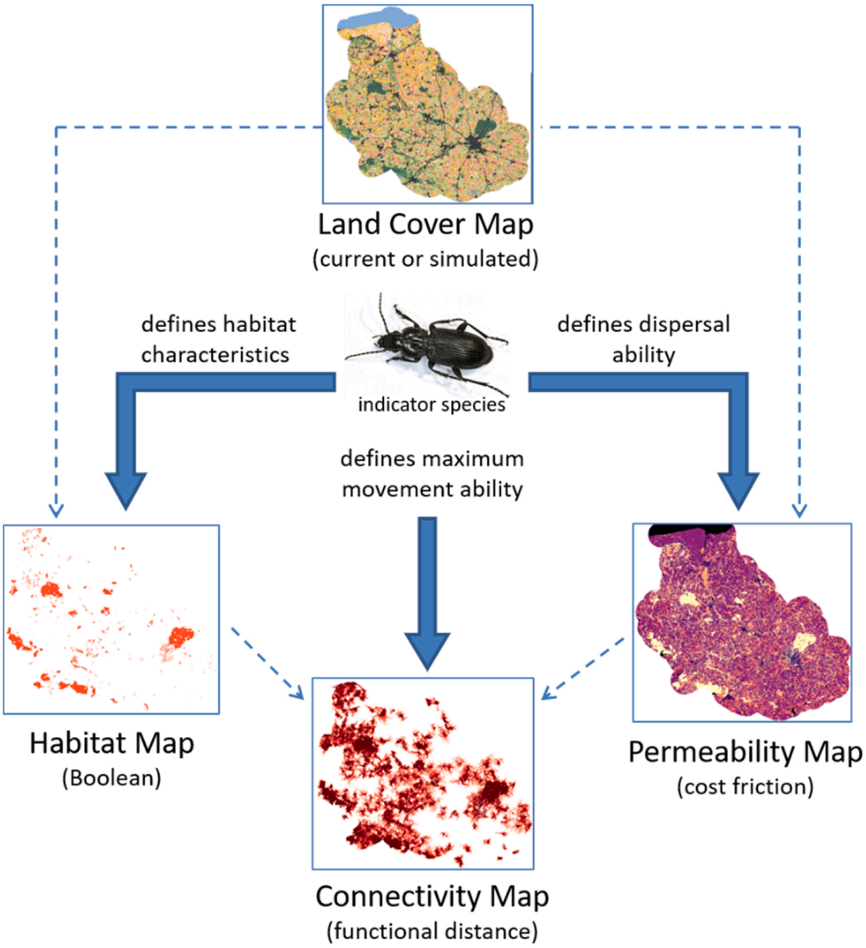

Fig. 3. Diagram of the method used to calculate landscape connectivity: an indicator species is selected (e.g. a carabid beetle); their potential habitat is derived from the land-cover map; from each land cover a friction is set according to its permeability for the species; and landscape connectivity is calculated as a functional distance for each species from its potential habitat to a maximum dispersal distance, given the frictions set.

Table 3
Parameters used to model landscape connectivity for each of the three indicator species.

Type of connectivity	Indicator species	Habitat	Permeability*	References
Woodland	Forest beetle (*Abax parallelepipedus*), with a maximum dispersal distance of 500 m	Woody elements surrounded by a dense network of hedgerows → mean Euclidean distance to woody elements (truncated at 100 m) in a 250 m radius must be < 20 m	+ ++ : forests and hedgerows + +: shrublands and permanent grasslands + : temporary grasslands -: crops - -: urban and roads - - - (barriers): water	Charrier et al. (1997), Loreau and Nolf (1993)
Grassland	Butterfly (*Maniola jurtina*) with a maximum dispersal distance of 150 m	Permanent grasslands surrounded by a dense grassland landscape → at least 40% of grasslands in a 500 m buffer	+ ++ : grasslands (all types) and hedgerows of woody elements + +: crops and water + : shrublands -: hedgerows, urban and roads - -: forests	Delattre et al. (2010)
Wetland	Water vole (*Arvicola sapidus*) with a maximum dispersal distance of 500 m	Permanent grasslands in wetlands (geographically defined from an in situ survey)	+ ++ : grasslands (all types) in wetlands and stream water + +: shrublands in wetlands + : woody elements in wetlands -: other wetlands (reservoirs) and grasslands (all types) not in wetlands - - (barriers): other land-cover types not in wetlands	Koenig et al. (1996), Centeno-Cuadros et al. (2011)

[*] Since the objective was to compare scenarios (rather than to predict realistic continuities), permeability values were relative.

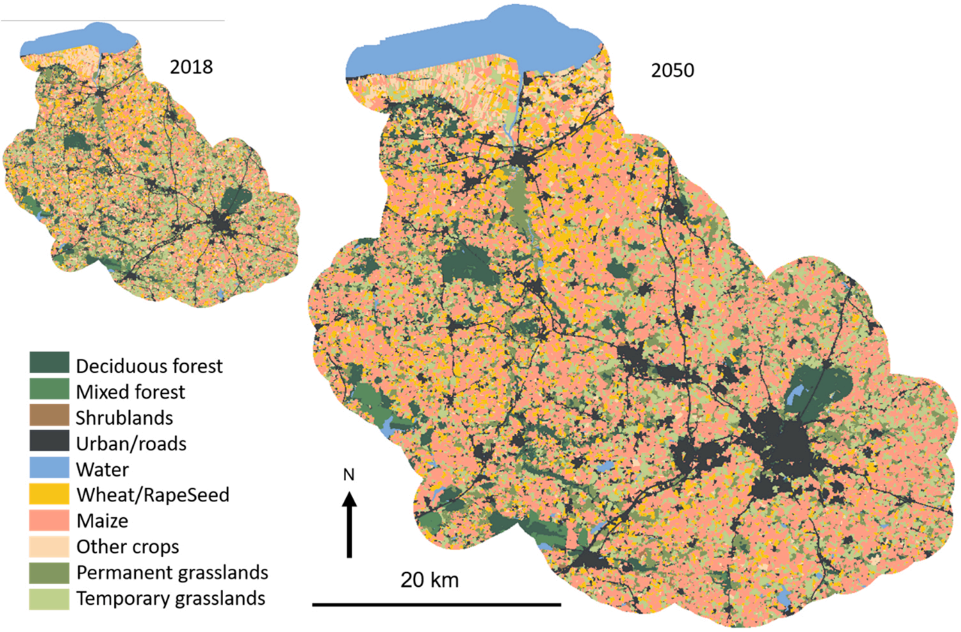

Fig. 4. Land-cover maps for the Couesnon watershed in 2018 (upper left) and predicted in 2050 with the FORESCEM framework for the Business-as-usual scenario.

current mindset of competition between municipalities, and urban sprawl occurs in peri-urban areas due to construction of subdivisions for single-family houses. Urban renewal occurs but remains limited: only some agricultural buildings are converted to residential use. At the same time, industrial zones continue to develop along the highway. Urban land use increases by 2 567 ha from 2018 to 2050. One emblematic change in the landscape is the creation of three major reservoirs and several small hillside reservoirs (Fig. 4). Indeed, tensions over water resources increase due to the cerealization of agriculture in the watershed and the demographic growth of the Rennes metropolitan area, accentuated by effects of climate change. Because this trend reverses ecological restoration of the hydrological network, the creation of these reservoirs is funded by Rennes.

3.1.2. *Green attractiveness*

Territorial development is centered on proximity and quality of life, while agricultural development promotes autonomous and diversified agriculture. Agricultural development is anchored in the territory, and farmers are paid for the ecosystem services they provide. The CAP encourages farmers to produce differently by supporting economic, social and environmental sustainability. PES encourage farmers to maintain and manage hedgerows and wetlands. In addition, local elected representatives actively promote introduction of organic and local products into the collective catering sector and small supermarkets. Land ownership has changed due to the initiative of local authorities, with the help of the authorities concerned. Land exchanges are facilitated to decrease fragmentation of farms, make savings and reduce specialization of crop islets (i.e. when cropping land use increases with the distance from the farmstead). Only the hedgerows in crop-oriented islets tend to disappear, but a dense hedgerow network is maintained. The landscape is dominated by dairy/livestock farms that feed grass-based forages, which makes maximum use of valley bottom grasslands, combined with a mosaic of crops oriented mainly toward food production (e.g. market gardening, cereals, productive seeds, oilseeds). On plateaus, a mosaic of crops and productive grasslands is associated with hedgerows, which provides wood for energy. This scenario, which represents an agroecological transition based on grasslands, shows a clear break with past trends, restoring a percentage of grasslands in 2050 (61.3%) similar that which existed in the early 1990 s. Maize covers 8% of the UAA. Hedgerows are preserved better than in the Business-as-usual scenario but still decrease in total length (7 741 km in 2050). Abandonment of less productive agricultural land in valley bottoms remains a strong trend (+2 334 ha) (Fig. 5). Nonetheless, fields are larger than in 2018. Wind turbines are installed in windy areas. Local elected officials invest massively in restoring watercourses and wetlands that had been drained. For town planning, urban renewal and eco-neighborhoods are favored outside of rural villages, which are revitalized by the search for a "green" living environment. A victim of its success and faced with demand, urbanization in the countryside increases slightly and does not meet the zero urbanization goal in 2040 (Fig. 5). Urban land use covers 15 139 ha in 2050 (2 295 ha more than in 2018). In general, the development of wind power and woodlands is encouraged to provide a local energy supply.

3.1.3. *Energy performance*

Agriculture (e.g. plant biomass, biofuels) and land planning support the energy transition. The macroeconomic context, demographics of the farming population and CAP sharply decrease the number of farmers in the region. Takeovers of farms by large cereal producers that come from other specialized regions (e.g. Normandy, Beauce) lead to an increase in farm size and specialization in cereal production due to the development of energy sources based on agricultural biomass: maize feeds biogas plants in the region, while wheat and rapeseed are used to produce biofuels. In the agrifood sector, industrial milk production decreases due to competition from more competitive central and eastern European countries. Local production of organic milk and meat increases in response to demand from the territory's inhabitants. A large percentage of organic farms sell directly to consumers. Some farms are large and have several partners who manage multiple products (e.g. cereals, milk) or even a small biogas plant. In this scenario, other cereals/oilseeds and other crops cover more than 60% of the UAA in 2050, while maize covers 25% and grasslands cover 15% (Fig. 6). Hedgerow length decreases by 22.5% (6 903 km in 2050), and land abandonment (i.e. shrublands and unmanaged woodlands) increases strongly (+6 804 ha), representing 14 591 ha in 2050.

Urbanization occurs mainly in the Fougères metropolitan area, in new positive-energy eco-neighborhoods (small buildings) or within the framework of High Energy Performance renovation operations planned in the SCoT, which favor urban densification. Zero urbanization is achieved by 2045, and urban land use increases by only 1 933 ha from

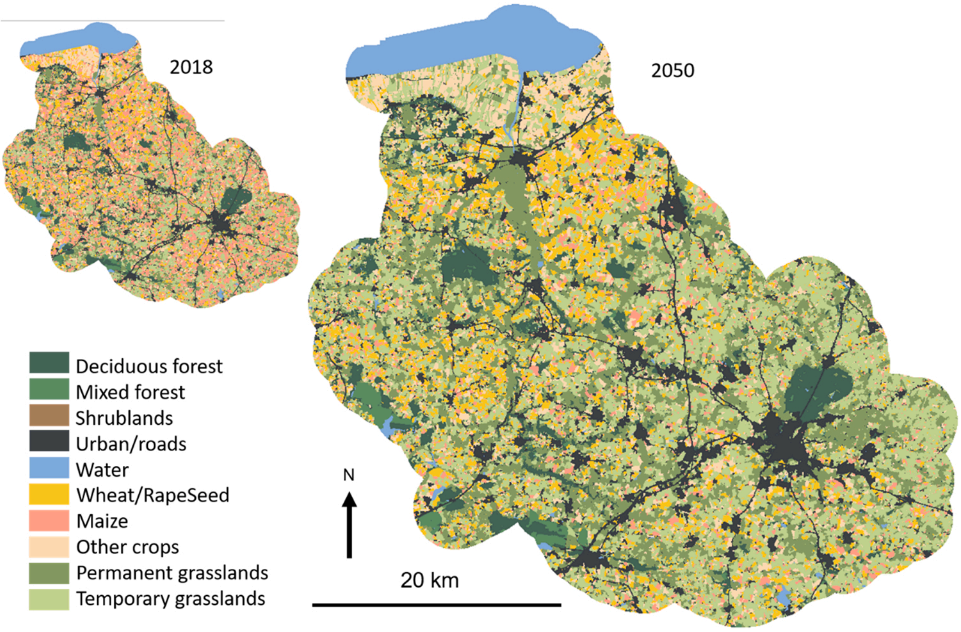

Fig. 5. Land-cover maps for the Couesnon watershed in 2018 (upper left) and predicted in 2050 with the FORESCEM framework for the Green attractiveness scenario.

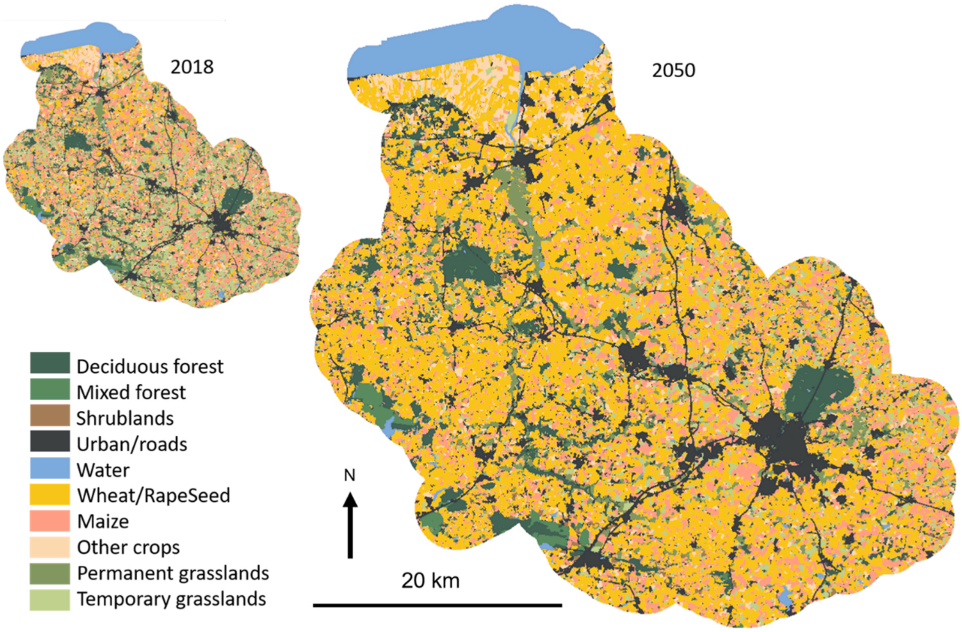

Fig. 6. Land-cover maps for the Couesnon watershed in 2018 (upper left) and predicted in 2050 with the FORESCEM framework for the Energy performance scenario.

2018 to 2050. The generalization of teleworking, used to decrease the use of energy for commuting, also contributes to the urbanization of attractive areas near the coast.

3.1.4. Comparison of landscape changes

Since agriculture occupies ca. 90% of the study area, three contrasting landscapes could be differentiated in 2050, each with a dominant land cover (Figs. 4, 5 and 6; Table 4): maize (Business-as-usual and Double performance), other cereals/oilseeds (Desert of cereals and Energy performance) and grasslands (Green attractiveness). As an indicator of agricultural intensification, the percentage of grasslands in the UAA (41.2% in 2018) highlighted differences in LUCC among scenarios. The Green attractiveness scenario, with an agroecological transition based on extensification of dairy/livestock production, had 61.3% grasslands, while scenarios associated with the agro-energy transition (Energy performance and Desert of cereals) had 15.6%. Scenarios that combined dairy/livestock intensification with better environmental practices (Business-as-usual and Double performance) had 35.8%. Although land abandonment was a strong trend due to the decrease in the farming population, its magnitude was correlated with grassland land use, which was more likely to be located in (less productive and accessible) valley bottoms. The more the grassland percentage decreased, the more farmland was abandoned: 2 334, 3 272, 3 695, 6 014 and 6 804 ha for the Green attractiveness, Business-as-usual, Double

Table 4
Landscape changes from 2018 (present) to 2050 for the five scenarios.

	Hedgerows (km)	Grasslands (ha)	Maize (ha)	Other cereals /oilseeds (ha)	Other crops (ha)	Abandoned farmland (ha)	Urban areas (ha)
2018 (present)	8 915	56 234	41 201	21 524	17 207	7 791	12 844
Business-as-usual	-1 617 (−18.1%)	-9 590 (−17%)	+ 13 761 (+33.4%)	+ 1 252 (+5.8%)	-11 420 (−66.4%)	+ 3 253 (+41.7%)	+ 2 568 (+20%)
Double performance	-1 616 (−18.1%)	-9 590 (−17%)	+ 13 764 (+33.4%)	+ 1 256 (+5.8%)	-11 426 (−66.4%)	+ 3 695 (+47.4%)	+ 2 297 (+17.9%)
Green attractiveness	-1 174 (−13.1%)	+ 24 508 (+43.6%)	-30 783 (−74.7%)	+ 1 045 (+4.9%)	+ 697 (+4%)	+ 2 334 (+30%)	+ 2 295 (+17.9%)
Desert of cereals	-2 012 (−22.5%)	-35 884 (−63.8%)	-8 808 (−21.4%)	+ 40 062 (+186.1%)	-4 107 (−23.9%)	+ 5 995 (+77%)	+ 2 566 (+20%)
Green biomass	-2 012 (−22.5%)	-35 884 (−63.8%)	-8 804 (−21.4%)	+ 40 058 (+186.1%)	-4 107 (−23.9%)	+ 6 804 (+87.3%)	+ 1 933 (+15%)

performance, Desert of cereals and Energy performance scenarios, respectively. The same conclusion was drawn for hedgerows, which decreased by 1 175 km for the Green attractiveness scenario to 1 617 km (Business-as-usual and Double performance) and 2 012 km (Energy performance and Desert of cereals).

Urban changes were subtle, but differed slightly among scenarios (Table 3). The area of land consumed by urbanization was limited well and concentrated in the Energy Performance scenario (1 933 ha). When urban growth was not limited well due to governance failures, urban sprawl occurred mainly near the A84 highway, consuming 2 566 ha (Business-as-usual and Desert of cereals). When social choices (e.g. desire for greening) did not align with urban land policies or objectives (e.g. for urban density), urban sprawl occurred in villages in the countryside as well, unlike in previous scenarios, and consumed up to 2 297 ha (Green attractiveness and Double performance).

3.2. Impacts on landscape connectivity

Agriculture strongly influenced the extent and quality of future landscape connectivity (Table 5, Fig. 7). See Appendix 4 for maps of grassland, woodland and wetland connectivity. Scenarios of agricultural intensification decreased the connectivity of wetlands by 12.8–48.8%, woodlands by 26.2–39.5% and grasslands by 24.4–84.1%. The quality of mean landscape connectivity decreased more than its extent, ranging from − 23.6% for dairy/livestock intensification to − 60.9% for the agro-energy transition. An agroecological transition (Green attractiveness) increased the extent of wetland connectivity by 47.1% and grassland connectivity by 38.2%. The decrease in hedgerow length decreased woodland connectivity by 9.5% in 2050 (Appendix 4a). In this scenario, the quality of mean landscape connectivity increased by 43%, while its extent increased by only 18.2%. In all scenarios, the quality of landscape connectivity was influenced more by future LUCC than its extent was, and in a non-linear manner. Along with the large number of areas whose landscape connectivity decreased due to agricultural intensification, the location of these areas also mattered (Fig. 7). Worst-case scenarios (cerealization assumption) highlighted that the Couesnon River and forested areas, which increase in valley bottoms, are the backbone of the landscape connectivity of the study area. The Sougéal marsh, located in the north central section of the watershed (Fig. 2b), remained the largest area with the highest mean connectivity, regardless of the scenario, which highlights its importance in the future, particularly under an assumption of agricultural intensification. Areas with no landscape connectivity were scattered across the entire study area. Compared to the current situation (Fig. 7a), the loss of landscape connectivity between the upstream and the downstream of the watershed was highest in the Desert of cereals and Energy performance scenarios and remained high in the Business-as-usual and Double performance scenarios. In dairy/livestock intensification scenarios, the increase in crop area influenced the extent of landscape connectivity, which became more scattered, while main corridors were preserved. In the Green attractiveness scenario, although woodland connectivity decreased (by 9.8%) compared to that in 2018, it was compensated by an increase in grassland and wetland connectivity. Finally, the polder area near Mont-Saint-Michel had little or no connectivity, regardless of the scenario.

The effectiveness of the BGIN strategy considered in the scenarios was assessed by comparing urbanization in the Desert of cereals vs. Energy performance scenarios, and in the Business-as-usual vs. Double performance scenarios. For the first pair, the Energy performance scenario assumed optimal preservation of BGINs against urbanization (connectivity > 50 in the regulatory BGIN map (Fig. 1 of Appendix 2)), while the Desert of cereals scenario assumed that only the most important corridors would be preserved (connectivity $= 100$). Nonetheless, the extent and quality of all types of connectivity differed by less than 2%. For the second pair, the two scenarios considered different social preferences (living in rural vs. urban areas) that may influence local governments to not always comply with the SCoT’s objective to concentrate urban development in cities. As with the first pair, urbanization in the landscape differed between the scenarios, but it did not influence landscape connectivity strongly, since the extent and quality of all types of connectivity differed by less than 2% between them.

Table 5
Change in the area (ha) and quality of landscape connectivity from 2018 (present) to 2050 for the five scenarios.

	Wetland connectivity		Woodland connectivity		Grassland connectivity		Mean landscape connectivity	
	Extent	Quality	Extent	Quality	Extent	Quality	Extent	Quality
2018	29 818.6	20 304.4	56 624.1	31 755.6	69 493.6	41 660.4	87 461.1	31 240.1
Business-as-usual	-3 823.8 (−12.8%)	-2 524.2 (−13%)	-14 995.9 (−28%)	-8 714.4 (−29.5%)	-13 573.8 (−19.5%)	-10 076.7 (−26%)	-13 407.1 (−15.3%)	-7 105.1 (−24.3%)
Double performance	-4 006.1 (−13.4%)	-2 574.1 (−13.2%)	-14 071.6 (−26.2%)	-8 122.4 (−27.7%)	-13 867.2 (−20%)	-9 977.2 (−25.7%)	-12 851.3 (−14.7%)	-6 891.2 (−23.6%)
Energy performance	-14 548.8 (−48.8%)	-9 115.5 (−46.9%)	-20 233.7 (−37.7%)	-10 606.4 (−36.2%)	-55 430.4 (−79.8%)	-32 329.4 (−83.3%)	-41 002.4 (−46.9%)	-17 350.5 (−59.4%)
Desert of cereals	-14 501.8 (−48.8%)	-9 303.5 (−47.9%)	-21 154.8 (−39.5%)	-11 161.4 (−38.1%)	-56 816.6 (−81.8%)	-32 883.8 (−84.7%)	-42 758.94 (−48.9%)	-17 782.9 (−60.9%)
Green attractiveness	14 039.9 (+47.1%)	+ 8 054.2 (+41.4%)	-5 083.2 (−9.5%)	-3 716.2 (−12.7%)	+ 26 525.6 (+38.2%)	33 329.8 (+85.9%)	+ 15 902.6 (+18.2%)	12 555.9 (+43%)

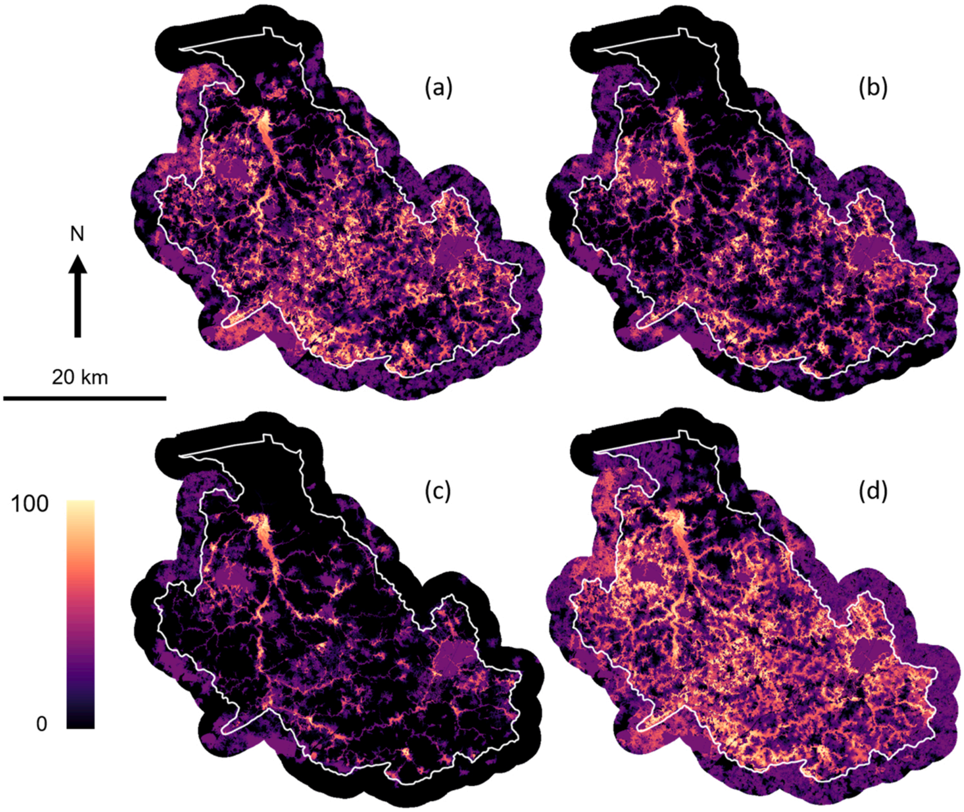

Fig. 7. Mean landscape connectivity (mean of wetland, woodland and grassland connectivities – normalized in %) for the Couesnon watershed (a) in 2018 and for the (b) Business-as-usual, (c) Energy performance and (d) Green attractiveness scenarios.

4. Discussion

4.1. *Does the BGIN strategy preserve biodiversity effectively over the long term?*

The originality of this study lay in combining LUCC scenarios and BGIN strategies with differing degrees of ambition in order to assess the effectiveness of the BGIN strategy over the long term and at a fine scale. This study highlights large differences in the extent and quality of landscape connectivity, which are impacted by the contrasting LUCC of CAP and Green Deal policies. The French BGIN strategy is highly specific, since it protects biodiversity reservoirs and ecosystem functioning by preserving the ecological corridors that connect them. The presence of Natura 2000 sites and other natural areas form the backbone of these BGINs, which makes sense for ecosystem services related to biodiversity only if they allow species to circulate for predation, reproduction and genetic mixing. Although this study focused mainly on biodiversity-related ecosystem services, BGINs can also contribute to the provision of many other ecosystem services. Nonetheless, this study shows that the BGIN strategy effectively protects landscape connectivity from gray infrastructure. When comparing the Desert of cereals and Energy performance scenarios, which had the most contrasting assumptions about housing demand and regulation (sprawl vs. densification, respectively) and about the preservation of BGIN, they had little impact on landscape connectivity, which decreased by no more than ca. 2%. These results express the impact of social preferences and household policies due to SCoT regulations and increased demand for land.

However, the preservation of ecological corridors in current local land-management plans seems to underestimate the influence of agricultural uses greatly. The scenarios of agricultural intensification were based on a strong assumption of maintaining a global economy, in which the CAP strongly influences farmers' decisions about which crops to produce (e.g. Chambre d'agriculture de Bretagne, 2016; Brisson et al., 2010; Bues et al., 2013). If land use continues along the current trend, or if it shifts towards production of bioenergy, agricultural LUCCs could render the BGIN strategy obsolete in the short-to-medium term (< 30 years). A 12%-point increase in the percentage of maize cultivation led to a mean loss of mean landscape connectivity of nearly 23% for dairy intensification. A 30%-point increase in the percentage of cereal cultivation led to a mean loss of mean landscape connectivity of more than 55% for intensification for bioenergy production.

One limitation of this study concerns the method used to assess impacts of LUCC on landscape connectivity. Although the parameters could be calibrated more finely, they have the advantage of quantitatively estimating and comparing initial and final states. Nonetheless, predicting LUCC trajectories could improve this assessment. Indeed, one key land cover is grasslands, which are located throughout the landscape and more specifically in wetlands. Dynamics of grassland configuration may influence landscape connectivity strongly (Mimet et al., 2016), allowing potential time lags of impacts of annual LUCC on biodiversity to be estimated (Watts et al., 2020), which the method we used cannot do. Although not used in this study, freely available scenario-based datasets (Houet and Palka, 2021a, 2021b) make it possible to perform research in this direction.

4.2. *Articulating and integrating BGIN strategy into existing EU policies*

At the European level, the EU Biodiversity and Farm to Fork strategies introduced in the European Green Deal could benefit biodiversity in agricultural areas. Indeed, the EU Biodiversity strategy promotes a wider and consistent network of protected areas and set the objectives of legally protecting at least 30% of EU land area and including ecological corridors in a "Trans-European Nature Network". The Farm to Fork strategy set the percentage of UAA under organic farming to 25% (European Commission, 2019c). The new 2023–2027 CAP should be designed to be consistent with the environment and climate-related commitments that are emerging from the Green Deal (European Commission, 2021a). The 2023–2027 CAP includes two major reforms that did not exist in its previous version: (1) eco-schemes, which rewards farmers who perform environmental and climate-related actions beyond the minimum requirements (European Commission, 2021b), and (2) national strategic plans, to enhance flexibility and conform to national characteristics. Although these new plans could support greener agriculture (Rac et al., 2020), there are concerns about the new CAP's ability to meet the Green Deal's objectives. The European Commission published the first proposal of the 2023–2027 CAP in June 2018, followed by Council and Parliament revisions, which lowered the CAP's biodiversity protection and restoration objectives. Following these revisions, Guyomard et al. (2020) recommended strengthening certain minimum requirements and ring-fencing mechanisms for climate-related and environmental actions to make the new CAP compatible with Green Deal objectives. The final version of the CAP presented in December 2021 does not reflect the recommended objective, which undermines compatibility between the new CAP and Green Deal objectives.

For instance, minimum requirements in the CAP 2023–2027 involve that farmers maintain permanent grasslands, with a tolerated decrease of 5%, while EU policy makers suggested lowered it to 2%. This tolerance for a decrease in permanent grasslands could encourage farmers to convert permanent grasslands into crops (Guyomard et al., 2020; Meredith and Kollenda, 2021). Similarly, the final version of the 2023–2027 CAP does not follow recommendations of Guyomard et al. (2020) or Meredith and Kolleda (2021) about the need to progressively increase the percentage of ecological focus areas (i.e. including non-productive lands and permanent grasslands) up to 10%. Indeed, the final version set the minimum percentage of UAA dedicated to non-productive elements to 3%, with the potential to receive support to achieve 7% (European Commission, 2021b, 2021c). Small farmers (< 10 ha of UAA) are granted some exemptions. Regarding the ring-fencing mechanism, the new PAC allocates 25% of direct payments to eco-schemes, compared to the 40% recommended by Guyomard et al. (2020). There are also concerns about the consistency between national strategic plans and Green Deal objectives. Weak connections between CAP climate- and biodiversity-related objectives and EU environmental legislation could result in a “race to the bottom” that undermines the ability of national strategic plans to reflect CAP objectives (Hart and Bas-Defossez, 2018; Guyomard et al., 2020; Rac et al., 2020). Given the decrease in the ambition of environmental objectives from the new CAP's first proposal to its final version, and that farmer decisions are driven mainly by prices of livestock or cereals on the global market (Kahan, 2013), the new CAP may not sufficiently support Green Deal objectives or the effectiveness of the BGIN strategy, as reflected in the co-constructed scenarios.

These elements therefore tend to contradict recommendations of the report to the EU on the effectiveness of BGINs (Mazza et al., 2011; European Commission, 2019a, 2019b). For its part, the CAP greening scenario considers that agriculture will no longer be remunerated for its production, but for the ecosystem services that it provides to society by maintaining and managing the landscape that hosts them. While the method for calculating PES needs to be clarified and refined (Guo et al., 2020), it is clear that its effects on biodiversity will be particularly effective. Without covering most of the landscape in grasslands, as in the Green attractiveness scenario, implementing mechanisms to counteract intensification of agricultural land use is essential to preserve biodiversity. Current policies (CAP, BGIN) are unlikely to succeed in this respect in the context of a large decrease in the farming population and an increase in farm size. While diversity in the landscape mosaic should be favored (Sirami et al., 2019) to improve local multifunctionality (Rega et al., 2019), promoting land-management practices of farms, such as maintaining extensive systems in the ecological corridors that are most important for preserving biodiversity, should consider local and regional characteristics. The location of farming practices in the landscape matters!.

Although the EU BGIN strategy has a multifunctional goal, the lack of a clearly defined method for designing BGIN and selecting their components poses problems (Liquete et al., 2015; Garmendia et al., 2016). This study highlights the importance of considering ecological corridors that connect biodiversity hotspots. Indeed, protected areas (e.g. Natura 2000) will not be influenced directly by urban or agricultural LUCCs in the future, but they could be disconnected from other reservoirs of biodiversity, which may reduce their influence. Moreover, since protected areas cover only a small percentage of the territory, the landscape as a whole, through the connectivity of unprotected areas, has a crucial influence on biodiversity, and even more on the provision of ecosystem services. Thus, biodiversity conservation areas and connectivity should not be the only elements of BGINs; other functional hotspots in the landscape should be considered that can enrich BGIN plans incrementally.

This study also highlights potential contradictions or controversial differences between EU agricultural policy and other environmental policies (e.g. Water and Habitats Directives). The BGIN strategy can play an integrated role in improving provision of ecosystem services but currently remains limited to protecting biodiversity from gray infrastructure, with no influence on agricultural land uses. It is necessary to include BGIN design and multifunctionality into existing policies (e.g. Water and Habitats Directives, CAP). For instance, it could help define specific economic mechanisms (e.g. PES, other subsidies) to favor extensive farming practices in previously identified corridors. Since the 3% (to 10%) of non-productive land or permanent grasslands on each farm imposed by the new CAP are not always located in BGINs at the landscape scale, Green Deal biodiversity objectives may not be achieved in the future. Connecting these policies in a more integrated way (at farm, municipality and landscape levels) is crucial for achieving the United Nations' Sustainable Development Goals. More broadly, this study also calls for making more multiscale landscape strategies (Primdahl et al., 2013; Primdahl and Kristensen, 2016).

4.3. *Limitations and perspectives*

While this study confirms the utility of using scenario-based assessment of landscape functioning to make policy more operational and sustainable (Helming and Pérez-Soba, 2011), the scenarios used were likely stereotyped when modeling them, since all farmers have similar practices and production systems. There was deliberately no ideal scenario; nonetheless, they allowed us to identify risk factors of unsustainable development and possible mechanisms for implementing future policies for land planning and management in this study area and beyond. The quantitative method developed provides interesting relative estimates of potential impacts, but they should be refined and used with caution.

This study focused on biodiversity through the lens of landscape connectivity. Despite biodiversity's recognized importance to ecosystem functioning from local to regional scales, decision makers often underestimate the knowledge of the ecosystem services provided by connectivity (e.g. pollination, insect regulation), if they consider it at all. However, PES can be legitimized by estimating impacts on other ecosystem services (e.g. related to water quality, water quantity, erosion risk, agricultural productivity) and the overall costs and benefits they will generate. Indeed, this study considered only changes in LULC. Current water-management issues in response to the European Water Framework Directive (2000) can be exacerbated by agricultural intensification and, as envisioned in climate-change scenarios, modification of rainfall regimes. For instance, the worst climate-change scenario (RCP 8.5) predicts an increase in annual rainfall (by 14–20%) but a decrease in summer rainfall (from 10% to 20% per month) in the study area. This decrease would have a strong influence on water quantity and quality (e.g. increase nitrate concentrations). Environmental and economic impacts need to be assessed quantitatively to increase the interest in such policies.

Finally, the last step of this study went beyond producing scientific knowledge about the future and consisted of disseminating results to a wide audience of stakeholders, such as local land users (e.g. farmers, other inhabitants), technicians, NGOs and elected representatives. The objective of this final step was to (1) provide a multidisciplinary and integrated vision of possible changes in the study area to those concerned by water and land management and (2) increase stakeholders' awareness of future challenges they will face and of their role in addressing them, and possibly (3) support long-term and well-informed decisions about land management. By diffusing the knowledge produced about possible changes in the territory and avoiding black-box modeling approaches, we wanted to help empower local stakeholders who can plan for challenges and encourage a more sustainable future (Pérez-Silos et al., 2021). Sharing this knowledge may favor the emergence of bottom-up policies and land-management actions that could be more effective than any scientific article.

5. Conclusion

This study used a scenario-based approach to assess the effectiveness of several BGIN strategies elicited by stakeholders and applied to the Couesnon watershed (western France). It combined participatory and modeling approaches to provide five contrasting spatially explicit futures for 2050 at a fine scale. These results can help decision makers assess impacts of a variety of future land-planning and agricultural land-use assumptions on landscape connectivity. The results showed that, while effectively limiting the development of gray infrastructure, BGINs depend mainly on agricultural land uses. The study also highlighted inconsistencies among existing EU policies. Indeed, even though the new CAP seems "greener" than the previous one, market-oriented agricultural intensification of cereals for agro-energy or dairy/livestock production can decrease landscape connectivity strongly. Any BGIN strategy can be jeopardized by future agricultural LUCCs that result from the CAP. This study also recommends more integrated assessment of impacts on ecosystem services and estimation of their economic value in order to integrate the BGIN strategy better into these policies. Finally, it emphasizes the importance of transdisciplinary research to increase awareness of local land users and other stakeholders about possible futures and to favor emerging initiatives for sustainability and innovative policies.

Data availability

Houet and Palka (2021a) Land-use and land-cover classifications for the Couesnon watershed in 1990, 2006 and 2018 (in French). INDIGEO. https://doi.org/10.35110/41dddc43-0108-4c22-8101-62ff7cda0031.

Houet and Palka (2021b) Simulated maps of land uses and land covers of the Couesnon watershed, for each scenario and each year from 2019 to 2050 (in French). INDIGEO. https://doi.org/10.35110/a0712f99-9e0c-4fcd-9a24-3f0d26efaff4.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2022.106277.

References

AUDIAR (2018) Artificialisation et consommation des espaces naturels agricoles et forestiers en Ille-et-vilaine, Une consommation d'espace élevée en Ille-et-Vilaine liée au dynamisme démographique et économique, Observatoire Foncier, 8 pages. https://www.audiar.org/sites/default/files/documents/observatoires/consommation-espace-naf_35_web.pdf (Accessed May 2021).

Bélisle, M., 2005. Measuring landscape connectivity: the challenge of behavioral landscape ecology. Ecology 86 (8), 1988–1995. https://doi.org/10.1890/04-0923.

Betbeder, J., Laslier, M., Hubert-Moy, L., Burel, F., Baudry, J., 2017. Synthetic Aperture Radar (SAR) images improve habitat suitability models. Landsc. Ecology 32 (9), 1867–1879.

Boussard H., Meurice P., Baudry J. (2020) Chloe - Landscape Metrics: a software for landscape pattern analysis. QGIS plugin produced by the authors at the BAGAP unit, Rennes, France. Available at the following web site: https://www6.rennes.inrae.fr/bagap/PRODUCTIONS/Logiciels.

Brisson, N., Gate, P., Gouache, D., Charmet, G., 2010. Why are wheat yields stagnating in Europe ? A comprehensive data analysis for France. Field Crops Res. 119, 201–212. https://doi.org/10.1016/j.fcr.2010.07.012.

Bues, A., Preißel, S., Reckling, M., Zander, P., Kuhlman, T., Topp, K., Watson, C., et al. (2013), The Environmental Role of Protein Crops in the New Common Agricultural Policy. European Parliament, Directorate General for Internal Policies, Policy Department B: Structural and Cohesion Policies, Agricultural and Rural Development.

Butler, S.J., Vickery, J.A., Norris, K., 2007. Farmland biodiversity and the footprint of agriculture. Science 315, 381–384. https://doi.org/10.1126/science.1136607.

Centeno-Cuadros, A., Roman, J., Delibes, M., Godoy, J.A., 2011. Prisoners in their habitat? Generalist dispersal by habitat specialists: a case study in southern water vole (*Arvicola sapidus*). PLoS One 6 (9), 24613.

Chambre d'agriculture de Bretagne. (2016), Céréalisation de la Bretagne ? Analyse des évolutions des productions agricoles.

Charrier, S., Petit, S., Burel, F., 1997. Movements of Abax parallelepipedus (Coleoptera, Carabidae) in woody habitats of a hedgerow network landscape: a radio-tracing study. Agric., Ecosyst. Environ. 61 (2–3), 133–144. https://doi.org/10.1016/S0167-8809(96)01101-2.

Delattre, T., Pichancourt, J.B., Burel, F., Kindlmann, P., 2010. Grassy field margins as potential corridors for butterflies in agricultural landscapes: asimulation study. Ecol. Model. 221 (2), 370–377.

Delattre, T., Baudry, J., Burel, F., 2018. An onion-like movement corridor? Possible guidelines emerging from small-scale movement rules. Ecol. Inform. 45, 48–58.

Dover, J.W., 2019. The Ecology of Butterflies and Moths In Hedgerows and Field Margins. The ecology of hedgerows and field margins. Routledge, pp. 186–209.

Dunlop, C., 2014. The possible experts: how epistemic communities negotiate barriers to knowledge use in ecosystems services policy. Environ. Plan. C: Gov. Policy 32, 208–228.

Etherington, T.R., 2016. Least-cost modelling and landscape ecology: concepts, applications, and opportunities. Curr. Landsc. Ecol. Rep. 1 (1), 40–53.

European Commission (2019a) Review of progress on implementation of the EU green infrastructure strategy COM(2019) 236 Final. Report from the commission to the European Parliament, the council, the European an economic and social committee and the committee of regions. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0236&qid=1562053537296&from=EN.

European Commission (2019b) Additional information on the review of implementation of the EU green infrastructure strategy. Commission Staff Working Document SWD (2019) 184 final. Report from the commission to the European Parliament, the council, the European an economic and social committee and the committee of regions. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019SC0184&qid=1562054969676&from=EN.

European Commission. (2019c), communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions. 640. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0640&from=EN.

European Commission. (2021a), Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the Common Agricultural Policy (CAP Strategic Plans). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R2115&qid=1645611615087&from=en.

European Commission. (2021b), A Greener and Fairer CAP. 〈https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/key_policies/documents/factsheet-newcap-environment-fairness_en.pdf〉.

European Commission. (2021c), Political Agreement on New Common Agricultural Policy: Fairer, Greener, More Flexible.https://ec.europa.eu/commission/presscorner/detail/en/IP_21_2711.

European Commission (2012) The Multifunctionality of Green Infrastructure. Science for Environment Policy. In-depth report. http://ec.europa.eu/environment/nature/ecosystems/docs/Green_Infrastructure.pdf.

European Environment Agency (2011). Green Infrastructure and territorial cohesion. Technical Report N° 18/2011. Copenhagen, https://www.eea.europa.eu/publications/green-infrastructure-and-territorial-cohesion/at_download/file.

France Stratégie, Fosse J. (2019) Objectif " zéro artificialisation nette ": quels leviers pour protéger les sols ? 54p., https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-rapport-2019-artificialisation-juillet.pdf (Accessed May 2021).

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use. Science 309 (309), 570–574.

Foltête, J.C., Vuidel, G., Savary, P., Clauzel, C., Sahraoui, Y., Girardet, X., Bourgeois, M., 2021. Graphab: an application for modeling and managing ecological habitat networks. Softw. Impacts 8, 100065.

Garmendia, E., Apostolopoulou, E., Adams, W.M., Bormpoudakis, D., 2016. Biodiversity and Green Infrastructure in Europe: Boundary object or ecological trap? Land Use Policy 56, 315–319.

Guo, Y., Zheng, H., Wu, T., Wu, J., Robinson, B.E., 2020. A review of spatial targeting methods of payment for ecosystem services. Geogr. Sustain. 1 (2), 132–140. https://doi.org/10.1016/j.geosus.2020.04.001.

Guyomard H., Bureau J.-C., Chatellier V., Detang-Dessendre C., Dupraz P., Jacquet F., Reboud X., et al. (2020) Research for AGRI Committee – The Green Deal and the CAP: Policy Implications to Adapt Farming Practices and to Preserve the EU's Natural Resources, Brussels. https://www.europarl.europa.eu/RegData/etudes/STUD/2020/629214/IPOL_STU(2020)629214_EN.pdf.

Hart K. and Bas-Defossez F. (2018) CAP 2021–27: Proposals for increasing its environmental and climate ambition, report for NABU by IEEP. https://ieep.eu/publications/cap-2021–27-proposals-for-increasing-its-environmental-and-climate-ambition.

Helming, K., Pérez-Soba, M., 2011. Landscape scenarios and multifunctionality: making land use impact assessment operational. Ecol. Soc. 16 (1), art50. http://www.ecologyandsociety.org/vol16/iss1/art50/.

Houet, T., Schaller, N., Castets, M., Gaucherel, C., 2014. Improving the simulation of fine scale landscape changes coupling top-down and bottom-up land use and cover changes rules. Int. J. Geogr. Sci. 28 (9), 1848–1876. https://doi.org/10.1080/13658816.2014.900775.

Houet, T., Marchadier, C., Bretagne, G., Moine, M.P., Aguejdad, R., Viguié, V., Bonhomme, M., Lemonsu, A., Avner, P., Hidalgo, J., Masson, V., 2016. Combining narratives and modeling approaches to simulate fine scale and long-term urban growth scenarios for climate adaptation. Environ. Model. Softw. 86, 1–13. https://doi.org/10.1016/j.envsoft.2016.09.010.

Houet, T., Grémont, M., Vacquié, L., Forget, Y., Bourrier, F., Peltier, A., Puissant, A., Bernardie, S., Grandjean, G., 2017. Downscaling scenarios of future land use and land cover changes using a participatory approach: an application to mountain risk assessment in the Pyrenees (France). Reg. Environ. Change 17 (8), 2293–2307. http://link.springer.com/article/10.1007/s10113-017-1171-z.

Houet and Palka, 2021a. Land-use and land-cover classifications for the Couesnon watershed in 1990, 2006 and 2018 (in French). INDIGEO. https://doi.org/10.35110/41dddc43-0108-4c22-8101-62ff7cda0031.

Houet and Palka, 2021b. Simulated maps of land uses and land covers of the Couesnon watershed, for each scenario and each year from 2019-2050 (in French). INDIGEO. https://doi.org/10.35110/a0712f99-9e0c-4fcd-9a24-3f0d26efaff4 .

INSEE Bretagne (2019a) Analyses Bretagne, Plus de 400000 habitants supplémentaires en Bretagne d'ici 2040, no. 89, https://www.insee.fr/fr/statistiques/4250821 (Accessed May 2021).

INSEE Bretagne (2019b) Analyses Bretagne, En Bretagne, la population augmenterait d'ici 2040 quel que soit le scénario envisagé, n°90, https://www.insee.fr/fr/statistiques/4250752 (Accessed May 2021).

Kahan, D., 2013. Market-oriented farming: An overview. In: Food and Agriculture Organization of the United Nations, 104.

Kazemi, H., Klug, H., Kamkar, B., 2018. New services and roles of biodiversity in modern agroecosystems: A review. Ecol. Indic. 93, 1126–1135.

Kindlmann, P., Burel, F., 2008. Connectivity measures: a review. Landsc. Ecol. 23 (8), 879–890.

Knaapen, J.P., Scheffer, M., Harms, B., 1992. Estimating habitat isolation in landscape planning. Landsc. Urban Plan. 23 (1), 1–16.

Koenig, W.D., Van Vuren, D., Hooge, P.N., 1996. Detectability, philopatry and the distribution of dispersal distances in vertebrates. Trends Ecol. Evol. 11, 514–517. https://doi.org/10.1016/S0169-5347(96)20074-6.

Kok, M.T.J., Kok, K., Peterson, G.D., Hill, R., Agard, J., Carpenter, S.R., 2017. Biodiversity and ecosystem services require IPBES to take novel approach to scenarios. Sustain. Sci. 12, 177–181.

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., George, P.S., Homewood, K., Imbernon, J., Leemans, R., Li, X.B., Moran, E.F., Mortimore, M., Ramakrishnan, P.S., Richards, J.F., Skanes, H., Steffen, W., Stone, G.D., Svedin, U., Veldkamp, T., Vogel, C., Xu, J.C., 2001. The causes of land-use and land-cover change: moving beyond the myths. Glob. Environ. Change 11, 261–269. https://doi.org/10.1016/S0959-3780(01)00007-3.

AnonLambin E., Geist H. (eds) (2006) Land-use and land-cover change: local processes and global impacts. The IGBP series. Springer-Verlag, Berlin.

Loreau, M., Nolf, C.L., 1993. Occupation of space by the carabid beetle Abax ater. Acta Oecologica 14 (2), 247–258.

Liquete, C., Kleeschulte, S., Dige, G., Maes, J., Grizzetti, B., Olah, B., Zulian, G., 2015. Mapping green infrastructure based on ecosystem services and ecological networks: a Pan-European case study. Environ. Sci. Policy 54, 268–280.

Lumbroso, S. (2019) Prospective et stratégies pour l'environnement: entre fabrique des futurs et situation de gestion, quelles prises pour l'action ? Etudes de l'environnement. Université Paris Saclay. Français.

Maron, M., Fitzsimons, J.A., 2007. Agricultural intensification and loss of matrix habitat over 23 years in West Wimmera, south-eastern Australia. Biol. Conserv. 135, 587–593. https://doi.org/10.1016/j.biocon.2006.10.051.

Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural intensification and ecosystem properties. Science 277, 504–509.

Mazza L., Bennett G., De Nocker L., Gantioler S., Losarcos L., Margerison C., Kaphengst T., McConville A., Rayment M., ten Brink P., Tucker G., van Diggelen R. (2011) Green Infrastructure Implementation and Effectiveness. Final report for the European Commission, DG Environment on Contract ENV.B.2/SER/2010/0059. Institute for European Environmental Policy, Brussels and London.

McKenzie, E., Posner, S., Tillmann, P., Bernhardt, J.R., Howard, K., Rosenthal, A., 2014. Understanding the use of ecosystem service knowledge in decision making: lessons from international experiences of spatial planning. Environ. Plan. C: Gov. Policy 32 (2), 320–340, 2005.

McRae, B.H., Dickson, B.G., Keitt, T.H., Shah, V.B., 2008. Using circuit theory to model connectivity in ecology, evolution, and conservation. Ecology 89 (10), 2712–2724.

Meredith S. and Kollenda E. (2021), CAP Trialogue Negotiations Briefing. Briefing Note by the Institute for European Environmental Policy, Brussels.

Meyfroidt, P., Lambin, E., Erb, K.H., Hertel, T.W., 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. Curr. Opin. Environ. Sustain. 5 (5), 438–444. https://doi.org/10.1016/j.cosust.2013.04.003.

Mimet, A., Houet, T., Julliard, R., Simon, L., 2013. Assessing functional connectivity: a landscape approach for handling multiple ecological requirements. Methods Ecol. Evol. Vol. 4 (Iss. 5), 453–463. https://doi.org/10.1111/2041-210x.12024.

Mimet, A., Pellissier, V., Houet, T., Julliard, R., Simon, L., 2016. A holistic landscape description reveals that configuration changes more over time than composition: implications for landscape ecology studies. PLOS One 11 (3), e0150111. https://doi.org/10.1371/journal.pone.0150111.

Palka G., Vacquié L., Forget Y., Houet T. (submitted for publication) Simulating interactions and feedbacks between land use and land cover changes for prospective scenarios with FORESCEM. Environmental Modelling and Software.

Pérez-Silos, I., Álvarez-Martinez, J.M., Barquin, J., 2021. Large-scale afforestation for ecosystem service provisioning: learning from the past to improve the future. Landsc. Ecol. 36 (11), 3329–3343. https://link.springer.com/article/10.1007/s10980-021-01306-7.

Primdahl, J., Kristensen, L.S., 2016. Landscape strategy making and landscape characterisation—experiences from Danish experimental planning processes. Landsc. Res. 41 (2), 227–238. https://doi.org/10.1080/01426397.2015.1135322.

Primdahl, J., Kristensen, L.S., Swaffield, S., 2013. Guiding rural landscape change: Current policy approaches and potentials of landscape strategy making as a policy integrating approach. Appl. Geogr. 42, 86–94. https://doi.org/10.1016/j.apgeog.2013.04.004.

Rac, I.R., Erjavec, K.E., Erjavec, E.E., 2020. Does the proposed CAP reform allow for a paradigm shift towards a greener policy ? Span. J. Agric. Res. 18 (3) https://doi.org/10.5424/sjar/2020183-16447.

Rega, C., Helming, J., Paracchini, M.L., 2019. Environmentalism and localism in agricultural and land-use policies can maintain food production while supporting biodiversity. Findings from simulations of contrasting scenarios in the EU. Land Use Policy 87, 103986.

Saura, S., Pascual-Hortal, L., 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: comparison with existing indices and application to a case study. Landsc. Urban planning 83 (2–3), 91–103.

Sirami, C., Gross, N., Bosem Baillod, A., Bertrand, C., Carrié, R., Hass, A., Henckel, L., Miguet, P., Vuillot, C., Alignier, A., Girard, J., Batáry, P., Clough, Y., Violle, C., Giralt, D., Bota, G., Badenhausser, I., Lefebvre, G., Gauffre, B., Vialatte, A., Calatayud, F., Gil-Tena, A., Tischendorf, L., Mitchell, S., Lindsay, K., Georges, R., Hilaire, R., Recasens, J., Solé-Senan, X., Robleño, I., Bosch, J., Barrientos, J.A., Ricarte, A., Marcos-Garcia, M., Miñano, J., Mathevet, R., Gibon, A., Baudry, J., Balent, G., Poulin, B., Burel, F., Tscharntke, T., Bretagnolle, V., Siriwardena, G., Ouin, A., Brotons, L., Martin, J.L., Fahrig, L., 2019. Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. Proc. Natl. Acad. Sci. 116 (33), 16442–16447. https://doi.org/10.1073/pnas.1906419116.

Theobald, D.M., Reed, S.E., Fields, K., Soulé, M., 2012. Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the United States. Conserv. Lett. 5 (2), 123–133.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284.

Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecol. Lett. 8 (8), 857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x.

Vogt, P., Ferrari, J.R., Lookingbill, T.D., Gardner, R.H., Riitters, K.H., Ostapowicz, K., 2009. Mapping functional connectivity. Ecol. Indic. 9 (1), 64–71. https://doi.org/10.1016/j.ecolind.2008.01.011.

Watts, K., Whytock, R., Park, K., Fuentes-Montemayor, E., MacGregor, N., Duffield, S., McGowan, P., 2020. Ecological time lags and the journey towards conservation success. Nat. Ecol. Evol. 4, 304–311. https://doi.org/10.1038/s41559-019-1087-8.

Yu, K., 1996. Security patterns and surface model in landscape ecological planning. Landsc. Urban Plan. 36 (1), 1–17.