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Correspondence
florence.matutini@ofb.gouv.fr

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Conservation networks do not match the ecological requirements of amphibians

Florence Matutini [1,2], Jacques Baudry [3], Marie-Josee Fortin [4], Guillaume Pain[1], and Josephine Pithon[1]

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Abstract

- Amphibians are among the most threatened taxa as they are highly sensitive to habitat degradation and fragmentation. They are considered as model species to evaluate habitats quality in agricultural landscapes. In France, all amphibian species have a protected status requiring recovery plans for their conservation. Conservation networks combining protected areas and green infrastructure can help the maintenance of their habitats while favouring their movement in fragmented landscapes such as farmlands. Yet, assessing the effectiveness of conservation networks is challenging.
- Here, we compared the ecological requirements of amphibian species with existing conservation network coverage in a human-dominated region of western France. First, we mapped suitable habitat distributions for nine species of amphibian with varying ecological requirements and mobility. Second, we used stacking species distribution modelling (SSDM) to produce multi-species habitat suitability maps. Then, to identify spatial continuity in suitable habitats at the regional scale, we defined species and multi-species core habitats to perform a connectivity analysis using Circuitscape theory. Finally, we compared different suitability maps with existing conservation networks to assess conservation coverage and efficiency.
- We highlighted a mismatch between the most suitable amphibian habitats at the regional scale and the conservation network, both for common species and for species of high conservation concern. We also found two bottlenecks between areas of suitable habitat which might be crucial for population movements induced by global change, especially for species associated with hedgerow mosaic landscapes. These bottlenecks were not covered by any form of protection and are located in an intensive farmland context.
- Synthesis and applications - We advocate the need to better integrate agricultural landscape mosaics into species conservation planning as well as to protect and promote agroecological practices suitable for biodiversity, including mixed and extensive livestock farming. We also emphasize the importance of interacting landscape elements of green infrastructure for amphibian conservation and the need for these to be effectively considered in land-use planning policies.

[1]ESA, Institut Agro, INRAE, BAGAP, F-49000, Angers, France, [2]Office français de la biodiversité, F-78610, Auffargis, France, [3]Independent researcher, F-35690, Acigné, France, [4]Dept of Ecology and Evolutionary Biology, Univ. of Toronto, Toronto, ON M5S 3B2, Canada

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Introduction

The biodiversity decline is still accelerating across the world affecting both scarce and common species (Dirzo et al., 2014; Gaston & Fuller, 2008) especially in agroecosystems (Kleijn et al., 2011; Seibold et al., 2019). To palliate this decline, the establishment of protected areas (PAs) is a relevant conservation tool in a human-dominated world (Rodrigues & Cazalis, 2020). However, PAs alone are not sufficient to protect biodiversity and they should be part of an ensemble of management and planning strategies aiming to create functional conservation networks. Green infrastructure (GI) (also called Green and Blue infrastructure in France) has been proposed as a way to address this issue (Chatzimentor et al., 2020; Salomaa et al., 2017). Such initiatives aim to maintain a coherent and functional network of suitable habitats and to improve biodiversity integration into land-use planning. GI design is based on the ecological network concept (Opdam et al., 2006) emphasizing the complementarity of core habitat patches and ecological corridors at different spatial and temporal scales (Opdam et al., 2006; Salomaa et al., 2017).

While conservation networks are crucial for biodiversity conservation, they might have some weaknesses in their design that need to be addressed. For example, ecological network design from landscape connectivity modelling poorly integrates biological data which may be problematic in operational contexts (Foltête et al., 2020). In France, GI has mostly been defined based on spatial analysis of land-cover data without considering species data. It is based on a simplistic classification of ecosystems reduced to broad categories of land cover data (i.e. different layers for forest or wetlands separately) with a poor consideration of habitat complementation. In contrast, PAs have usually been defined according to the needs of focal endangered species and/or habitats, often charismatic species such as birds and endangered plants, which might be poorly representative of species-habitat relations and ecosystem processes (Rodrigues et al., 2004).

Evaluating the efficiency of conservation networks (here PAs and GI) is a real challenge (e.g., Rodrigues & Cazalis, 2020). Gap analysis and conservation prioritization are common approaches for a first-step assessment of the effectiveness of a conservation network and to inform decisions for conservation measures (Jennings 2000; Moilanen et al. 2005). To conduct a gap analysis, outputs of spatial modelling are particularly useful (Ahmadi et al., 2020). Species distribution models (SDMs) are commonly used to make spatially explicit predictions of the suitable environment of a given species from biological data (Guisan & Zimmermann, 2000) and multi-specific approaches have recently been developed (Scherrer et al., 2018; Thuiller et al., 2015). In addition, recent methods integrate both graph theory and SDMs for ecological network modelling (Duflot et al., 2018; Godet & Clauzel, 2020). These multi-species and integrative approaches could be relevant for gap analyses and spatial prioritization but remain underused (Foltête et al., 2020).

In western Europe, traditional hedgerow landscapes are of high conservation concern for numerous taxa such as plants, amphibians, birds, bats, and arthropods (Baudry et al., 2000; Boissinot et al., 2019). In France, these rural landscapes are associated with dense hedgerow networks interconnected with a mosaic of small, interlocked patches of pastures, cultivated fields and bushes with high pond density (Burel & Baudry, 1995). They have been greatly impacted by agricultural intensification and have declined from 40% to 80% in Europe (Bazin & Schmutz, 1994). Amphibians are good candidates to assess the ecological quality of human-dominated landscape mosaics and to question the efficiency of existing conservation networks. Indeed, they are among the most threatened taxa with rapid and widespread population declines in both natural and modified habitats (Stuart et al., 2004). They have a bi-phasic lifecycle with different ecological requirements inducing seasonal migrations between habitat patches (Sinsch, 2014). Their poor mobility and their permeable skin increase their sensitivity to anthropogenic disturbances, pollution and ecological fragmentation induced by urbanization and intensive agriculture (Cushman, 2006; Hamer & McDonnell, 2008; Stuart et al., 2004). Hence, some authors consider amphibians as good ecological indicators of general environmental health (Collins and Storfer 2003; Díaz-García et al. 2017 but see Sewell & Griffiths, 2009). In addition, amphibians have been the target of several citizen science programs in different countries around the world (De Solla et al., 2005; Petrovan & Schmidt, 2016) leading to a large amount of available data over wide areas which could be relevant for conservation tools assessment (Snäll et al., 2016).

The aim of this study is to propose a method to assess the ecological quality of agricultural mosaics landscapes from species data and to conduct a gap analysis on existing conservation networks. In a human-dominated region of western France with traditional hedgerow landscapes of high conservation concern, we compared the predicted habitat requirements of amphibian species with existing conservation network coverage (of both protected areas and green infrastructure). Specifically, we: (1) used single habitat suitability maps from Matutini et al. (2021b) and produced multi-species habitat suitability maps for amphibians with differing ecological requirements and mobility (2) compared these habitat suitability maps with existing conservation networks (PAs and GI), and (3) identified gaps in conservation coverage which could be a priority for new potential conservation areas. Additional analyses on all the species in the region were carried out to discuss the potential generalization of the results obtained on rare species.

Material and Methods

Regional context and studied species

Ecological context

The study area is located in a region of western France (Pays-de-la-Loire) covering 32,082 km². Intensification of agricultural practices has greatly transformed the landscape over the last century from a complex matrix of small fields, meadows and woody elements (i.e. traditional hedgerow landscapes) to more homogeneous landscapes with larger fields. With 20 native species of amphibian (out of 36 native species recorded in metropolitan France), of which 12 are priority species for conservation, the region has considerable responsibility for the preservation of amphibian species and their habitats, including traditional hedgerow landscapes and wetlands.

Studied species

Nine amphibian species in the Pays-de-la-Loire region were studied (see Table 1 for species list and conservation issues). Three form a “FOR” group of forest species or species associated with dense hedgerow mosaic landscape (*Triturus marmoratus*, *Rana temporaria* and *Salamandra salamandra*) and five form a “GEN” group of more generalist species (*Lissotriton helveticus*, *Bufo spinosus*, *Hyla arborea*, *Rana dalmatina* and *Triturus cristatus*). *Pelodytes punctatus* is a pioneer species mainly associated with disturbed open environments, emblematic of alluvial valleys. Finally, the “ALL” group contained all nine studied species. Species were selected according to data availability (i.e., at least 500 presence after filtering operations according to the number of predictors used for species distribution modelling, see Matutini et al. (2021a). Supplementary information about data, species selection and other species of the region are presented Appendix 1.

Biodiversity conservation policies

In France, there are different conservation tools including protected areas, green infrastructures, and inventoried sites with recognised biodiversity value but that are not protected (Categories “PA”,”GI” and “INV” respectively in Table 2). We defined five groups of conservation tool based on IUCN categories and protection levels (Table 2 and Figure 1). For two types of PAs (SCEN and ENS in PA-Group 2), mapped site boundaries were not available unlike other PAs and GI where we have more precise GIS data. As a result, only a point location according to the site centroid was considered in the analysis (see Appendix 2). If one conservation area was overlapped by another, we classed the area into the group with the strongest protection level and therefore all PAs were excluded from GI. French GI is divided into different land cover or landscape classes (Table 2). Each GI layer includes two types of elements: habitat nodes, considered as “biodiversity reservoirs”, and “corridors” ensuring potential continuity between nodes based on geographical criteria.

Table 1 - Description of the studied species. RL FR: France red list (2015); RL Region: regional red list of Pays-de-la-Loire (2021); Priority: regional priority level for species conservation from the regional red list from 0 (low) to 3 (very high) defined by Marchadour et al. (2021); Hab. Dir. N2000: habitats directive classification (Natura 2000); Nb presence data: Number of presence-only data were calculated after a 100 m-resolution rasterization and correspond to the number of pixels with at least one observation of the species. In bold, vulnerable or near threatened species at the regional scale. See appendix 1 for species selection and presentation of other species present in the studied area.

	Species	RL FR	RL Region	Hab. Dir. N2000	Nb presence data (Atlas)
Species used for SSDM	***Pelodytes punctatus***	**LC**	**NT**		**1714**
	Triturus marmoratus	**NT**	**NT**	**IV**	**906**
	Rana temporaria	**LC**	**VU**	**V**	**848**
	Lissotriton helveticus	LC	LC		4580
	Bufo spinosus	/	LC		6071
	Hyla arborea	NT	LC	IV	4555
	Rana dalmatina	LC	LC	IV	6118
	Triturus cristatus	**NT**	**NT**	**II & IV**	**1040**
	Salamandra salamandra	LC	LC		3514

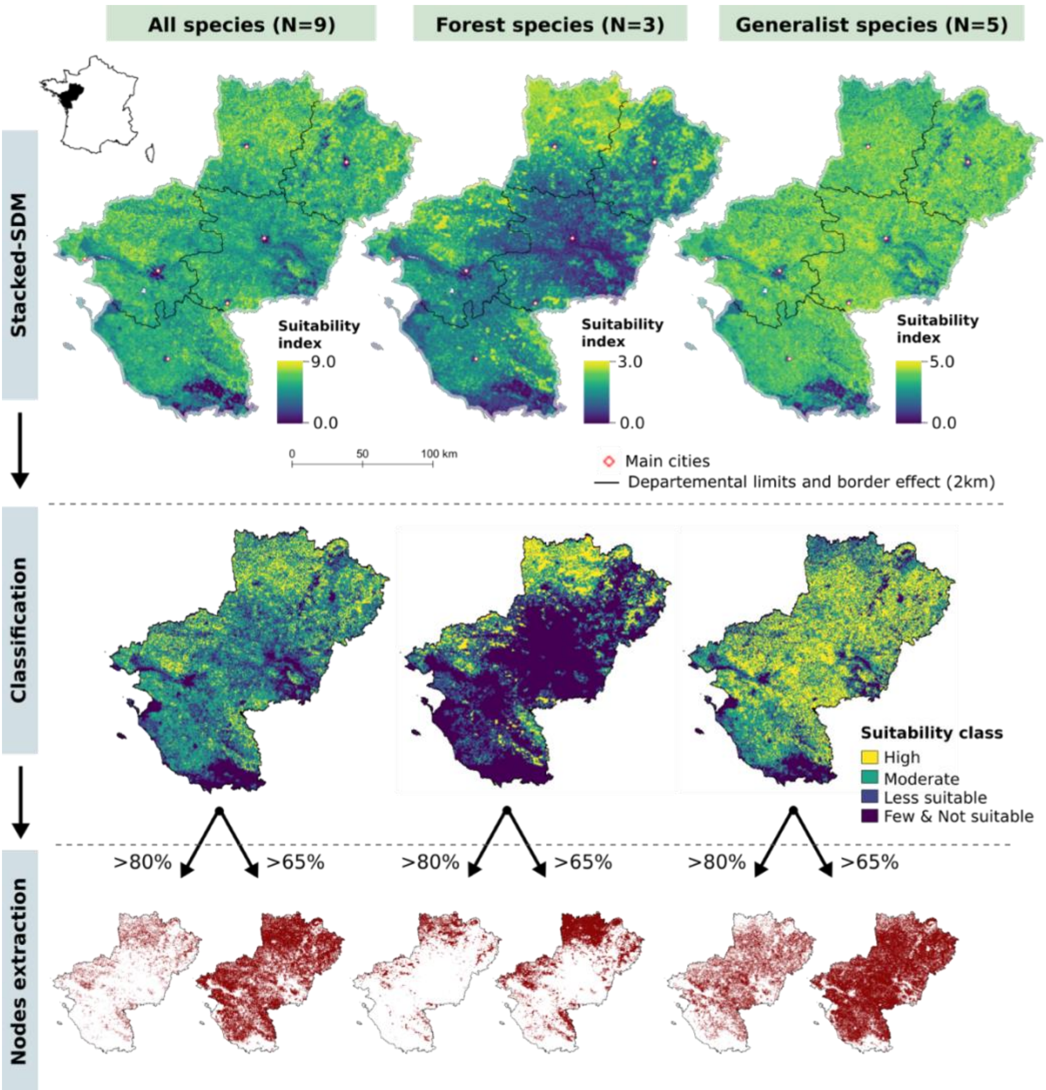


Figure 1 - Identification of highly suitable and suitable multi-specific patches of habitat using stacked habitat suitability map for three species groups.

Single and multi-species habitat suitability maps

We used 100 m-resolution habitat suitability maps from Matutini et al. (2021a). This used heterogeneous data from citizen sciences completed by professional surveys to perform and evaluate (with independent dataset) presence-only habitat suitability modelling with functional friction-based and multi-scale predictors (see Matutini et al., 2021a and Matutini et al., 2021b for full details and method tests). Model calibration sets were opportunistic presence-only data from a regional Atlas project with distance-based filtering to reduce spatial autocorrelation coupled with a weighted pseudo-absence selection to reduce sampling bias. SDM were performed combining Random Forest and General additive models. An independent and a standardised detection-nondetection dataset, stratified by model predictions for each species, were used for a robust model evaluation. This dataset included 576 ponds monitored by experts at least 2 nights with a 5-min acoustic survey followed by a visual inspection using halogen light and direct sampling using a fishing net. Data are described Appendix 1.

Table 2 - Classification of main conservation areas according to protection levels used in Pays-de-la-Loire (France). PA: protected area; GI: Green infrastructure; INV: area with an inventory of biodiversity and having a strong natural heritage interest but not protected by regulatory tools (ZNIEFF, type I and II). The level of protection varies from 0 (null) to +++ (strong).

Cat.	Group	Protect. level	Code name	UICN class	Protection approaches	Level	French denomination
PA	1	+++	RNN	I-IV	Regulatory	National	National Nature Reserve
		++	SIN,SCL	III	Regulatory	National	Classified site and Registred site
		++	RNR,RB, SCL,APB	I-V	Regulatory essentially	National or Regional	Biological Reserve, Conservatoire du littoral Site, Regional Nature Reserve, Biotope Protection Order
	2	+/++	SCEN, ENS	I-VI	Regulatory, Contractual management or Land purchase and management	Regional	Area managed by Natural Area Conservation Societies (CENs)
		+	PNR	V	Contractual management	Regional	Regional Nature Park
	3	+/++	N2000	/	Contractual management	European	Natura 2000 sites (N2000)
GI	4	0	BOCAGE	/	Non-regulatory Advisory / informative	National to local	Traditional hedgerow mosaic landscapes Infrastructure
		0	WOOD	/			Woodlands infrastructure
		0	WET	/			Wetlands infrastructure
		0	COAST	/			Coastlands infrastructure
		0	OPEN	/			Natural open fields infrastructure
		0	Corridor	/			Ecological cooridors
INV	5	0	ZNIEFF	/	Biodiversity inventories only	National	Natural areas of special ecological, faunal and floral value

We produced multi-species suitability maps by compiling individual species maps (Stack-SDM, e.g. Ferrier & Guisan, 2006) using a simple probabilistic stacking method (pSSDM, see Zurell et al., 2019). We summed continuous individual maps without binary "presence-absence" conversion (Calabrese et al., 2014; Scherrer et al., 2020) for three focal species groups: (1) forest species (FOR), (2) generalist species (GEN), and (3) all species (ALL). According to the ecological context of our region (i.e., a hedgerow landscape with small, interlocked landscape elements) for a best integration of mosaic effect for landscape evaluation, we summed species maps at 500 m-resolution after 100 m-pixels aggregation using maximum suitability values (see Appendix 3 for additional information and selection tests). Hence, we compiled single species standard deviation maps to obtain a general representation of levels of confidence in our mapped distributions. To assess the accuracy of the three pSSDMs, we compared multi-species suitability index (i.e., the sum of single species suitability values from 0 to 1) with species richness from independent pond monitoring (Matutini et al., 2021b). We calculated a community-AUC (Scherrer et al., 2020) and R2 value for each species group with 500 iterations. For each iteration, the evaluation-set was built by randomly selecting the pixels (500m) containing evaluation data respecting a distance of 1km between each pixel (independence) and stratifying the pixels along the suitability gradient of the predicted map (methods tested and validated in Matutini et al., 2021b).

Reclassification and core habitat node definition

For each species and stacked species group, we reclassified the final suitability map into five categories of potential habitat: not suitable (below the ten-percentile value P10th method in Huang et al., 2020), Less suitable (P10th-55%), moderately suitable (55%-65%), suitable (65%-80%), and highly suitable (>80%).

Network patterns

To map potential connections between each highly suitable patch (i.e., patch with a suitability index above 80%) at regional scale, we used circuit theory with Circuitscape software (McRae et al., 2016). Circuit theory considered each cell as an electric node connected to neighbouring cells by resistors and defined by a landscape resistance (or conductance) value (McRae et al., 2008). We used highly suitable core habitats as source patches, and a friction map as a measure of conductance (i.e., conductance of each raster 100m cell for movement). This method provides an exploration of potential links between nodes according to landscape permeability combining habitat suitability and connectivity modelling (Ahmadi et al., 2020; Koen et al., 2014).

Habitat suitability could however be a poor proxy of permeability as species may move in unsuitable habitats (Keeley et al., 2017). Hence, the friction map was computed using different friction cost values derived from the multi-species habitat map and landcover data (Keeley et al., 2016, 2017). Therefore, we considered moderately to highly suitable habitat classes (i.e., from 65% to 100%) as permeable features except for pixels crossed by a linear barrier. In less suitable habitats (i.e., under the 65% threshold), we calculated a friction cost based on a 100m-grid analysis performed over 10 m-resolution landscape layers followed by a classification procedure (see Appendix 4). As a precaution, the friction values were defined according to the least mobile species of each group. 100m-resolution were selected to reduce computational power needed for Circuitscape analysis and to consider landscape complementation of fine-scale landscape elements (e.g., ditches, hedgerows and field margins, Pope et al., 2000; Mazerolle, 2005). The cost values of impermeable barriers (i.e., high-density urban area, highspeed train line, highway and dual carriageways) were considered as infinite. Permeable features facilitating movement across barriers (e.g., viaduct, wildlife pass and others, see Table 2) were digitized from aerial photographs. To reduce border effects, we allocated resistance values to a 5km-buffer around the studied region which were randomly selected if land-cover data were not available.

Gap analysis and prioritizing for conservation

We based the gap analysis framework on a method used by Ahmadi et al. (2020) that compared reclassified suitability maps with areas covered by PA. We calculated "total conservation coverage" (i.e., the proportion of suitable habitat overlapping a PA or GI), "conservation efficiency" (i.e., the proportion of PA or GI overlapping suitable habitats) and plotted histograms showing the total distribution of suitability values covered by different types of conservation area. To complete the analysis, we overlaid the existing conservation network with the final regional maps obtained using Circuitscape for each species group to discuss network configuration in relation to potential regional continuities. All spatial analyses were performed using R environment v. 3.5.3 (R Development Core Team, 2019).

Results

Multi-species maps and core habitat definition

For each group, the AUC varied from 0.76 (forest species) to 0.87 (generalist species) and R^2 from 0.23 (forest species) to 0.31 (nine studied species) (Table 3). The suitable maps are shown in Figure 1 while associated confidence maps are available Appendix 5. For the nine studied species, highly suitable habitats covered 12% of the region and suitable habitats covered 49% of the region (Figure 1). Highly suitable habitat for the forest species, covered 11% and suitable habitat covered 17% of the region. Larger amounts of highly suitable and suitable habitats were available to generalist species, covering 33% and 40% of the region respectively.

Table 3 - Accuracy of stacked species distribution models for three species groups according to the nine studied amphibian species. Results obtained with external data with 500 permutations. AUC were calculated from predicted multi-species suitability values compared to observed species diversity. Community AUC (AUCc) were obtained with predicted suitability index for each species compared to the presence/absence observations in the assemblage (Scherrer et al. 2020). Individual AUC and SEDI are evaluation metrics obtained by Matutini et al. (2021b) for each species specific map.

Species group	R^2	AUC	AUCc	Min individual AUC / SEDI	Max individual AUC / SEDI
All nine species (*n*=9)	0.31	0.86	0.79	0.73 / 0.67	0.86 / 0.89
Forest species (*n*=3)	0.23	0.76	0.96	0.78 / 0.68	0.86 / 0.84
Generalist species (*n*=5)	0.30	0.87	0.86	0.73 / 0.67	0.81 / 0.89

Protected areas (PAs)

The distribution of protected areas along the habitat suitability gradients modelled for each species or species group (FOR, GEN, ALL) is shown Figure 2.

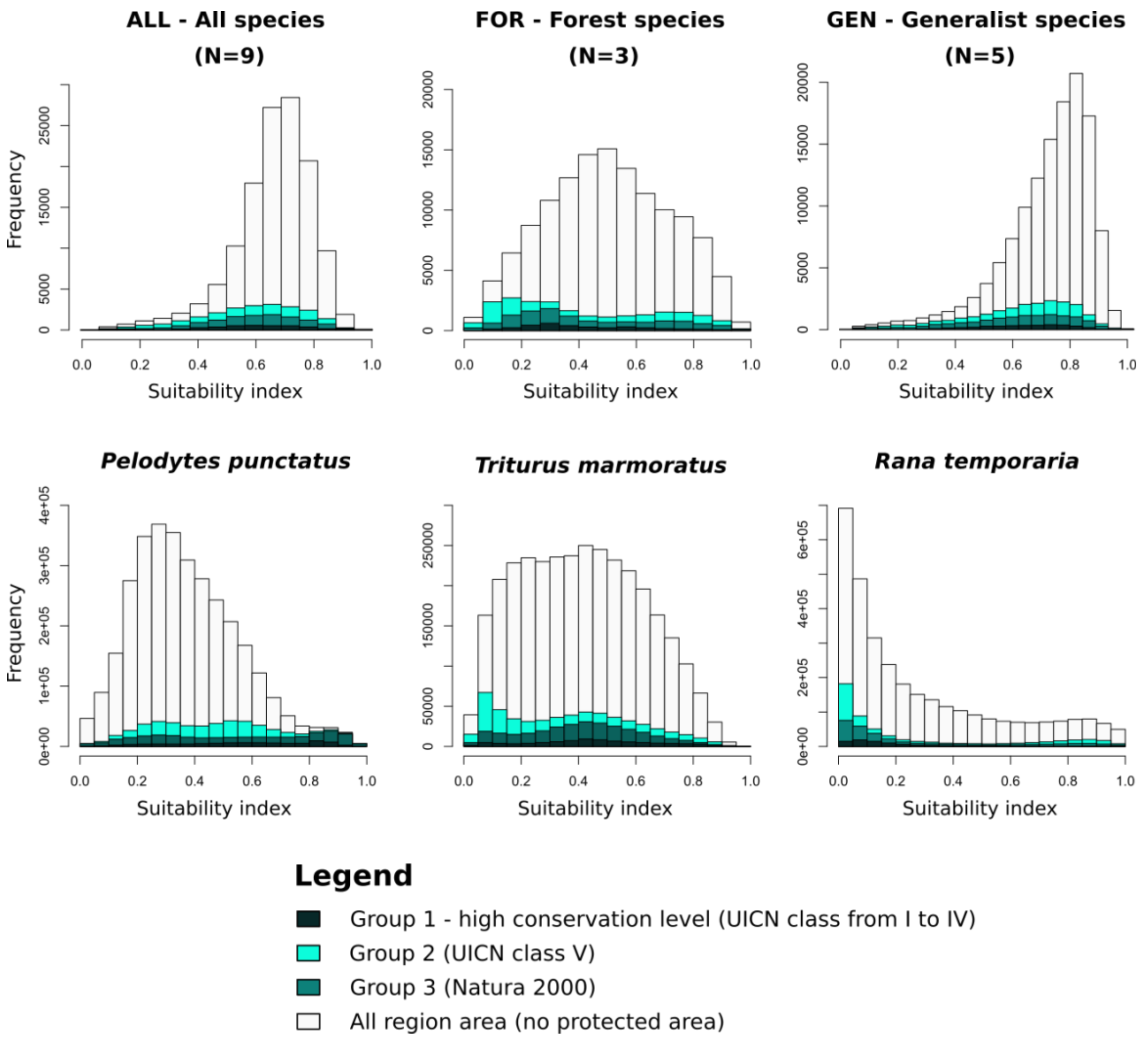


Figure 2 - Distribution of pixels along the regional habitat suitability gradient covered or not by protected area. Suitability index (from the habitat suitability map) is calculated for each species and varies from 0 to 1. Suitability index of the three groups (ALL, FOR and GEN) is the sum of the individual species index related to each group (pSSDM) divided by the number of species in order to have a suitability index on the same scale. The frequency corresponds to a number of pixels covered by protected areas from the Group 1, 2, 3 in relation to the whole region area.

Conservation coverage

PAs covered a relatively low proportion of highly suitable habitat: 15%, 19% and 8% for all species, forest species and generalist species respectively (Table 4). The most strictly protected areas protection (PA group 1) covered even lower proportions of suitable habitat: 1% of highly suitable habitat and 2% of suitable habitat for each species group. Similarly, for two of the three species of high conservation concern, PA covered only a relatively low 17% or 26% of highly suitable habitat, for *T. marmoratus* and *R. temporaria* respectively. Only for *P. punctatus* was conservation coverage high: 90% of highly suitable habitat was included in PA. We also found (see Appendix 1) low conservation coverage of PAs for rarer species based on available presence-only data, except for *Pelobates cultripes* with 72% of presence data located in protected areas (of which 37% in PA Group 1).

Conservation efficiency

Among PA-Group 1, no sites with the highest level of protection (names "RNN", see Table 2) contained highly suitable area for any species group or individual forest species except *P. punctatus* (12% of RNN areas contain high suitable habitat) (Table 4). Other PA-Group 1 protection levels were covered by 7 to 24% of multi-species core area and by 3 to 24% of species-specific highly suitable habitat, with a higher proportion for *P. punctatus*. Regional Park (PA-Group 2) and Natura 2000 network (PA-Group 3) included less than 16% multi-species core area and lower proportions for the two-forest species individually. For SCEN and ENS (in PA-Group 2) 26%, 12% and 8% of these sites were located in highly suitable habitats for generalists, forest species and all nine species respectively. Overall, PAs contain a higher proportion of highly suitable habitat for *P. punctatus* than for other species.

Inventoried sites (INV)

Inventoried sites with known ecological value but no legal protection (INV-Group 5) covered 13% of the region. 20% to 34% of their areas were covered by multi-species highly suitable habitat (24 to 57% for suitable area). 11%, 21% and 1% are covered by highly suitable habitat of *T. marmoratus*, *R. temporaria* and *P. punctatus* respectively (Table 4). INV-Group 5 covered the most suitable and highly suitable habitat of all studied groups and species except for *P. punctatus* with a poor overlapping between this species issues and areas of INV-Group 5 (i.e., 2%).

Green infrastructure (GI)

GI included and covered a larger area of highly suitable and suitable habitat for amphibian species than PA particularly hedgerow networks BOCAGE followed by WOOD and WET (see Table 2). Globally, GI covered around 50% of potential habitat for amphibian species. Among the five GI's classes (Table 4), GI relating to traditional hedgerow landscapes (BOCAGE) were the most widespread and covered from 16% to 33% of highly suitable habitat of species or species groups (especially *T. marmoratus* with 33% and excluding *P. punctatus* with only 2%). In addition, the GI BOCAGE contained 42% highly suitable habitat for generalist species and between 12-21% for other species except *P. punctatus*. GI relating to woodlands (WOOD) and wetlands (WET) covered more than 10% of highly suitable habitat except for *T. marmoratus* and *P. punctatus*. GI relating to coastland (COAST) and natural open grasslands (OPEN) covered small areas compared with other GI and a low area of suitable habitat for studied species.

Potential multi-habitat continuities patterns

The distribution patterns associated with highly suitable and suitable habitats are shown Figure 1 and supplemented in Figure 3 by a more detailed analysis of the spatial organisation and potential links between habitat patches. The central and the southern parts of the region have a few patches of highly suitable habitat, especially for forest species. Generalist species have a more homogeneous distribution of suitable habitats spreads over the region. Suitable and highly suitable habitat distribution patterns associated with forest species are mostly common with other species, except for large suitable forest patches especially at the north of the region. Indeed, 92% and 81% of highly and suitable habitat of FOR species (i.e., suitability index > 65%) are include in GEN and ALL species' high and suitable habitat respectively.

Regarding potential multi-specific regional continuities, two major sectors form "bottlenecks" to north-south (sector B, Figure 3) or east-west continuity axis and potential movements (sector A, Figure

3). This is particularly marked for forest species. These two sectors contain few protected areas and show a cover mismatch with GI (Figure 3).

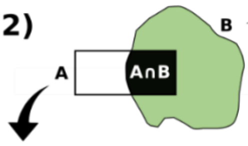
Table 4 - Proportion of the conservation area covered by different habitat suitability classes (1. conservation efficiency) and proportion of different habitat suitability classes covered by the conservation area (2. conservation coverage) for different species and species groups. Classes of conservation area: Protected (groups 1 to 3) – classes I to V derived from the UICN classification; EURO: European conservation network from Natura 2000; Non-protected: GI (Green infrastructure) and INV (inventoried sites define as "high naturalist interest"). Suitability class for each groups or species: "+++" = highly suitable (>0.80) ; "++" = suitable (>0.65) ; +/- = "moderately or not suitable" (<=0.55). See Table 2 for "code names" details. Names with * show sites with point data only (surface area is not available).

1)

A∩B / A — CONSERVATION EFFICIENCY

	Group	Name	Class	Area (ha)	SSDM 500m resolution: All studied species (n=9) +++	++	+/-	Forest species (n=3) +++	++	+/-	Generalist species (n=5) +++	++	+/-	SDM 100m resolution: *Triturus marmoratus* +++	++	+/-	*Rana temporaria* +++	++	+/-	*Pelodytes punctatus* +++	++	+/-
Protected (PA)	1	RNN	I-IV	3183	0	23	26	0	19	26	0	21	24	0	3	21	0	4	12	12	1	4
		SIN,SCL	III	80912	7	33	36	7	11	18	12	35	29	8	13	19	4	2	3	24	18	20
		RNR,RB,SCL,APB	I-V	4902	17	30	28	20	12	8	24	32	28	3	12	17	22	4	2	14	11	15
	2	SCEN,ENS*	I-VI	/	12	50	26	12	24	23	26	44	19	8	21	20	6	7	7	6	10	15
		PNR	V	358668	11	28	27	15	15	10	13	32	24	5	10	13	15	8	4	10	12	24
	3	N2000	EURO	144070	10	33	36	10	16	12	19	34	26	2	10	23	10	8	6	24	14	13
Non protected (GI & INV)	4.1	BOCAGE	GI	424568	20	63	17	21	26	29	42	43	13	12	27	30	15	11	9	0	3	10
		WOOD	GI	176157	26	55	18	38	25	23	38	38	20	6	20	22	31	12	11	0	1	4
		WET	GI	270266	19	56	22	21	25	25	38	44	15	5	18	26	15	11	11	1	3	8
		COAST	GI	9376	2	51	35	0	12	30	4	59	26	12	34	25	0	0	0	13	20	26
		OPEN	GI	19445	15	53	28	11	22	20	42	41	13	1	5	11	13	11	12	1	5	17
		Total core hab.	GI	650572	20	60	19	24	25	27	40	43	15	9	24	26	18	10	9	0	3	9
	4.2	Corridor	GI	378391	17	52	25	13	21	26	39	41	16	5	14	20	9	8	9	0	4	14
	5	ZNIEFF	INV	279266	20	57	20	29	24	25	34	44	18	11	28	25	21	9	10	1	4	10
		REGION		**3236407**	**12**	**49**	**28**	**11**	**17**	**23**	**33**	**40**	**17**	**5**	**13**	**19**	**9**	**7**	**7**	**3**	**6**	**15**

2)



A∩B / B — CONSERVATION COVERAGE

	Group	Name	Class	SSDM 500m resolution: All studied species (n=9) +++	++	+/-	Forest species (n=3) +++	++	+/-	Generalist species (n=5) +++	++	+/-	SDM 100m resolution: *Triturus marmoratus* +++	++	+/-	*Rana temporaria* +++	++	+/-	*Pelodytes punctatus* +++	++	+/-
Protected	1	RNN	I-IV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		SIN,SCL	III	1	2	3	1	2	2	1	2	4	4	2	2	1	1	1	19	8	3
		RNR,RB,SCL,APB	I-V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	2	SCEN,ENS*	I-VI	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
		PNR	V	10	6	10	14	10	5	4	9	15	11	9	8	20	13	6	35	23	18
	3	N2000	EURO	4	3	6	4	4	2	3	4	7	2	3	5	5	5	4	35	11	4
Non protected	4.1	BOCAGE	GI	21	17	8	24	20	17	16	14	10	33	27	20	23	21	17	2	8	9
		WOOD	GI	11	6	3	18	8	5	6	5	6	7	8	6	20	9	9	1	1	2
		WET	GI	13	10	7	16	12	9	10	9	7	8	12	11	15	14	14	2	4	5
		COAST	GI	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1
		OPEN	GI	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1
		Total core hab.	GI	33	25	13	42	30	24	24	21	17	39	36	28	43	32	28	3	11	13
	4.2	Corridor	GI	16	13	10	14	15	13	14	12	10	12	12	12	12	15	16	2	9	11
	5	ZNIEFF	INV	14	10	6	22	12	10	9	9	9	21	18	11	21	12	12	2	6	6

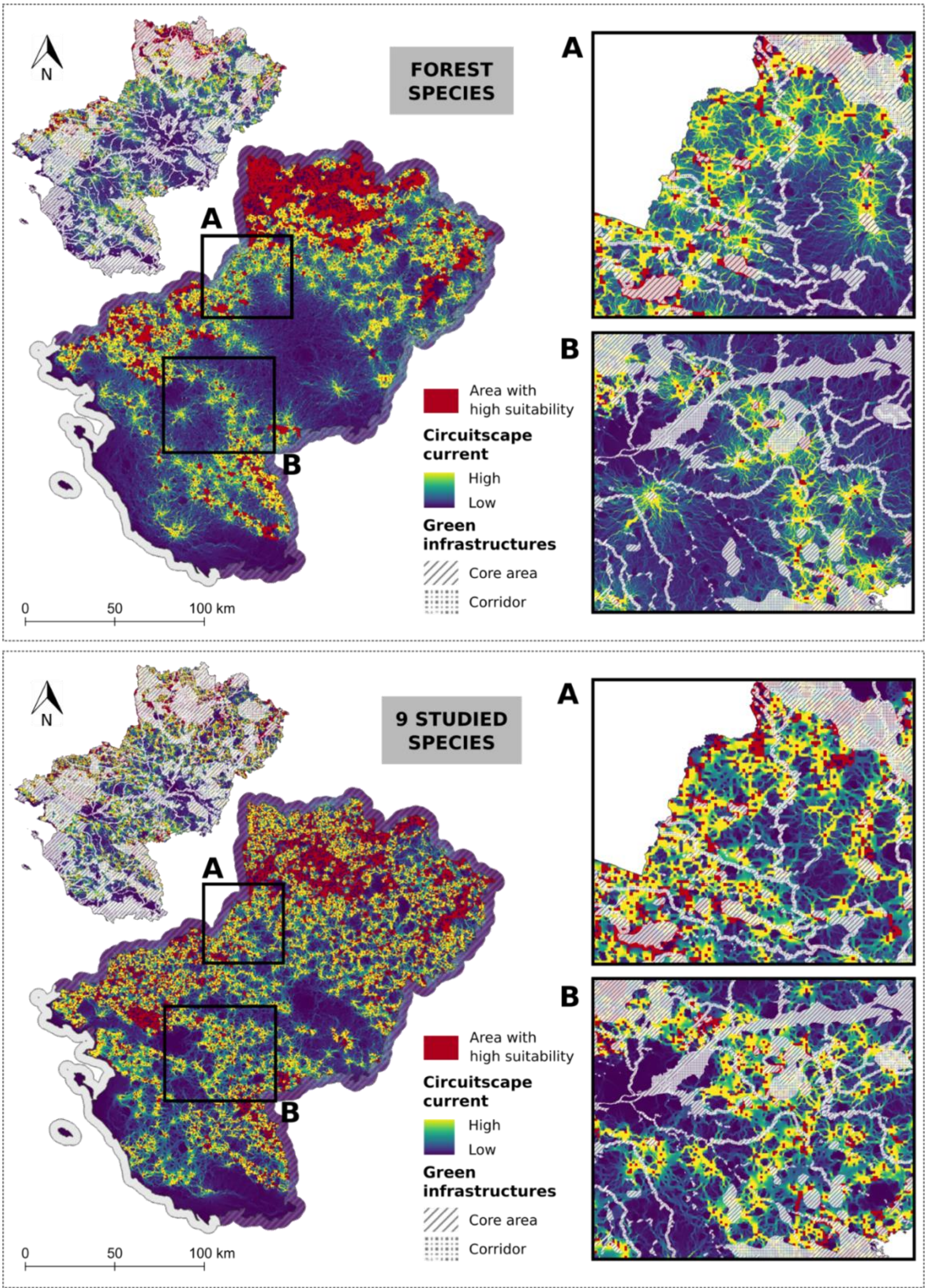


Figure 3 - Large scale permeability between high suitability areas and associated continuities patterns confronted with regional green infrastructure. A and B show potential conflict area and issues for continuity conservation at regional scale with a mismatch with the green infrastructure network.

Discussion

We highlighted a mismatch between the most suitable habitats for studied species at regional scale and the existing conservation network, in particular protected areas (in coverage and efficiency). Indeed, habitat patches with a high suitability index associated with common or slightly rarer species were poorly covered by PA except for one species of high conservation concern: *P. punctatus*. Analysis of other rarer species distributions suggest that the observed mismatch concerns other species present in the studied region (Appendix 1). However, most suitable areas were better covered by GI (especially GI layers associated with wood, hedgerow landscapes and wetlands) and by INV sites (inventoried sites with ecological value but no regulatory protection). Difference in coverage and efficiency obtained for PAs and INV highlights that some sites with amphibian conservation issues are known but not protected. In addition, we identified two narrow “bottlenecks” in suitable habitat continuities at regional scale which are only very sparsely covered by the conservation network (PAs and GI).

General limits and interpretation framework

In addition to the limits related to the presence-only SDM detailed in Matutini et al. (2021a) recently developed stacking-SDM methods require further development to improve their evaluation. SDM are useful tools to predict the distribution of habitat suitability but rarely predict the biology of populations (Lee-Yaw et al., 2022). The multi-species networks identified should be considered simply as maps of highly suitable habitat (habitat perspective) – measured with highly sensitive and biphasic amphibian species – rather than as a real multilayer network of amphibian communities (species perspective). In addition, resistance values based on literature and expert opinions or derived from SDM values are still debated (see Godet & Clauzel, 2020 for methods comparison and discussion) and information about species movement and dispersion processes are still very scarce in the literature (Pittman et al. 2014).

Amphibians also have poor movement capacities, rarely exceeding a few kilometres during dispersal movements (Sinsch, 2014). In this work, continuities were identified from habitat distributions at regional scale and species level reflecting long-term ecological processes and population movements across decades. This study takes a first step towards assessing potential barriers to species distribution shifts in response to global change, but does not directly include landscape dynamics and climate change scenarios. Rather it provides elements at regional scale to guide regional policies and further studies to improve multi-scale integration and efficiency of measures for biodiversity conservation. Collect and integrate independent genetic data to assess our final maps, particularly in the two bottleneck sectors, would be important to evaluate connectivity and complete the investigation in view to propose relevant conservation or restoration measures.

A mismatch for the conservation of amphibians

Two main reasons may explain the mismatch between location of PAs and amphibian habitat requirements. Firstly, PAs are generally defined according to the needs of rare and/or emblematic species or habitats). In the study region, most PA focus on birds or plants species, large open wetlands near the western coast or the Loire River valley but only a few target species of amphibian and these tend to be rare species (e.g., *P. cultripes*, see Appendix 1). Most local, rare species of high conservation concern are pioneer species and/or associated with loose or sandy soils with poor vegetation that are found in particular on the coast, along the Loire River and in some quarries. Their ecology contrasts with the other studied species, except for *P. punctatus* which shares many of the same ecological requirements, explaining the better conservation coverage and efficiency of PA for this species.

Secondly, PA definition in the region presents a “location bias”. Indeed, PAs are defined primarily in areas of low economic interest, less used for human activities (Rodrigues et al., 2004). This bias is common worldwide and widely described in the literature (Ahmadi et al., 2020; Joppa & Pfaff, 2009). It can be especially problematic for species living in human-dominated landscapes, like most amphibian species. For example, Rodrigues et al. (2004) demonstrate that amphibians contain a large number of “gap species” worldwide, i.e., they are the biological group least covered by the global PA network. In addition, our results show a potential “network bias” similar to Ahmadi et al. (2020), i.e., the extension of PA is established without sufficiently considering their position within the network. Indeed, the current PA sites (and the sites intended for the future extension of PAs – see Appendix 5) are not located in the two areas with highest potential defined by our primary analysis of the regional continuity of suitable habitats.

Green infrastructure (GI) as a complementary tool for biodiversity conservation

Our results show GI offers better coverage of highly suitable habitats than PAs for amphibian species groups, but this remains partial, in particular in the two identified "bottleneck" sectors. Indeed, agricultural areas are poorly covered by PAs, generally due to a conflict of economic interest (Rodrigues et al. 2004) while GI provides complementary coverage in areas dominated by human activities. Agricultural landscapes with high conservation value for biodiversity such as hedgerow mosaic landscapes depend on the maintenance of traditional farming practices that may even be inhibited by PAs conservation (Schmitz et al., 2017).

In addition, we underline the importance of GI layers associated with wetlands, woodlands, and traditional hedgerow mosaic landscapes for amphibians. Consequently, our results highlight the importance of considering several GI layers with potential interactions. GI tends to compartmentalize conservation issues by splitting them into distinct layers of habitat types considered as independent "subnetworks", where the "habitat" concept is limited to landcover categories (see Pilosof et al., 2017 for general perspective on multi-layer nature of ecological networks). Species survival is however conditioned by different ecological processes which generally go beyond a single type of land cover class. Amphibian habitat network studies supporting GI definition mainly focus on pond networks but natural or semi-natural forest patches, especially mature forest (e.g. >70 years) and even small woodlots (Boissinot et al., 2015), are essential for amphibian population persistence, in particular in agricultural regions (Hartel et al., 2010; Collins & Fahrig 2017). Species other than amphibians may also have very contrasting requirements during their life cycle (e.g., many holometabolous insects, odonates, and bats).

Lastly, we expected a higher overlap of the GI layer called Bocage (traditional hedgerow mosaics in agricultural) based on knowledge of amphibian ecology (Boissinot et al., 2019). This GI layer was mapped using combined land use data (i.e., hedges, ponds and meadows only) at 1km-resolution with a poor consideration of the interactions between these elements (i.e., simple metrics as density or area related to hedges, ponds and meadows were combined independently). Of course, other elements of the landscape are important for amphibians, such as small streams and wooded patches, as well as more complex processes related to landscape complementation and structural heterogeneity (Boissinot et al., 2019; Collins & Fahrig 2017).

Therefore, an important weakness of GI is its exclusive reliance on land use data without including biological data and landscape complementation as well as the multi-layered nature of ecological networks. Ecological niche modelling tools such as SDM, coupled with ecological connectivity models, are of particular interest for improving the ecological realism of identified networks and supporting related decisions (Clauzel & Godet 2020). These modelling tools need to be used and interpreted with care (e.g., within the framework specified in 4.1.).

Implications for conservation

First, we identified "bottleneck" sectors not covered by any conservation tools such as PA or GI despite high potential conservation value. These areas might be especially important for amphibian populations in a context of global change requiring distribution shifts to maintain suitable conditions for population viability. Indeed, according to Préau et al. (2019), important distribution shifts at regional scale are expected for certain amphibian species based on global change predictions. These two "bottlenecks" are located in a context of open fields and intensive farming which are considered by nature protection organisations to have limited potential for biodiversity. In these areas, some semi-natural elements such as small woods associated with wetlands may nonetheless play a key role in maintaining functionality and connectivity of the network at regional scale and should be strengthened. In these two areas, habitat continuities are maintained by riparian woods (sometime very thin and degraded) and associated river landscapes with a higher proportion of pastures and hedgerows, as well as small wood patches close to wetlands including ponds. Considering the general limits of this studies (see 4.1), these two areas need further investigation - especially connectivity evaluation by integrating genetic data – in order to defined appropriate conservation and restoration measures.

Overall, the protected areas network needs to be strengthened and supplemented by conservation tools more adapted to landscapes with strong interactions between biodiversity and human activities. Green infrastructure (GI) has better efficiency and coverage in particular because it concerns landscapes where natural and semi-natural habitats and human activity are closely intertwined. However, GI is not regulatory. Other effective area-based conservation measures (OECMs) are new conservation tools intended to complement protected areas (PAs) and might strengthen GI at local scale by sharing the common objective of restoring large scale connectivity (Convention on Biological Diversity, 2018). OECMs might be the complementary regulatory brick to PAs and GI with, in a European context, a better consideration and recognition of management practices and certain agroecological farming practices that are more biodiversity-friendly.

The different maps obtained from this study provide support for prioritizing certain regional policies with different objectives: (1) strengthening PA network, GI and future OECM (Appendix 6 provides more specific information to prioritize new protected or conservation area from a regional preselected set of sites according to our results); (2) identifying potential conflict points with transport networks (i.e., roads and railways); (3) spatially prioritizing actions supporting the agroecological transition, particularly in the two bottleneck areas considered as "degraded" for biodiversity. Conservation actions for amphibian conservation often focus on ponds and pond networks. The complementarity of ponds (or wetlands) and forest patches should be considered to define conservation actions (Cushman, 2006; Denoël & Lehmann, 2006; Pope et al., 2000) as well as certain associated extensive and traditional farming practices in western Europe (Boissinot et al., 2019; Hartel et al., 2010). In our region, amphibians have interactions with traditional agricultural practices and with related landscape dynamics. As multi-habitat species, amphibians have potential as biodiversity indicators of ecological quality of hedgerow network landscapes, composed of a mosaic of trees, grasslands, and ponds upon which they depend. The success of conservation measures depends on our ability to integrate biodiversity issues into farming practices for the benefit of amphibians but also many other forms of biodiversity benefiting from such landscape mosaics.

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Authors' contributions

Florence Matutini: Conceptualization (Equal), Data curation (Lead), Formal analysis (Lead), Funding acquisition (Supporting), Methodology (Lead), Investigation (Lead), Visualization (Lead), Writing-original draft (Lead), Writing-review & editing (Lead); Marie-Josée Fortin: Conceptualization (Equal), Methodology (Supporting), Supervision (Supporting), Writing-original draft (Supporting), Writing-review & editing (Supporting); Jacques Baudry, Guillaume Pain & Josephine Pithon: Conceptualization (Equal), Supervision (Equal), Writing-original draft (Supporting), Writing-review & editing (Supporting), Funding acquisition (Lead).

Data and code availability

Data sample, scripts and maps are available online: https://doi.org/10.5281/zenodo.7096821, Matutini et al. (2023).

Conflict of interest disclosure

The authors of this preprint declare that they have no financial conflict of interest with the content of this article.

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Appendices

Appendix 1. species data, supplementary analysis on other species and model transferability

Data used for SDM calibration and validation (completed from Matutini et al. 2021)

Opportunistic presence data (calibration dataset)

Table A1.1 - Data sources for model calibration

Database name	Type	General website	Data
Faune_anjou	Citizen bases with validation process by professionals	https://www.faune-anjou.org/	25%
Faune_maine		https://www.faune-maine.org/	10%
Faune_vendee		https://www.faune-vendee.org/	10%
Faune_loire_atlantique		https://www.faune-loire-atlantique.org/	11%
Biolovision		https://data.biolovision.net/	18%
URCPIE	Professional & volunteers	http://urcpie-paysdelaloire.org/	12%
Bretagne Vivante	Naturalist group	https://www.bretagne-vivante.org/	2%
ONF_BDN	Professional	https://www.onf.fr/	3%
SICEN	Professional	http://www.cenpaysdelaloire.fr/	3%
BASEPARC PNRMP / OPN	Professional	https://pnr.parc-marais-poitevin.fr/	2%
Naturalistes en lutte	Naturalist group	https://naturalistesenlutte.wordpress.com/	2%
Sterne 2.0	Professional	http://www.sterne2.com/	1%
Les naturalistes vendeens	Naturalist group	http://naturalistes-vendeens.org/	1%
Gouret_FLA	Naturalist individual base	-	<1%
Cap Atlantique	Professional	https://www.cap-atlantique.fr/accueil	<1%
Undragon.org	Citizen base	http://undragon.org/	<1%
ONCFS	Professional	http://www.oncfs.gouv.fr/	<1%

Table A1.2 - Description of the presence-only data used for each of nine species for calibration of habitat suitability models.

	Opportunistic presence-only dataset (model calibration and cross- validation)	
Species	Total nb of presence	Nb of 500 m presence-cells
Anurans:		
Bufo spinosus	8320	4127
Hyla arborea arborea	6344	3353
Pelodytes punctatus	2711	1103
Rana dalmatina	9073	3752
Rana temporaria	1525	477
Urodeles:		
Salamandra Salamandra terrestris	4916	2242
Triturus marmoratus	1478	629
Triturus cristatus	1791	766
Lissotriton helveticus	7047	2835

Standardised detection-nondetection data (external validation dataset)

Name of the citizen science program: “Un Dragon dans mon Jardin”

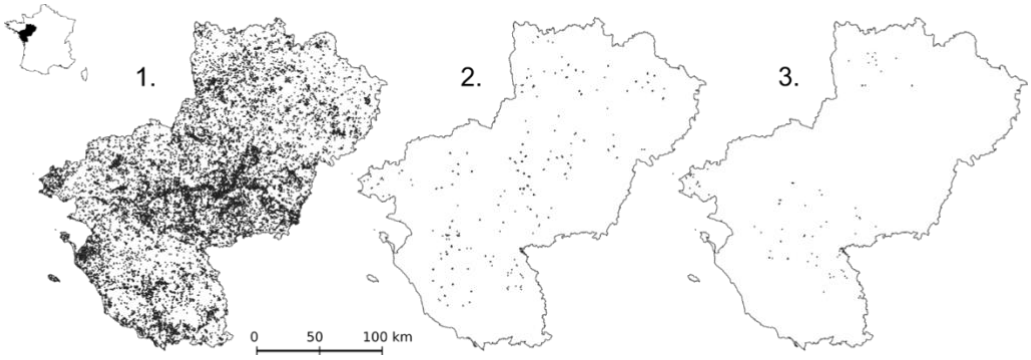
Coordination: URCPIE – “Union régionale des centres d’initiatives pour l’environnement ».

For external SDM validation, we extracted detection-nondetection_amphibian data from a regional citizen science database. This database contained 576 monitored aquatic sites for the period 2013-2019, with observations made in the context of a programme aiming to estimate amphibian population trends (regionally called “Un Dragon dans mon Jardin”). Observers had to follow a standard protocol; each site had to be monitored three times separated by at least one month - one diurnal between January and March and two nocturnal between March and June – to cover different species’ breeding periods, during good weather conditions (no frost, no rain, no or weak wind). For each survey, three complementary methods were used to detect amphibians: an acoustic survey (5 min at 5 metres from the site without light) to detect breeding calls of male Anurans specie; an active visual survey using a flashlight torch (500-1000 lumens) to observe individuals and eggs and a catching survey using a net (3 net sweeps per site) if the observer had specific authorization. These methods are commonly used for amphibian community surveys. If the protocol was not respected and/or if the observer was not sufficiently experienced, only the presence data were considered valid (exclusion of the absence data). In addition, a threshold value for minimum sampling effort required were used to validate non-detection as absence data. See Matutini et al. 2020

Table A1.3 - Description of the filtered datasets for each of nine species used for external validation of habitat suitability models. DET: 500 m cells with detection of the species; NoDET: 500m nondetection-cells. Results for 1 interaction

	EVAL		EVAL_STRAT
	Nb of DET	**Nb of NoDET**	Nb data/strat
Anurans:			
Bufo spinosus	97	187	23
Hyla arborea arborea	136	204	23
Pelodytes punctatus	40	249	8
Rana dalmatina	186	162	30
Rana temporaria	17	231	15
Urodeles:			
Salamandra Salamandra terrestris	79	186	25
Triturus marmoratus	62	213	16
Triturus cristatus	52	241	25
Lissotriton helveticus	176	164	13

Figure A1.1 - Distribution of the 500m² cells with data for the opportunistic dataset and the external evaluation dataset (e.g. *CS.1+ABS+SUP*). (1) All 500m² cells with at least one opportunistic observation (all species); (2) 500m² cells used as presence-absence data (with at least three surveys performed by an expert observer or six surveys by an intermediate observer) for external validation; (3) 500m² cells used only as presence if the species had been detected (sampling effort too weak for absence data) for external validation. The external dataset for validation is a compilation of (2) (presence-absence) and (3) (presence).



Supplementary analysis on other species and model transferability

Species description

Among all the species present in Pays-de-la-Loire described below, we have excluded from this analysis:

- Exotic and/or invasive species;
- Rare species at the limit of the distribution area (i.e. with very little data at the edge of the study area) and/or species with less than 5 points;
- Species of the Pelophylax genus subject to identification errors because they are morphologically very similar and can hybridize. Given the number of observations and

conservation issues, Pelophylax kl. esculentus was however included in the analysis (expert data with validated identification only).

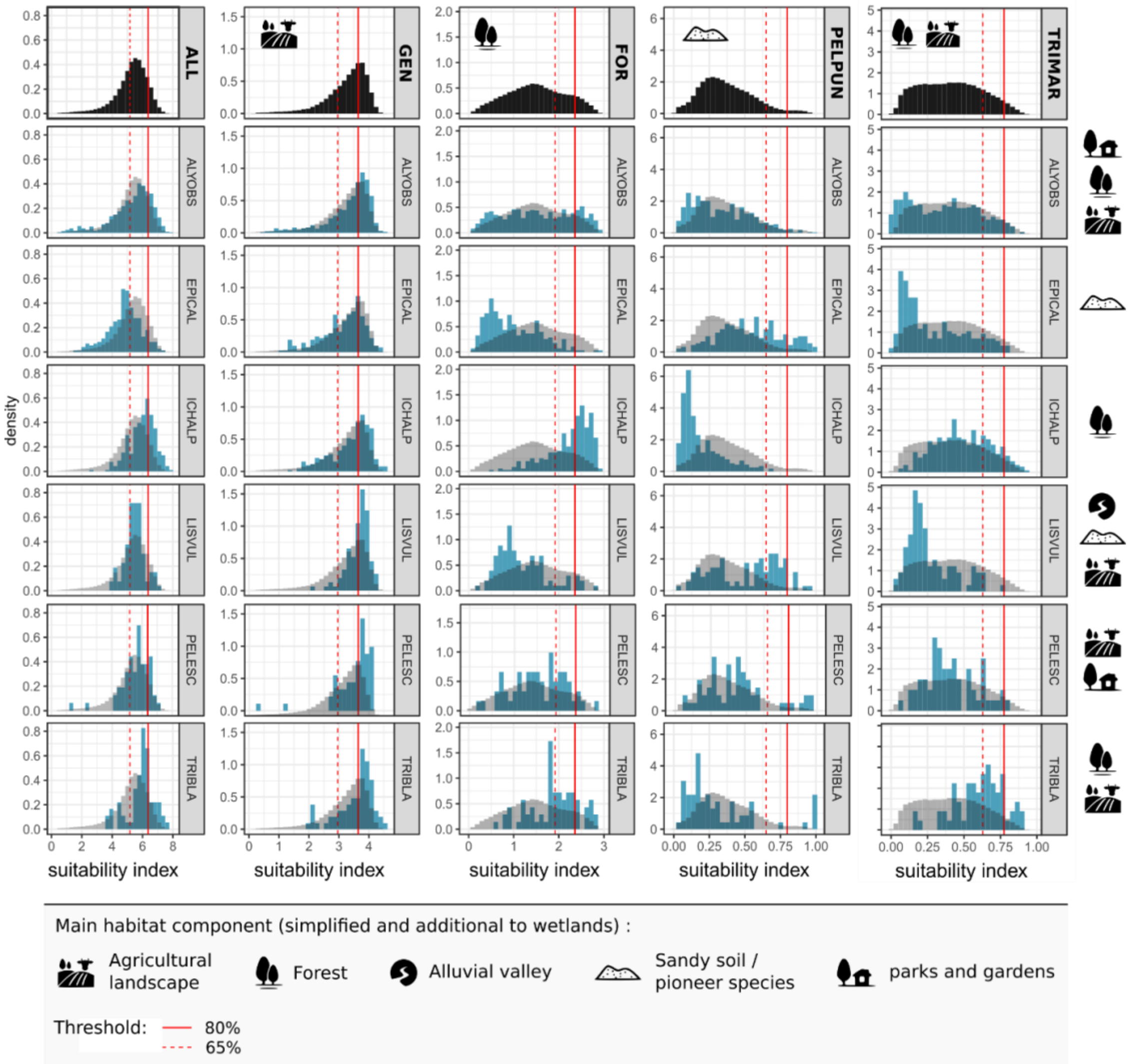
Table A1.4 - Description of the amphibian's species of Pays-de-la-Loire. RL FR: France red list (2015); RL Region: regional red list of Pays-de-la-Loire (2021); Priority: regional priority level for species conservation from the regional red list from 0 (low) to 3 (very high) defined by Marchadour et al. (2021); Hab. Dir. N2000: habitats directive classification (Natura 2000); Nb presence data: Number of presence-only data were calculated after a 100 m-resolution rasterization and correspond to the number of pixels (cells) with at least one observation of the species. Species names with an asterisk (*) has been included to the complementary analysis (see exclusion criteria presented above).

	Code	Species	RL FR	RL Region	Regional priority (2009/2021)	Hab. Dir. N2000	Nb presence data (Atlas) – 100m-cell	Nb presence data (Atlas) – 500m-cell
Species used for SSDM	*PELPUN*	*Pelodytes punctatus*	LC	NT	2/1		1828	1316
	TRIMAR	***Triturus marmoratus***	**NT**	**NT**	**3/3**	**IV**	**890**	**703**
	RANTEM	*Rana temporaria*	LC	VU	2/1	V	891	515
	LISHEL	*Lissotriton helveticus*	LC	LC	1/1		4509	3279
	BUFSPI	*Bufo spinosus*	/	LC	0/1		6772	5006
	HYLARB	*Hyla arborea*	NT	LC	0/1	IV	5026	3919
	RANDAL	*Rana dalmatina*	LC	LC	0/1	IV	6275	4481
	TRICRI	*Triturus cristatus*	NT	NT	0/2	II & IV	1126	894
	SALSAL	*Salamandra salamandra*	LC	LC	0/0		3703	2625
Other species	*EPICAL*	*Epidalea calamita**	LC	NT	2/1	IV	443	275
	LISVUL	***Lissotriton vulgaris****	**NT**	**EN**	**2/2**		**116**	**102**
	ICHALP	*Ichthyosaura alpestris**	LC	NT	2/0		480	346
	ALYOBS	*Alytes obstetricans**	LC	NT	1/1	IV	1059	820
	TRIBLA	*Triturus x blasii**	/	/	/	/	79	69
	/	***Bombina variegata***	**VU**	**CR**	**3/3**	**II & IV**	**31**	**13**
	/	***Pelobates cultripes***	**VU**	**EN**	**3/3**	**IV**	**127**	**48**
	/	*Hyla meridionalis*	LC	LC	1/0	IV	323	229
	/	*Xenopus laevis*	/	/	/		131	112
	/	***Pelophylax lessonae***	**NT**	**VU**	**3/2**	**IV**	**5**	**5**
	PELESC	***Pelophylax kl. esculentus****	**NT**	**NT**	**0/2**	**V**	**63**	**60**
	/	*Pelophylax ridibundus*	LC	/	/	V	140	131
	/	***Pelophylax perezi***	**NT**	**EN**	**0/2**	**V**	**1**	**1**
	/	***Pelophylax kl. grafi***	**NT**	**EN**	**0/2**			
	/	***Pelophylax sp.***	*/*	*/*	*/*	*/*	**10390**	**7277**

* species included in the complementary analysis Figure 2

Transferability of SSDM to rarer species

Figure A1.2 - Distribution of presence-only data of selected species according to the different suitability gradients modelled (SDM) for two species (PELPUN and TRIMAR) and for tree species groups (Stack-SDM for ALL, GEN and FOR). Lines show the two thresholds 65% and 80% in the suitability index. For species code, see Table 1. PELPUN and TRIMAR are the two species considered by thresholders as model species to asses regional ecological network functionality.



Conservation coverage for rarer species (with presence data only)

Table A1.5 - Proportion of presence data covered by the conservation area (conservation coverage) for species not included in species distribution modelling. 1. Presence data used in the analysis are defined as a 100m-pixel with at least one observation of the species. 2. Same as 1 but we add a distance condition of 500m between each species observations. See Table 2 (main text) for "code names" details and Table 1 for species names. * show species at limit of their geographic ranges or species with very few presence data.

1.

			No minimal distance between 100m pixel with at least 1 presence data								
Grp	Name	classe_UICN	ALYOBS	EPICAL	LISVUL	ICHALP	TRIBLA	PELESC	PELCUL*	BOMVAR*	PELLES*
1	RNN	I_IV	0,00	0,01	0,00	0,00	0,00	0,00	0,03	0,00	0,00
1	SIN_SCL	III	0,04	0,09	0,07	0,00	0,01	0,00	0,28	0,00	0,00
1	RNR_RB_SLit_APB	IV	0,00	0,03	0,01	0,01	0,02	0,00	0,06	0,00	0,00
2	SCEN_PNR	V	0,10	0,34	0,05	0,08	0,07	0,16	0,16	0,02	0,00
3	N2000	INT	0,06	0,10	0,44	0,16	0,12	0,06	0,19	0,00	0,20
4	BOCAGE	GI	0,09	0,02	0,05	0,14	0,15	0,10	0,02	0,12	0,00
4	WOOD	GI	0,07	0,07	0,02	0,32	0,12	0,05	0,00	0,00	0,00
4	WET	GI	0,09	0,09	0,12	0,24	0,20	0,14	0,00	0,04	0,00
4	COAST	GI	0,00	0,04	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4	OPEN	GI	0,01	0,03	0,02	0,00	0,01	0,00	0,00	0,00	0,00
4	Total core hab/	GI	0,19	0,15	0,16	0,47	0,39	0,19	0,02	0,12	0,00
4	Corridor	GI	0,11	0,04	0,05	0,09	0,06	0,16	0,00	0,51	0,40
5	ZNIEFF	INV	0,08	0,11	0,10	0,31	0,33	0,06	0,05	0,04	0,00
/	SCAP	PROP	0,14	0,41	0,43	0,21	0,14	0,17	0,77	0,00	0,20
	TOTAL REGION (nb data)		1160	504	122	541	84	63	187	31	5

2.

			Minimal distance of 500m between 100m pixel with at least 1 presence data								
Groupe	PA	classe_UICN	ALYOBS	EPICAL	LISVUL	ICHALP	TRIBLA	PELESC	PELCUL*	BOMVAR*	PELLES*
1	RNN	I_IV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1	SIN_SCL	III	0,04	0,09	0,07	0,01	0,02	0,00	0,21	0,00	0,00
1	RNR_RB_SLit_APB	IV	0,00	0,02	0,01	0,01	0,03	0,00	0,07	0,00	0,00
2	SCEN_PNR	V	0,10	0,33	0,06	0,10	0,08	0,15	0,17	0,14	0,00
3	N2000	INT	0,07	0,12	0,36	0,13	0,11	0,06	0,24	0,00	0,25
4	BOCAGE	GI	0,12	0,02	0,06	0,14	0,16	0,09	0,03	0,00	0,00
4	WOOD	GI	0,07	0,07	0,02	0,23	0,11	0,06	0,00	0,00	0,00
4	WET	GI	0,09	0,12	0,13	0,15	0,17	0,13	0,00	0,00	0,00
4	COAST	GI	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4	OPEN	GI	0,01	0,02	0,02	0,00	0,02	0,00	0,00	0,00	0,00
4	Total core hab/	GI	0,21	0,17	0,19	0,39	0,38	0,19	0,03	0,00	0,00
4	Corridor	GI	0,10	0,04	0,07	0,11	0,08	0,17	0,00	0,14	0,50
5	ZNIEFF	INV	0,09	0,13	0,11	0,25	0,27	0,06	0,07	0,14	0,00
/	SCAP	PROP	0,14	0,37	0,38	0,13	0,16	0,17	0,76	0,00	0,25
	TOTAL REGION (nb data)		693	211	90	272	63	54	29	7	4

Appendix 2: studied conservation network in the region Pays-de-la-Loire

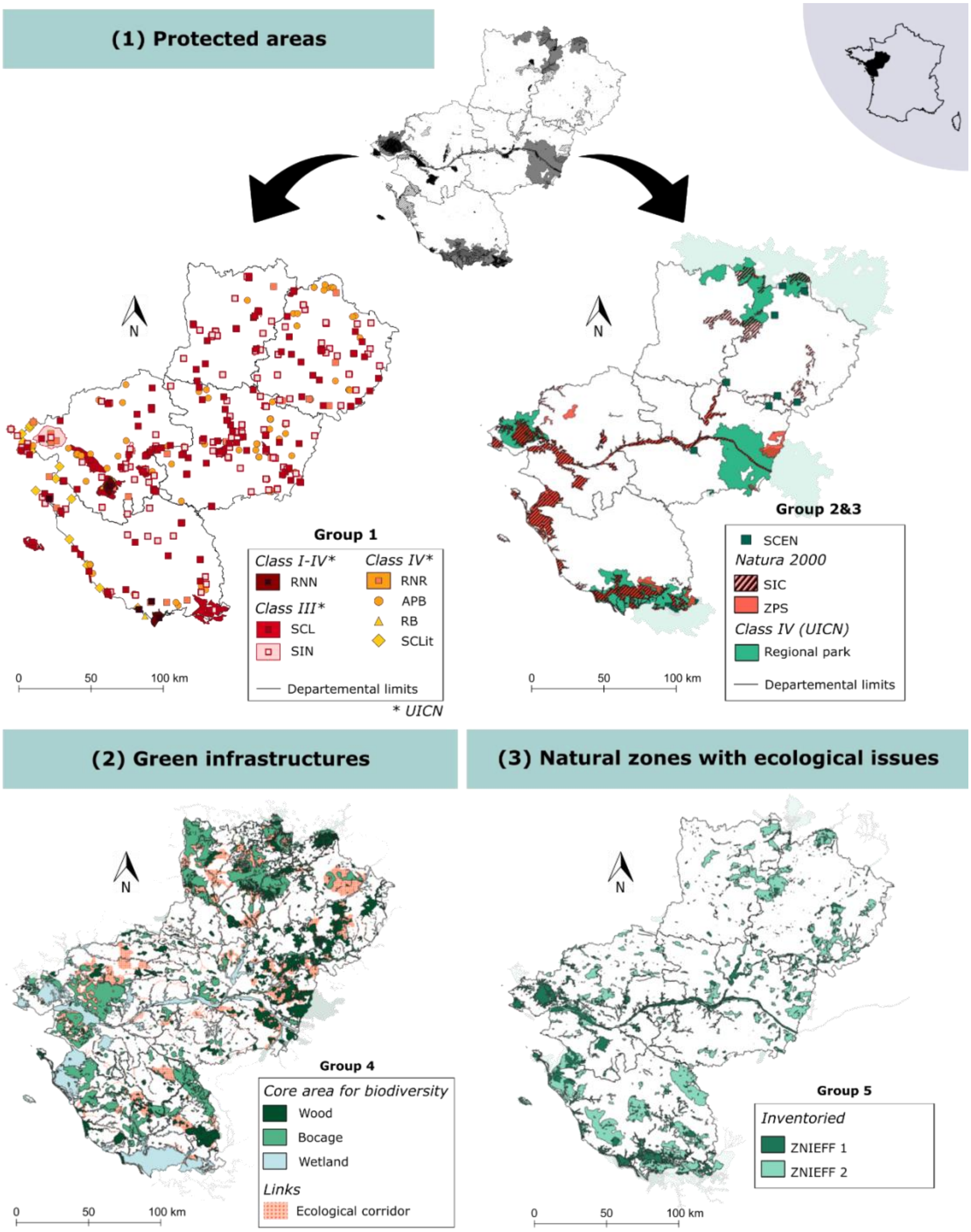


Figure A2.1 -Existing conservation area network including protected area (PA), Green infrastructure (GI) and surveyed natural zones with ecological value (INV). Groups and categories are detailed Table 2. The GI named COAST and OPEN was not mapped because of their low surface and a secondary ecological interest for conservation of studied species.

Appendix 3: Method selection for Stacking-SDM

Table A3.1 - Accuracy of stacking species distribution models using different stacking methods. Results obtain with 100 permutations. Bold values show selected model and coloured cells show model uses for further analysis.

					9 studied species		Forest species		Generalist species	
Stacking method	**Initiale resolution**	**Finale resolution**	**Aggregation technique**	**Assemblage**	**R^2**	**cAUC**	**R^2**	**cAUC**	**R^2**	**cAUC**
pixels addition without aggregation	100m	100m	/	sum continuous SDM (pSSDM)	0.22	0.76	0.12	0.69	0.24	0.76
	100m	100m	/	sum binary SDM (bSSDM)	0.18	0.75	0.01	0.57	0.07	0.68
reducing resolution: pixels aggregation before addition	100m	500m	max value	sum continuous SDM (pSSDM)	**0.31**	**0.86**	**0.23**	**0.76**	**0.30**	**0.86**
	100m	500m	mean value	sum continuous SDM (pSSDM)	0.29	0.84	**0.23**	**0.76**	0.29	0.83

Appendix 4: Friction values attribution

Table A4.1 - Friction values based on **literature and expert opinions**

	Land cover	Description	Friction cost
1. Barrier without pass	Railway for high-speed train	Pixel with a railway for high-speed train	200
	Stream>50 m	Pixel with a river larger than 50 m	200
	Topographic barriers (Slope>45%)	Pixel with high slope, mainly rare cliffs and gorges	200
	Urban (high density)	Pixel with 100% of dense urban area	200
	Primary road (highway and dual carriageways)	Pixel with a high traffic road as highway and dual carriageways	200
	Railway	Pixel with a railway	100
2. Linear barrier with underway pass	Underway pass:		
	secondary road underpass		60
	Pipe		60
	Stream		10
	Path/track		50
	Wildlife bridges		20
	Viaduc		1-20
3. Presence of pond/lake If not -> 4	Pond:		
	+wood>50%	Pixel with at least 1 pond and more than 50% of woods	1
	+wood20-50%	Pixel with at least 1 pond and small amount of woods	2
	+hedgerow	Pixel with at least 1 pond and 50 m hedgerows	5
	+meadow	Pixel with at least 1 pond, no tree but more than 50% of meadow	10
	+culture 100%	Pixel with at least 1 pond, no tree, in a 75% crop context	20
	+urban	Pixel with at least 1 pond, no tree, in a 100% urban context	40
4. Presence of stream If not -> 5	Stream <50 m:		
	+wood	Pixel with a small stream and at least 50% of wood	1
	+hedgerow	Pixel with a small stream and at least 50 m of hedgerows	2
	Wood<50 and/or Hedgerow<50 and meadow	Pixel with a small stream and few trees in meadow context (>50%)	2
	no tree (nt) + meadow	Pixel with a small stream and no tree	5
	+nt+crop 100%	Pixel with a small stream and no tree in crop context (>50%)	20
	+urban dense	Pixel with a small stream and no tree in urban context (>50%)	30
5. other class (no stream and no pond)	Path with hedgerows (ditches)	Pixel with a path with at least 1 side with hedgerow	5
	Path without trees (ditches) + non urban	Pixel with a path in a non-urban open area	10
	Riparian forest	Pixel with a riparian forest (75%)	2
	Deciduous and mixed wood	Pixel with more 75% of deciduous and or mixed wood	5
	Evergreen forest	Pixel with more 75% of evergreen wood	5
	Meadow	Pixel with more than 50% of meadow	15
	Meadow + wood	Pixel with more than 50% of meadow and small wood	10
	Meadow in high MPH (humidity index)	Pixel with more than 50% of Wet meadow (MPH>=1)	10
	Meadow in high MPH (humidity index) + hedgerow or shrubs	Wet meadow (MPH>=1) with at least 50 m hedgerow and/or shrubs	5
	Meadow in sandy soil (>50%)	Pixel with more than 50% of meadow aver sandy soil	20
	Shrubs	Pixel with more 75% of shrubs	20
	Stream from 15 m to 50 m	Pixel with a stream large from 15 to 50	50
	Crop 100%	Pixel with 100% of crops	50
	Crop + urban 100%	Pixel with 100% of crop/urban	20
	Secondary roads	Pixel with a secondary road	50
	Urban low density (no farm)	Pixel with 100% of low dense urban area (houses + gardens)	50
Un classed pixels (<5%)			20

Appendix 5 – Confidence maps and sensitivity to thresholds selection

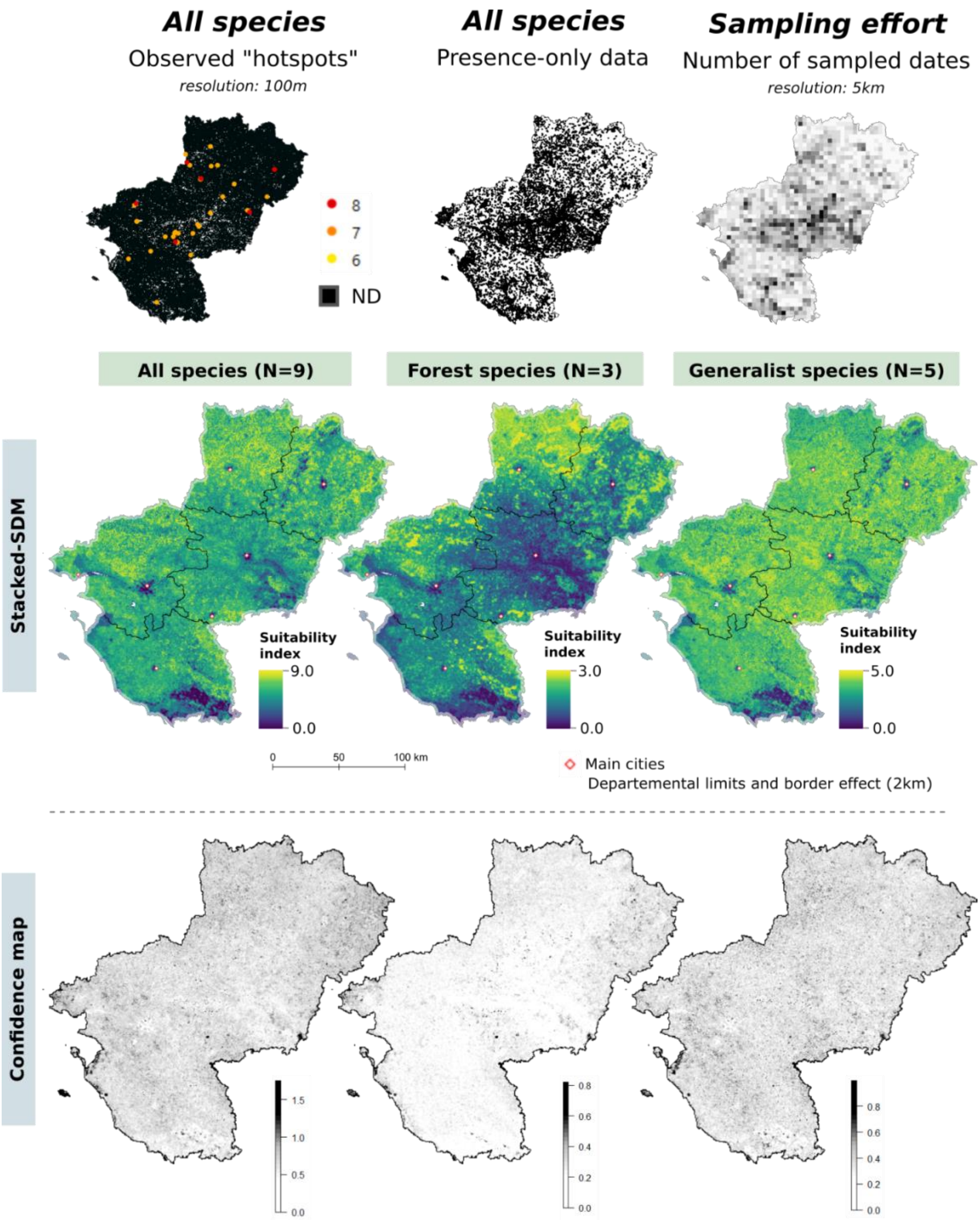


Figure A5.1 - Suitability maps from stacking species distribution models (SSDM) and associate confidence maps. Confidence maps are the sum of individual species standard deviation map obtained by Matutini et al. 2021. Map resolution is 100m

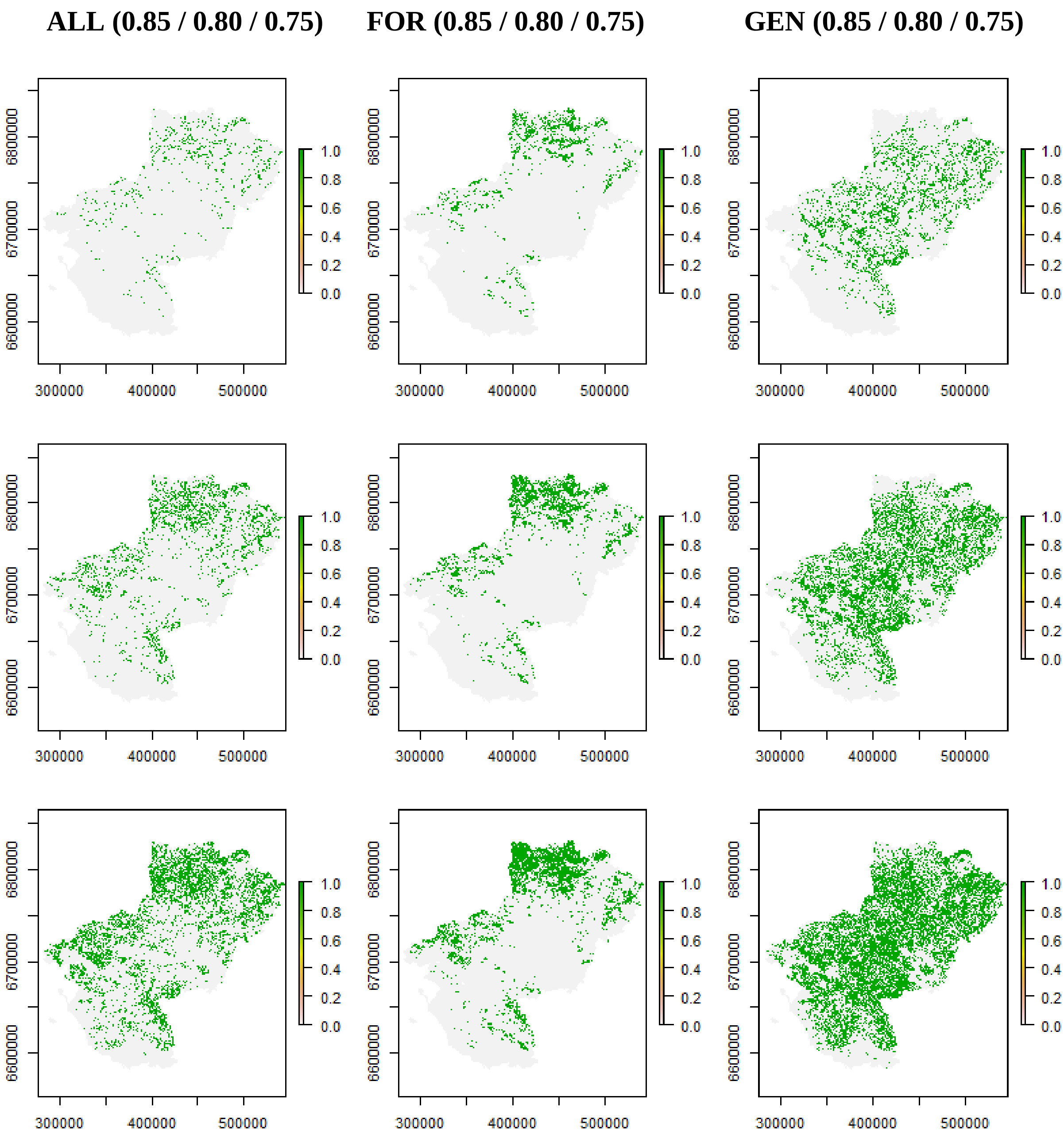


Figure A5.2 - Maps sensitivity to different thresholds selection. Left to right (species group) : ALL, FOR and GEN ; up to down (threshold value) : 0.85, 0.80 and 0.75

Appendix 6 – SCAP and future protected area projects

The SCAP (national strategy for the creation of protected areas) was set up in 2007 and aims to strengthen the existing network by creating new protected areas to reach 2% of the PA territory. On a regional scale, these sites were defined using Atlas biological data available on the territory for 121 priority species, including 3 amphibians. In total, 174 sites were defined and 35 sites were selected in 2020 and are awaiting validation: 18 sites whose protection and / or management is to be reinforced (GR 18) as a priority by 2023, and 17 for 2030 (GR 17).

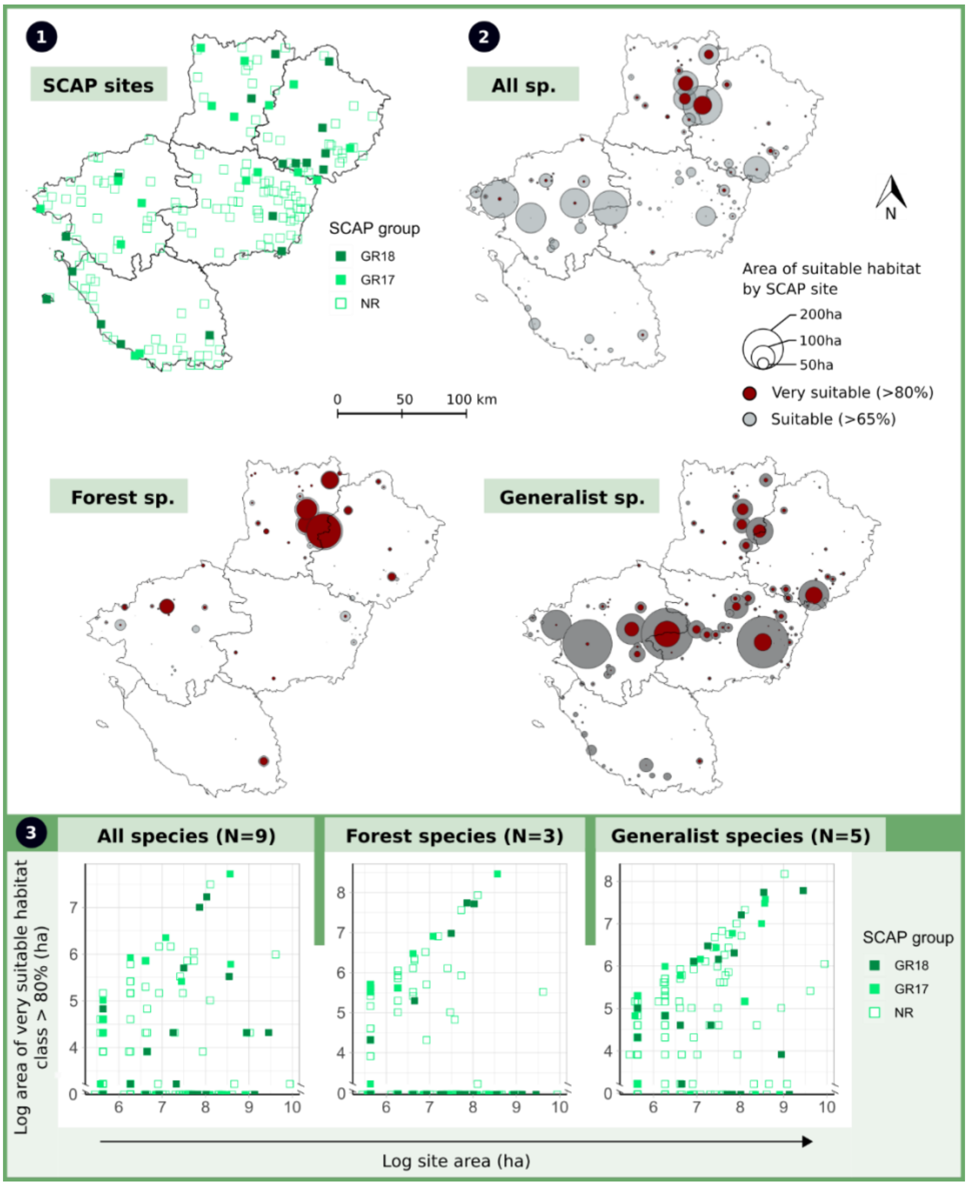


Figure A6.1 - Proportion of potential high suitable habitats for nine studied amphibian species sites proposed as future protected area according to SCAP strategy.