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Maps of conservation and restoration value for corridors under different scenarios

Jeremy Dertien, Diogo Alagador, Tom Hackbarth, Louise O'Connor, Peter Verburg, Piero Visconti, Néstor Fernández

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Dynamics of Pan-European Connectivity Under Future Scenarios

D6.3 Maps of conservation and restoration value for corridors under different scenarios

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Deliverable description	This dataset and report are a product of task 6.4. We used the NFF scenarios approach and maps (WP5) to project the impacts of future land-use and climate on the structural and functional connectivity of the network (T6.3). Using the same graph-based approaches as in T6.3 we quantify changes in connectivity metrics that may result from the modification of resistance surfaces (T6.3) and as a result of climate and land-use changes. Considering an optimized distribution of TEN-N nodes (WP7) and scenarios of land-use change (WP5), we estimate the conservation value, connectivity bottlenecks, and risks, associated with different ecological corridors, while highlighting the restoration potential for enhancing connectivity in TEN-N.
Keywords	Connectivity conservation, ecological corridors, structural and functional connectivity, Omniscape, conservation planning, Graph Theory, Circuit Theory, Shared Socioeconomic Pathways (SSP), land-use change, Nature Futures Framework

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Abbreviations

dPC	Change in the Probability of Connectivity
EU	European Union
MS	Member State
NFF	Nature Futures Framework
NRR	Nature Restoration Regulation
OSM	Open Street Map
PA	Protected Area
PC	Probability of Connectivity
SDM	Species Distribution Model
SSP	Shared Socioeconomic Pathway
TEN-N	Trans-European Nature Network
WP	Work Package
WDPA	World Database of Protected Areas

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1. Introduction

The increasing global awareness of improving ecological connectivity has developed from collections of local and regional conservation projects focused on the maintenance of individual charismatic species to international spatial planning exercises aimed at global biodiversity conservation (Belote et al., 2020; Crooks et al., 2011; Santini et al., 2016). This expansion of attention has meant that the protection and restoration of ecological connectivity is increasingly incorporated in transportation, settlement and protected area planning (Beger et al., 2022; Hilty et al., 2020; Lynch, 2019). However, despite its widening inclusion in planning and policy initiatives, there is relatively limited on-the-ground implementation (Moreira et al. 2024). The inclusion of connectivity concerns and goals into these broader national and international plans also points to the need for a greater detailed understanding of where ecological connectivity is most likely to occur under future environmental change, where it is at risk and being highly constrained (i.e., a bottleneck) and where it is already being blocked.

With ever dynamic anthropogenic global change of land, oceans and climate comes the need for the incorporation of likely future conditions into ecological connectivity models and understanding. The global alteration of land uses by humans is the driving force for the fragmentation and thus loss of landscape connectivity, but the threat of increasing climate change adds greater uncertainty around where conservation and restoration action should take place (Morelli et al., 2017; Nuñez et al., 2013; Schloss et al., 2022). Therefore, as many countries plan to expand the overall protected area network in the European Union and globally, understanding the most efficient locations for connectivity conservation and recovery must rely on predictions derived both from present conditions and from future land use and climate projections.

1.2 Scenario projections and the Nature Futures Framework

The current extent and configuration of the world's protected area networks are likely too constrained and fragmented to adequately meet the needs of species that that are in need of shifting ranges to meet their needed climatic profile (Batllori et al., 2017; Parks et al., 2023). Projecting the future of connectivity is difficult, however, since models for ecological connectivity, functional connectivity especially, often rely upon current habitat distribution and land cover data, making the identification of bottlenecks and other priority corridors naturally biased towards past legacies and current conditions. Planning for future landscape conditions allows for expanded predictions on potential land cover configurations and species distributions. Scenarios of future land cover/land use based on differing social priorities and trajectories, therefore, make it possible to model how landscapes are likely to have increasing or decreasing fragmentation. This, in turn, enables more effective prioritisation of the conservation of currently threatened ecological corridors and the strategic restoration of habitat in areas where future landscape change is predicted to create opportunities for connectivity, including connections that are not evident under present-day land-use conditions.

The Shared Socioeconomic Pathways (SSPs) are a set of global scenarios developed to explore how differing patterns of socioeconomic development may influence future

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environmental change and human society's capacity to mitigate and adapt to climate change (O'Neill et al., 2014). The SSPs describe alternative futures based on varying assumptions about population growth, economic development, technological progress, governance, and land-use policies as well as different projections of ongoing climate change. This framework has been extensively used to explore plausible biodiversity futures, showing that rates of biodiversity loss due to land-use and climate change will largely depend on the implementation of sustainability policies (Pereira et al., 2024).

For this study, in particular, three SSP land-use scenarios were considered. SSP1 ("Sustainability"), which represents a future characterized by environmental stewardship, efficient resource use, and sustainable land management, considered to result in lower habitat loss and fragmentation. SSP2 ("Middle of the Road") assumes that historical development trends continue with moderate environmental protection and land-use change. Finally, SSP3 ("Regional Rivalry") depicts a fragmented world with limited international cooperation, slower technological development, and increasing pressure on natural ecosystems through agricultural expansion and reduced conservation investment, all which may lead to greater habitat degradation and fragmentation.

While the SSPs primarily describe socioeconomic trajectories and their associated land-use outcomes, they do not explicitly explore alternative societal values toward nature. To address this limitation, the Nature Futures Framework (NFF) was developed with support from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as a complementary scenario framework that places human–nature relationships at the centre of future development pathways. The framework recognizes that sustainable futures can arise from different societal priorities and conceptualizes three broad value perspectives: Nature for Nature (N4N) which prioritizes biodiversity conservation and ecosystem integrity, Nature for Society (N4S) which emphasizes the benefits and services ecosystems provide to people, and Nature as Culture (NaC) which highlights the reciprocal relationships between people, identity, and nature through stewardship and cultural values. The NFF builds upon the SSPs by exploring how different societal value systems can shape biodiversity outcomes under similar socioeconomic conditions (Pereira et al., 2020).

Previous work in the NaturaConnect project has provided extensive and detailed scenario projections on how future climate change and socio-ecological planning and decision-making may shape the spatial distribution of land use across Europe (Venier-Cambron et al., 2025; Hackbarth et al. 2026). This has included, through multiple stakeholder engagements, the construction of new narratives to drive NFF modelling (Fornarini et al., 2024; D'Alessio et al., 2025). This was subsequently implemented into updated NFF scenarios that incorporated both the narratives and other biodiversity spatial inputs from the NaturaConnect consortium, including large mammal connectivity (Venier-Cambron et al., 2025). The approach was further expanded upon through the inclusion of Trans-European Nature Network (TEN-N) protected area expansion scenarios constructed to achieve 30% land protection goals (O'Connor et al. 2026, Deliverable 7.2).

In this study, the three Nature Futures scenarios are implemented using SSP1 as the underlying socioeconomic pathway, which ensures that differences among NFF scenarios arise primarily from alternative conservation priorities rather than contrasting levels of economic development or climate mitigation. This approach allows closer comparison between a sustainability-focused SSP and biodiversity-centred futures that emphasize

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ecosystem protection, ecosystem services, or human–nature relationships. By comparing connectivity patterns across both the SSPs and Nature Futures scenario frameworks, we can evaluate not only how broad socioeconomic change may alter landscape connectivity, but also how different conservation philosophies could influence the long-term persistence and movement of terrestrial vertebrate populations across Europe.

Given the varying and complex narratives simulated through the NFF and SSP scenarios we first sought to evaluate and compare connectivity metrics separately for these two families of scenarios using their own baseline conditions. Then for the identification of restoration and conservation priorities, use all scenarios to prioritize those areas that consistently show high connectivity value despite the future conditions, and which are threatened the most by high landscape resistance. This framework thus allowed us to take into consideration multiple biodiversity-centric pathways while incorporating the potential realities of more a challenging landscape shaped by climate change.

2. Future Continental Connectivity

2.1. Connectivity Methods

2.1.1. Land Use Scenarios

We evaluated landscape connectivity across seven different scenarios, one current baseline land cover for the year 2020 and six future land use scenarios, all of which were projected for the year 2050. The future scenarios included three SSPs: SSP1, SSP2, and SSP3 (Sandström et al., 2023; Tita et al., 2025; Venier-Cambron et al., 2025) and three NFF scenarios based on N4N, N4S, and NaC simulated using the land-system model CLUMondo (Van Asselen and Verburg, 2013). The SSP scenarios varied in their coupling with future climate projections with SSP1 closer to RCP 2.6, SSP2 to RCP 4.5, and SSP3 to RCP7.0. The NFF scenarios followed different simulation strategies. Broadly the N4N scenario had a strong focus on conversion of mixed and mosaic landscapes into single-use systems and had the largest gain in forest-related biodiversity, N4S had a strategy focused on multifunctional landscapes that improved the nature's contribution to people, and NaC focused on strengthening connections between human and natural lands (Hackbarth et al. 2026).

The NFF scenarios were constructed using SSP1 as their underlying socioeconomic and land-use trajectory. Therefore, the SSP1 layer was used as a baseline to compare the different NFF scenarios against one another while the three SSP scenarios were evaluated relative to contemporary land cover conditions. This design separated the effects of contrasting socioeconomic development pathways from the effects of alternative societal values and conservation priorities within an otherwise sustainability-oriented future.

Besides the differences in the stakeholder derived narratives driving the three NFF simulations, these iterations also included spatial prioritization outputs developed by NaturaConnect (Deliverable 7.2). These spatial data constituted the potential expansion of Europe's protected area network to achieve the expanded TEN-N. Therefore, deviations from the SSP1 land use scenario were a combination of the NFF narratives and expanded protected area coverage. Given the complexity in the parameterization of the different land use simulations an absolute perfect comparison between the baseline and future scenarios is

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very difficult, therefore, care should be taken in assessing changes in connectivity solely on the basis of only one difference between land use scenarios. Total difference between scenarios should be considered when inferring causation.

As the purpose of this exercise was to compare how future land use scenarios could influence continental-scale connectivity, connectivity was modelled for a subset of archetypes developed and utilized in the previous NaturaConnect Deliverables 6.1 and 6.2 (Dertien et al., 2025; Moreira et al., 2024). We focused on four terrestrial vertebrate archetypes representing contrasting movement strategies and responses to land use: relatively mobile long distance dispersing bats, large swimming frogs, large terrestrial lizards, and medium-to-large terrestrial mammalian predators (Figure 1).

The seven categorical land cover layers were converted to continuous resistance surfaces by assigning each land-cover class an archetype-specific resistance value. These values were assigned on a relative scale from 1 (lowest resistance) to 1,000 (highest resistance) based on published information on habitat associations, movement ecology, and sensitivity to habitat fragmentation, infrastructure and increasing human settlement (Table A1.1). Low values thus represented land-cover types expected to have high permeability with comparatively little energetic cost or mortality risk, whereas high values represented habitats expected to restrict movement or function as substantial barriers. Values are therefore better interpreted as relative movement costs rather than empirically measured probabilities of movement (Zeller et al., 2012). The resulting design included 28 archetype–scenario combinations (see Annex 1 for resistance values and references).

Figure 1: The four species archetype profiles used for modelling current and future connectivity. Archetype groupings were taken from those utilized in Dertien et al., 2025. Photo used under Creative Commons license 4.0: (bat) "Barbastella barbaselleus" Sylvain Montagner. Photos used under Unsplash license: (frog) Ed van Duijn, (lizard) "Ramarro orientale" Alessia Tomeo, and (lynx) "lynx watching" Kenny Goosen.

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2.1.2. Protected Areas Layer and Node Identification

Protected area (PA) spatial data for Europe is complex given the high-level of overlapping designations (Degulgnet et al., 2017) and heterogeneous human use within PAs. Complexities that we sought to account for were the (1) overlapping of polygons for the same PA space, (2) shared boundaries between larger PAs with multiple smaller PAs and (3) human modification and heterogenous land uses in many of the Natura 2000 sites (Figure A3.1). We included Natura 2000 PAs (EEA 2023) and other nationally-designated PAs from the World Database of Protected Areas (UNEP-WCMC and IUCN 2025). To avoid dissolving the polygons into one giant combination of PAs we chose to iteratively absorb smaller PAs into overlapping or neighbouring larger PAs to produce clusters that can represent the true continuity of protection on the landscape (further details available in Figure A3.1).

2.1.3. Cost Distance and Graph Metrics

We estimated the graph dynamics of PAs and the PA network under future land use with the Probability of Connectivity index (PC) developed by Saura and Rubio (2010) and more recently made available in the “Makurhini” (v.3.0) R package (Godinez-Gomez et al., 2026; Saura and Torné, 2009). For each archetype-scenario combination, we calculated the overall network PC and the contribution of each individual PA node (dPC). The dPC metric estimates the proportional reduction in overall connectivity that would occur if a node and its associated links were removed from the network. This index can be further decomposed into dPC intrapatch, dPC flux, and dPC connector components to evaluate the contributions of habitat area, direct connections, and stepping-stone functionality, respectively.

We identified unique combinations of potentially connected protected areas (PAs) for each archetype. A pair of PAs was considered potentially connected when both areas met the minimum availability threshold and were separated by a distance less than the archetype-specific threshold, as defined in NaturaConnect Deliverable 6.2. (Dertien et al., 2025). The binary suitability surface was used to identify the amount of suitable habitat within each PA for each archetype; the PA suitable habitat area was then used as the node attribute. We then calculated the cumulative cost distance for each pair using the corresponding archetype-scenario resistance raster. This cost distance matrix was then supplied for the calculation of PC and dPC instead of simple Euclidean distances.

Node-level dPC values were calculated for every archetype-scenario. Changes in node importance were then estimated by subtracting the appropriate baseline dPC value from the future value. As noted, the Current land use conditions served as the baseline for SSP1, SSP2, and SSP3, while SSP1 served as the baseline for the three Nature Futures scenarios. Positive changes indicated that a protected area became more important to the future network, whereas negative changes indicated a decline in its contribution. Protected-area changes were subsequently summarized by biogeographical region and within a 50km resolution grid to identify geographic patterns in connectivity gains and losses.

Cost-distance values were further analysed across the archetype-land use scenario combinations to better evaluate the influence of different futures on landscape permeability, using mixed-effects models. We estimated the accumulated cost distance between a pair of PAs divided by the Euclidean distance between those PAs as response variable in these models. This normalization controlled for differences in the physical lengths of corridors and

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threshold distances between archetypes, allowing the response to be interpreted as the average landscape resistance encountered per unit of straight-line distance (see Annex 2 for further details on the cost-distance analyses). Lower normalized cost-distance values represented more permeable landscapes and therefore greater potential functional connectivity, whereas higher values represented increased resistance to movement. Linear mixed models and the estimation of marginal means were completed using the “lme4” and “emmeans” R packages (Bates et al., 2015; Lenth et al. 2026).

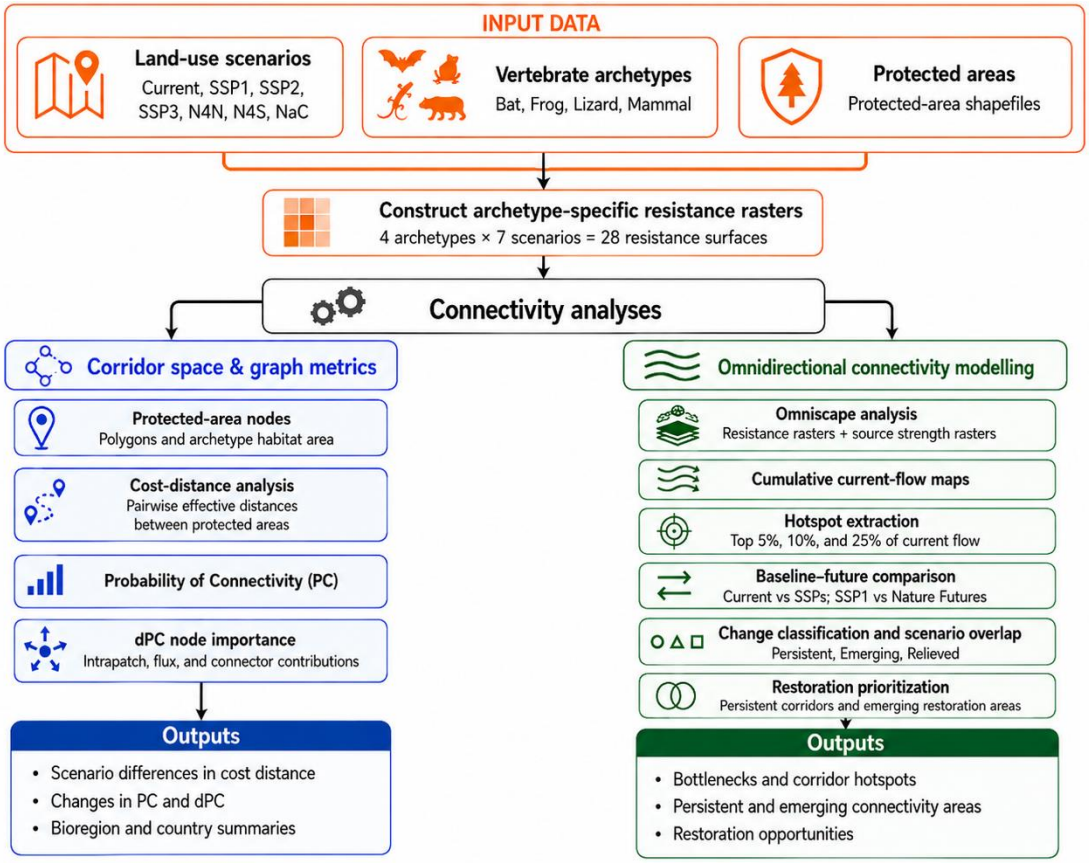

Figure 2: Overview of the connectivity modelling workflow. Having established the archetype-scenario specific resistance rasters we performed two connectivity pathways. First, using graph theory metrics we measured corridor cost distance, overall Probability of Connectivity (PC) for the complete protected area (PA) network and the individual importance of each PA for network connectivity (dPC). Simultaneously we performed Omniscape analyses on all archetype-scenario combinations. From the cumulative current flow output we then derived hotspots for connectivity and used comparisons with baseline land use scenarios to derive key priority areas for conservation and restoration. Workflow image generated using AI.

2.1.4. Omni-directional Connectivity Modelling

We used the Omniscape algorithm to identify connectivity bottlenecks and other key ecological corridors across the continent and to compare changes in those bottlenecks across future scenarios (Landau et al., 2021; McRae et al., 2016, 2008). Omniscape is an omnidirectional circuit-theory model that uses a moving window approach to model random-walk movement simultaneously from multiple pathways regardless of PA presence. Input resistance values restrict electrical current flow, while suitable habitat cells act as potential movement sources.

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This approach is therefore especially useful for identifying landscape bottlenecks and connectivity dynamics.

Omniscape requires two primary inputs: the resistance raster describing the relative difficulty of movement and a source raster describing the relative availability suitable habitat. For each archetype-scenario, the corresponding resistance surface was paired with a source raster derived from the raster of each matching land use scenario. Source cell values were derived using each archetype's profile, areas such as high intensity cropland, grassland and settlement and permanent cropland were excluded as sources for all archetypes. Furthermore, values below 0.25 were excluded to prevent areas of very low suitability from contributing to modelled movement.

As with the threshold distances used for PC and dPC calculation, the radius of the moving window was specified separately for each archetype (Dertien et al., 2025). Threshold distances represented differences in dispersal capacity for bats and mammals, or mean metapopulation size for lizards and frogs. Therefore, interpretation of corridor connections varies temporally between these archetypes.

Omniscape produces a cumulative and a normalized current density raster for every archetype–scenario combination. Cumulative current represented the total potential movement passing through each cell across all moving-window calculations. Normalized current rasters are calculated by dividing cumulative current by potential flow (an additional raster layer estimated for a landscape with uniform resistance), allowing areas where current was concentrated due to landscape resistance to be distinguished from locations receiving high current primarily because of their source density (i.e., related only to the dynamics of pixel values given in the source raster).

2.1.5. Priority and Restoration Identification

We developed a spatial synthesis of the cumulative current-flow surfaces produced by Omniscape to identify areas where landscape connectivity was likely to persist or emerge as important. Cells were classified according to whether they occurred within the 95th, 90th or 75th percentile (i.e., upper 5%, 10%, or 25% of values) of cumulative current values producing 3 different high percentile binary rasters for each archetype-scenario combination (n = 72). These binary hotspot maps were contrasted between baseline and future conditions to classify cells as either persistent connectivity areas, emerging connectivity areas, relieved or lost connectivity areas, or areas that were never classified as a hotspot or bottleneck under either scenario (Table 1). SSP surfaces were compared with Current conditions, while Nature Futures surfaces were compared with SSP1. Turnover rates for each classification were then calculated as the proportion of emerging land area divided by the sum of persistent and emerging area, which provided a standardized metric of spatial variation among scenarios.

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Table 1: Definitions of different classifications used to identify changes in connectivity hotspot or bottleneck priorities between baseline and future land use scenarios. Current land use was used a baseline scenario to compare to SSP1, 2 and 3, while the SSP1 scenario was used to compare with Nature for Nature, Nature for Society and Nature as Culture.

Classification	**Definition**
Persistent	Bottleneck in both the baseline and future scenarios
Emerging	Not a bottleneck in the baseline, but appears as one in the future scenario
Relieved/Lost	Bottleneck in the baseline, but no longer one in the future scenario
Never	Not a bottleneck in either scenario

Persistent areas represented connectivity hotspots whose importance was maintained across the modelled land-use changes. These areas were interpreted as relatively stable components in need of continued conservation and/or increased restoration because high current flow remained concentrated in them despite changes in the surrounding landscape. Emerging areas represented locations that gained relative importance for movement under a future scenario. Importantly, an emerging hotspot does not necessarily indicate that habitat quality improved at that location. Increased current can result from improved landscape permeability that creates a new movement opportunity, deterioration of alternative pathways or relief of other bottlenecks in the system allowing for newer areas to be prioritized. Emerging hotspots were therefore interpreted as areas of increasing future connectivity importance.

To better prioritize restoration areas, we coupled the persistent and emerging hotspots with surrounding resistance values. Resistance values at the corridor pixel level will inherently be around the lowest of the surrounding landscape, therefore, we applied a focal moving window (radius = 10km) to each archetype-scenario resistance raster to estimate the mean resistance surrounding each pixel. This approach thus aimed to quantify the level of human pressure, difficult terrain or other surrounding pressures on connectivity threating a persistent or emerging corridor hotspot. This approach was chosen rather than incorporating other human impact data such as the Human Modification Index since these data would only capture contemporary pressures and not the differences across the different scenarios.

We then calculated the 50th percentile of resistance values within all persistent and emerging pixels to divide the previously identified corridors into either low or high resistance categories. This produced restoration priority maps by archetype where persistent high resistance hotspots followed by emerging high resistance hotspots were identified as the highest priority areas for habitat restoration, respectively. Archetype level priorities were then further cumulated into multi-archetype restoration maps bringing together data from all six future scenarios.

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2.2. Connectivity Results

2.2.1. Cost Distance

We analyzed cumulative cost distance for each of the 28 combinations of archetype and land cover scenarios totaling 63,910 potential corridors. Normalized cost distance (NCD) estimates (cost distance divided by the straight-line distance between two nodes) varied consistently between archetypes with the bat and large mammal archetype having by far the lowest cost distance estimates and the frog archetype exhibiting the highest across land use scenarios (Figure 3). All archetypes were significantly lower in their NCD estimates within the three NFF scenarios and SSP1 while within archetype NCD estimate variance was highest for Current, SSP2 and SSP3 land uses. This was especially evident for mammals and frogs, the latter of which exhibited the highest NCD estimates (Figure 3).

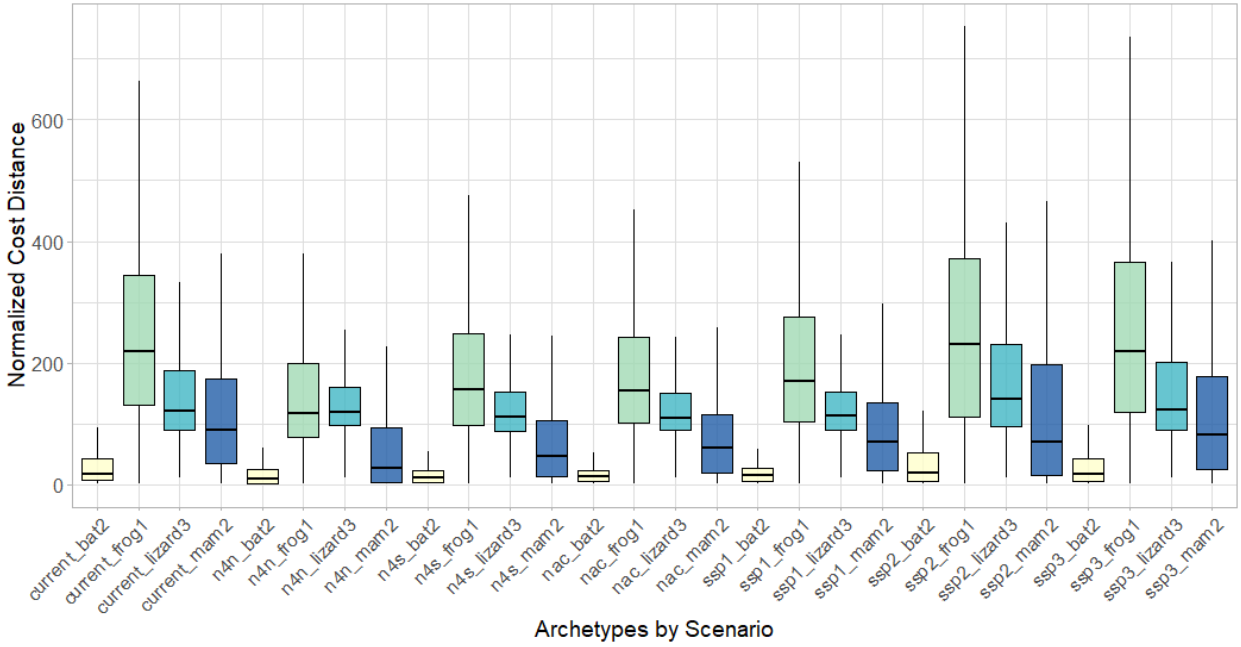

Figure 3: Cost distance estimates for every protected area to protected area connection were normalized with the straight-line Euclidean distance between those protected areas.

Mixed effects models of NCD further elucidated the substantial differences among archetypes and land-use scenarios. The mixed-effects model containing an interaction between land-use scenario and archetype performed better than the additive-only model, demonstrating that the effects of future land-use change differed among the four vertebrate groups. SSP1 conditions reduced NCD relative to Current conditions for every archetype, pointing to increased future landscape permeability under a sustainability scenario. The estimated reduction was greatest for bats, for which cost distance declined by 25.8%, followed by mammals (19.7%), frogs (16.7%), and lizards (12.3%) (Figure 4a). In contrast, a middle-of-the-road scenario SSP2 generally produced the least favourable conditions for landscape movement, with NCD increasing for the four groups, especially for lizards (17.2%) and bats (27.2%). SSP3 showed an increase of cost distance in three of four archetypes with only large carnivores (-2.2%) showing a slight reduction compared to contemporary land use. The magnitude of cost distance increase was less than SSP2, however, despite the SSP3 scenario including a stronger impact from climate change and lower environmental protections.

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Most contrasts between scenarios remained statistically significant following correction for multiple corridor comparisons, indicating that the observed differences represented consistent changes across the protected-area connections rather than isolated changes in a small number of corridors (Figure 4a).

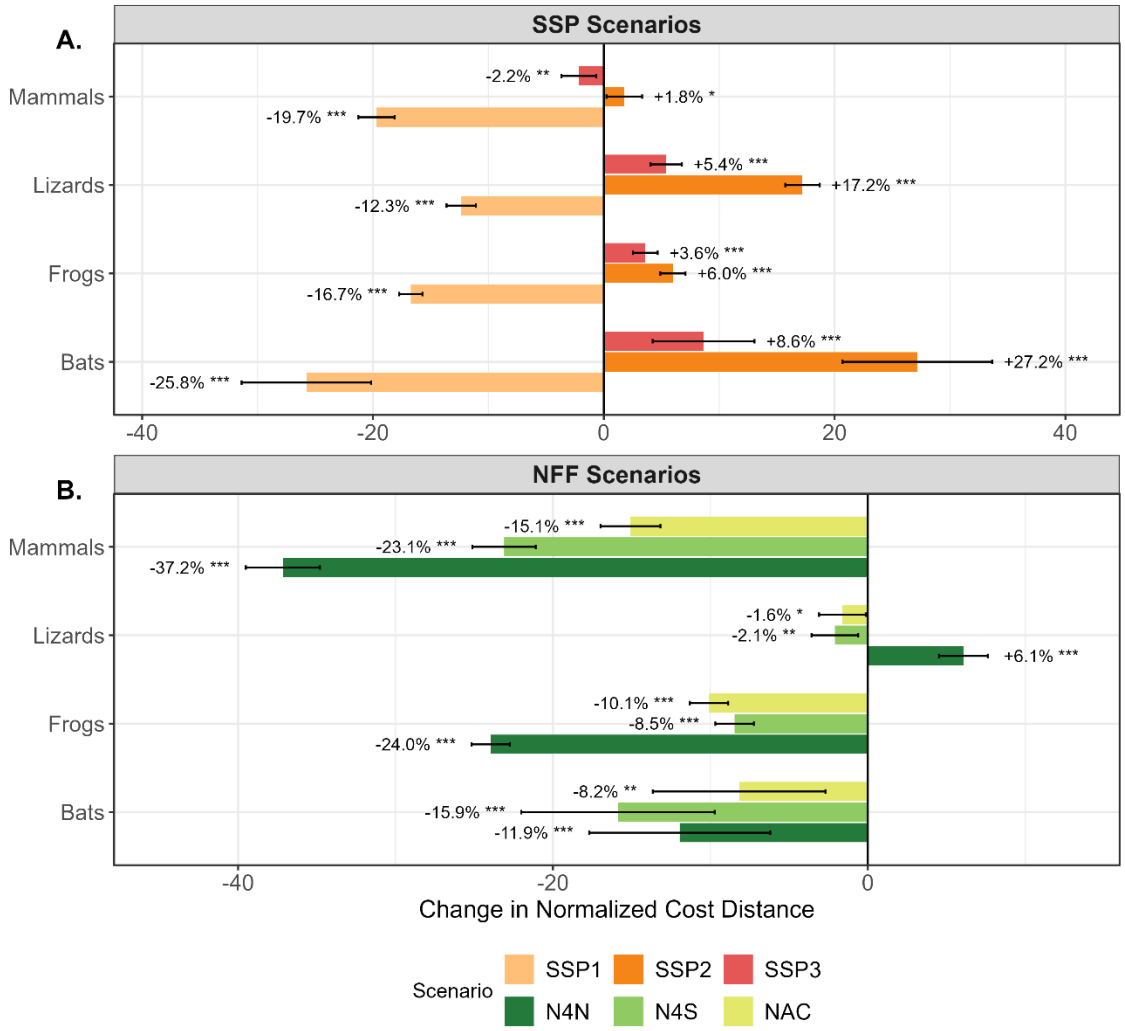

*Figure 4: Mixed effects model results comparing the least-cost distance of corridors in baseline versus future land use scenarios. SSP scenarios are compared with the Current land use (**A**) Nature Futures scenarios are compared with SSP1 (**B**). Negative values indicate reduced movement cost and therefore improved connectivity. Nearly all archetypes showed reduced cumulative cost distance in the Nature Futures scenarios, whereas thee SSP1 scenario showed overall decreased cost distance in comparison to Current land use. Significance classifications: * p < 0.05; ** p < 0.01; *** p < 0.001.*

The NFF scenarios generally reduced movement costs beyond those already achieved under SSP1, with the highest magnitude of decrease happening for mammals, followed by frogs and bats (Figure 4b). Relative to SSP1, estimated NCD for mammals precipitously declined by 37.2% under Nature for Nature, 23.0% under Nature for Society, and 14.3% under Nature as Culture. Nature for Nature also substantially reduced frog NCD while Nature for Society produced the largest improvement for bats, decreasing cost distance by 15.9%. The lizard archetype was considerably less responsive to the Nature Futures scenarios compared with the other three groups. Nature for Society and Nature as Culture produced reductions of only

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2.1% and 1.6%, respectively, while Nature for Nature showed the only increase of NCD across the NFF scenarios.

2.2.2. Continental Graph Metrics

Changes in the Probability of Connectivity (PC) generally corresponded with the overall trends with cost-distance. Scenarios that reduced landscape movement costs tended to increase overall PC by strengthening effective connections among PAs. Conversely, scenarios associated with higher cost distances produced lower PC scores overall.

SSP1 generally improved PC relative to Current land use, whereas SSP2 and SSP3 produced weaker results and, for lizard and bat archetypes, reductions in network connectivity. However, there were not major reductions in overall network PC scores for SSP2 and SSP3 as may have been expected given their projections of increased habitat fragmentation. The NFF scenarios generated the clearest increases in PC, building upon the increases already present in the SSP1 scenario. The mammal archetype showed particularly strong increases with an over doubling of PC for N4N scenario and 51.0 % increase for N4S scenario. Similar to the SSPs, lizard and frog archetypes showed marginal change with lizards showing a 1.1% reduction in the N4N scenario (Figure 5).

Figure 5: The overall network probability of connectivity (PC) increased for most of the scenarios in relation to their baseline conditions. The large carnivore mammal archetype showed by far the greatest increase of PC including over 100% increase in PC from the SSP1 land use to the Nature for Nature (N4N) land use.

Results showed that changes in overall network connectivity were unevenly distributed among protected areas. While dPC is a measure of individual node importance, comparing average change across bioregions can provide better understanding of the spatial distribution of land-

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use effects on priority PAs under different scenarios (Figure 6). Under the N4N and N4S scenarios, protected area nodes within the Continental, Atlantic and to a lesser degree Mediterranean and Alpine increased in connectivity importance. The Continental biogeographic under the N4N scenario especially showed a 17.15% increase in mean dPC. These changes were less evident or in contrast with the NaC scenario which saw larger changes in mean dPC in the Mediterranean but slightly negative change in dPC in the Continental region.

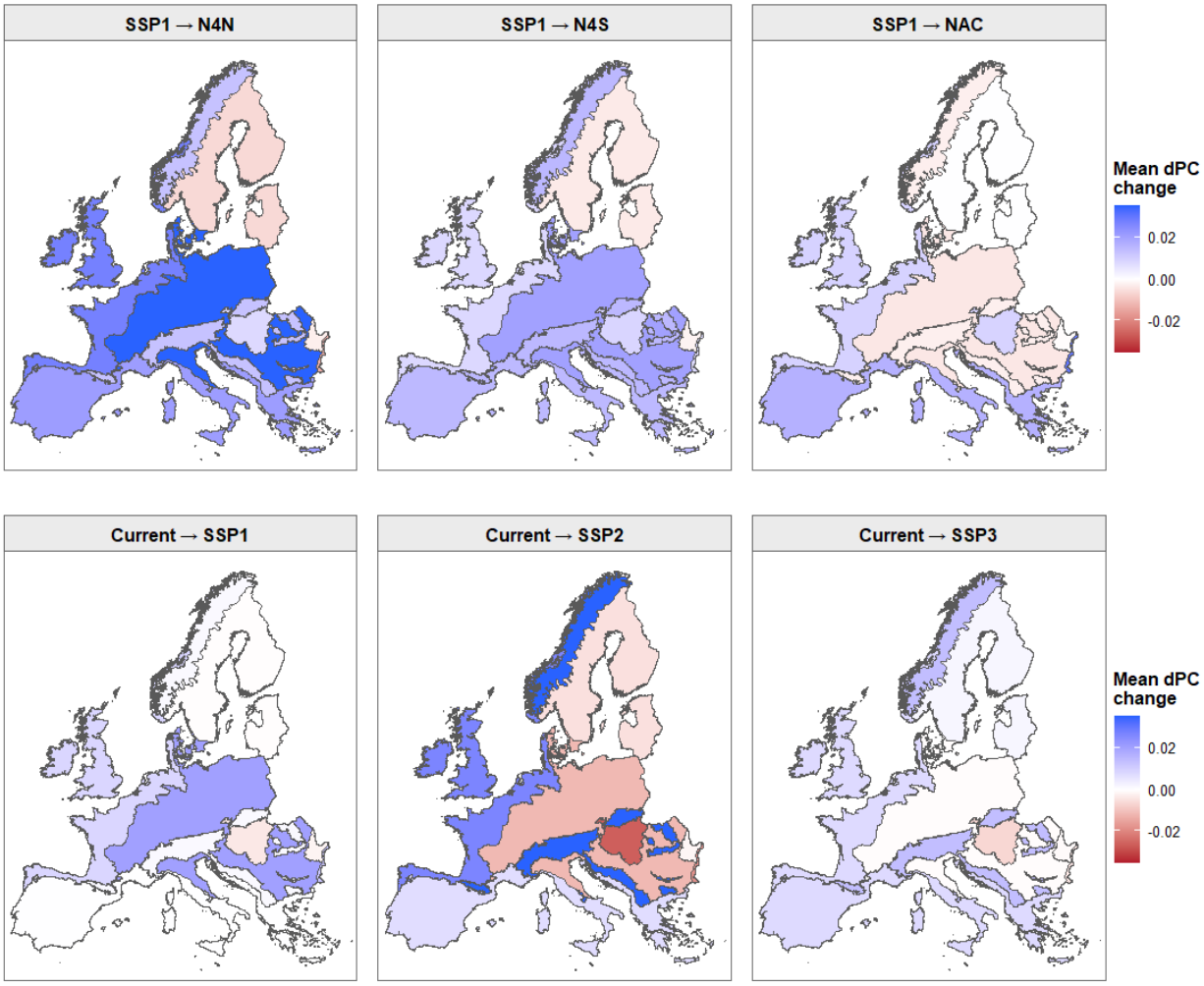

Figure 6: Maps showing spatial dynamics in the mean dPC of protected areas by Europe's major biogeographic regions. The spatial disparity in the change of mean dPC scores shows how protected areas in each bioregion contribute to the overall network of protected areas and hints at the opportunities and risks of land use and climate change on overall connectivity conservation. Across all scenarios and archetypes the mean and median dPC value was 0.093 and 0.005, respectively. We present the change in raw dPC values versus percentage change to reduce bias of smaller biogeographic regions with very low of PA sample sizes.

2.2.3. Connectivity Bottlenecks: Persistence and Turnover

We conducted 28 Omniscape analyses for each of the archetype-scenario combinations and extracted the 75th, 90th and 95th percentiles of the cumulative current density flows. Contrasting the high percentile cumulative current density layers between the NFF scenarios and SSP1 and the different SSP scenarios with contemporary conditions allowed for the identification and classification of persistent and emerging connectivity bottlenecks. Overlaying cumulative

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current density rasters showed that most corridor spaces persisted in both sets of scenarios, but there was still a relatively high spatial turnover especially among the NFF scenarios (Table 2).

Table 2: Persistent and emerging corridor area calculated by taking the 90th percentile cumulative current density of the future and of the baseline scenario. Persistent corridor spaces were those that were maintained in 90th percentile in both scenarios. Emerging corridor spaces appeared only in future scenarios. Turnover was calculated as the emerging corridor area divided by the sum of persistent and emerging.

Land Use	Archetype	Persistent (km²)	Emerging (km²)	Turnover
N4N	Bat	270872	226179	45.50%
N4N	Frog	304836	192215	38.67%
N4N	Lizard	348917	148134	29.80%
N4N	Mammal	277567	219484	44.16%
N4S	Bat	367026	130025	26.16%
N4S	Frog	354349	142702	28.71%
N4S	Lizard	358290	138761	27.92%
N4S	Mammal	379109	117942	23.73%
NaC	Bat	320779	176272	35.46%
NaC	Frog	342198	154853	31.15%
NaC	Lizard	398493	98558	19.83%
NaC	Mammal	328656	168395	33.88%

Land Use	Archetype	Persistent (km²)	Emerging (km²)	Turnover
SSP1	Bat	411434	85617	17.22%
SSP1	Frog	396603	100448	20.21%
SSP1	Lizard	384743	112308	22.59%
SSP1	Mammal	417274	79777	16.05%
SSP2	Bat	304818	192233	38.67%
SSP2	Frog	324335	172716	34.75%
SSP2	Lizard	332424	164627	33.12%
SSP2	Mammal	329219	167832	33.77%
SSP3	Bat	396255	100796	20.28%
SSP3	Frog	427251	69800	14.04%
SSP3	Lizard	411470	85581	17.22%
SSP3	Mammal	413088	83963	16.89%

The N4N scenario showed the highest turnover of bottlenecked pixels ($\hat{x}$ = 39.53%), primarily due to improved habitat conditions reducing the concentration of movement previously identified in SSP1 corridors. Across the NFF scenarios this shift of priorities to emerging corridors resulted from more connected landscape (Table 2 & Figure 7). Other turnover, to a lesser magnitude, was driven by corridors shifting and rerouting as habitat patches or riparian habitat conditions changed. Nature for Society was the most spatially similar in its corridor network with the SSP1 scenario, across the four archetypes. It had an average turnover of

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26.63%, with a mean of approximately 365,000 km² of persistent bottleneck space and 132,000 km² of emerging corridor space.

Persistence to emerging turnover was less pronounced in the SSP1 and SSP3 scenarios as there was more agreement with the contemporary land use scenario on the geographic locations of the bottlenecks. This contrasted with SSP2 which showed much higher turnover ($\hat{x}$ = 35.08%), of bottleneck locations with a mean emerging corridor space of 174,352 km². This turnover partly resulted from the degradation of habitat conditions blocking previous connections. It should be noted that because the same percentile thresholds were used to identify high-current areas in each scenario, persistent and emerging areas summed to approximately 497,000 km² (at the 90th percentile) for each archetype–scenario combination. Turnover consequently represented the proportion of future bottleneck space that did not overlap the total baseline land use bottleneck distribution.

2.2.4. Connectivity Bottlenecks: Restoration Priorities

Further categorization of persistent and emerging connectivity hotspots allowed for increased discernment of connectivity restoration areas. At the individual archetype-level, bat and large carnivore archetypes identified more continuous connections in part due to the extended dispersal ability of the two archetypes. The large carnivore archetype in particular identified the most land area as persistent high resistance hotspots ($\hat{x}$ = 4385.02 km^2; Figure 8) followed by the bat archetype ($\hat{x}$ = 1843.01 km^2). The frog and lizard archetypes, which were more limited in their dispersal distance, highlighted larger clusters of persistent/low resistance habitat with persistent/high resistance areas mostly concentrated on the edges or ecotones of these larger hotspot clusters (Figure A5.3). Persistent high resistance hotspot areas for frogs ($\hat{x}$ = 864.00 km^2) and lizards ($\hat{x}$ = 531.00 km^2) were substantially less than two mammal archetypes. Finally, we combined persistent high resistance and emerging high resistance layers across archetypes, keeping areas that overlapped with two or more archetypes (Figure 9). This resulted in a multi-archetype restoration prioritization that identified priority corridors and edges representing the entire study area.

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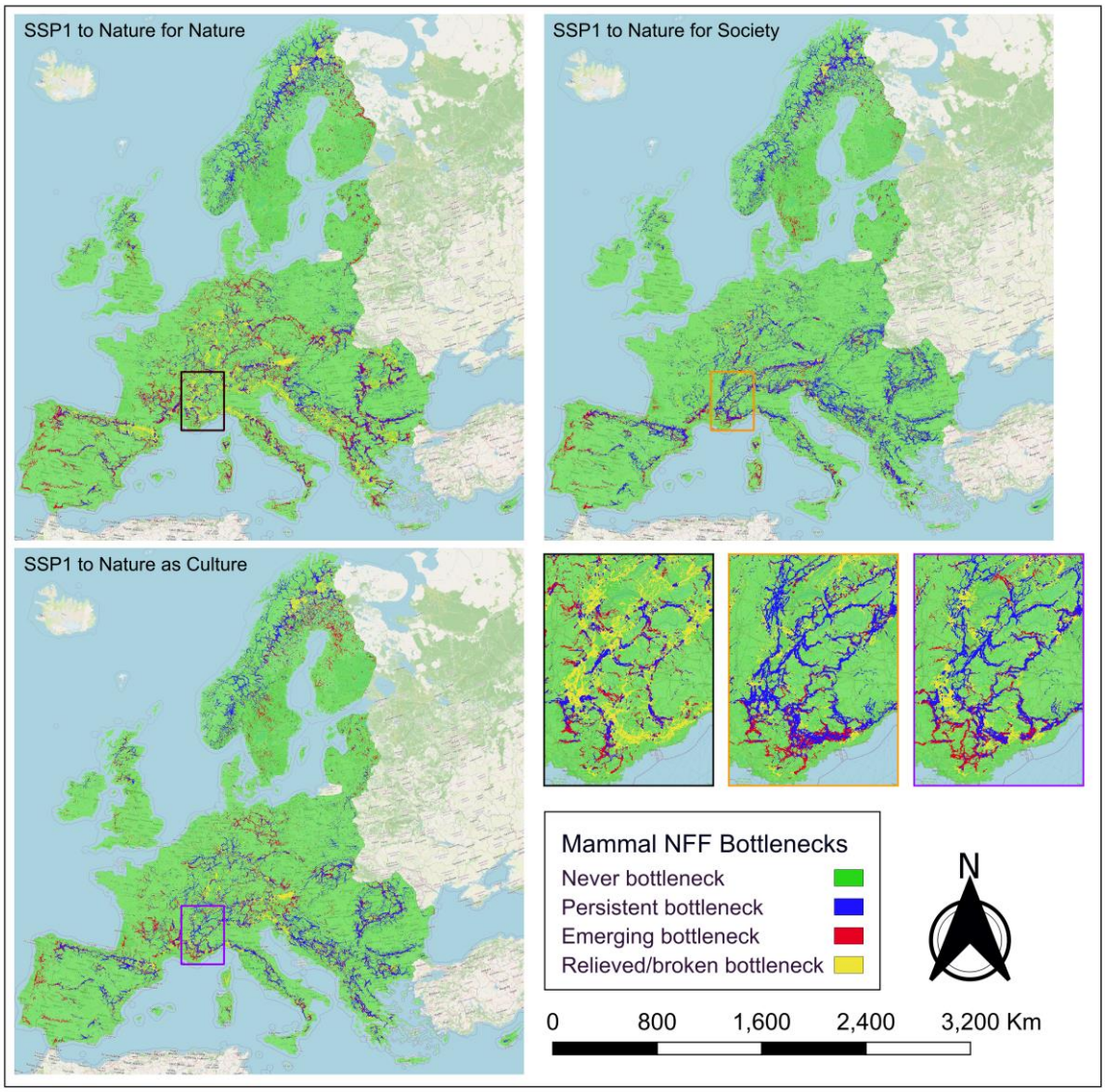

Figure 7: These maps focus on the shifts in key connectivity bottlenecks from a baseline SSP1 scenario to each of the Nature Futures Framework (NFF) scenarios for only the large carnivore ("mammal") archetype. Taking the 90th percentile of the highest current densities identified areas of the highest potential for connectivity bottlenecks. Comparison then of the 90th percentile SSP1 to each of the NFF scenarios highlighted where a key bottleneck persisted, emerged as important within the NFF scenario or was relieved due to a decrease in current density. The Nature for Nature scenario showed by far the most dynamics in the number of relieved bottlenecks as habitat especially forested patches widened relieving pressure on narrower corridors. Zoomed-in extents of the three NFF scenarios provide an example of the difference in one highly important region for ecological connectivity at the confluence of Mediterranean, Alpine, and Continental biogeographic regions. The border color of the zoomed-in extent matches those on their corresponding full extent map.

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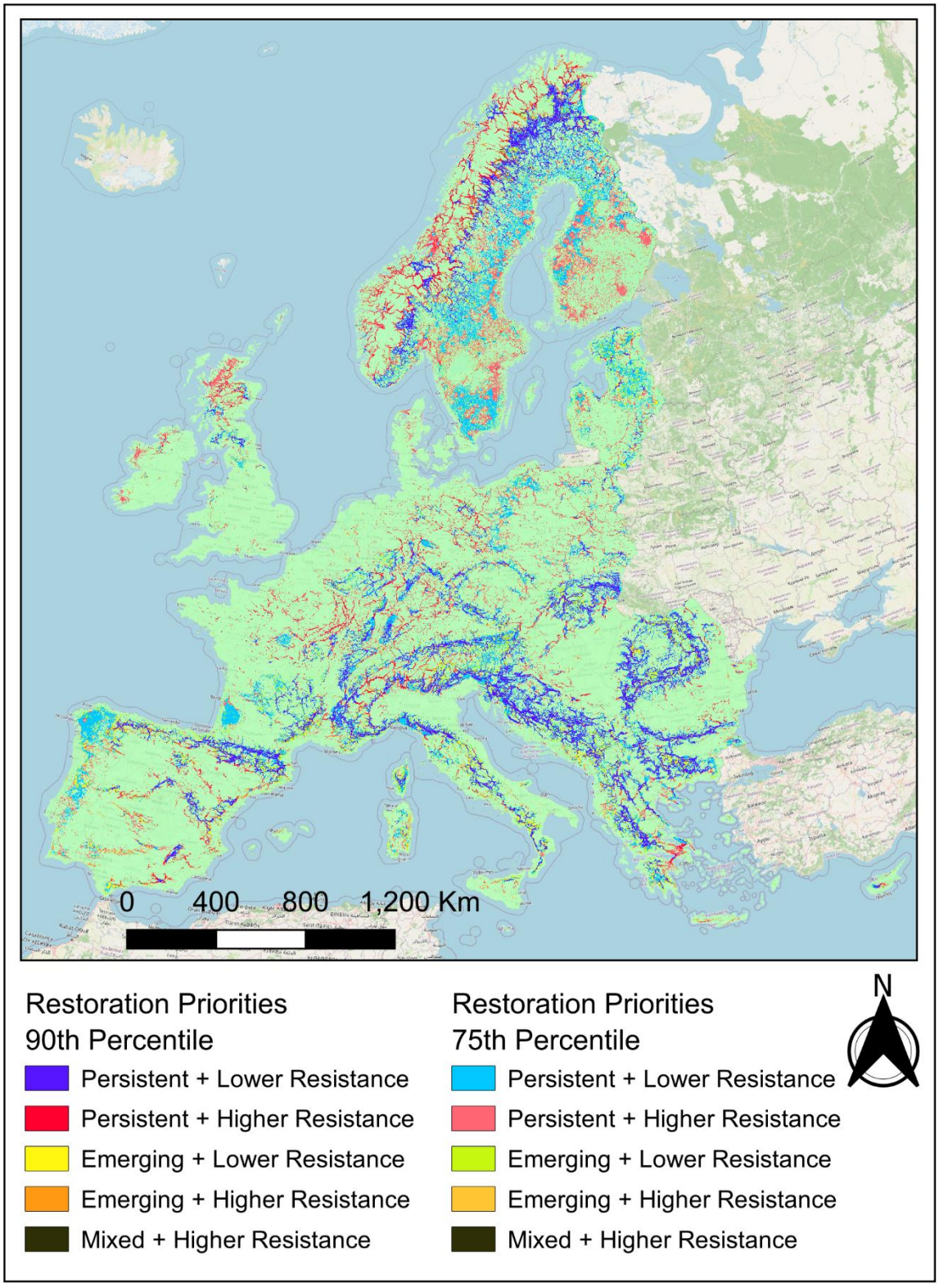

Figure 8: Large carnivore ("mammal") restoration priorities in 75th percentile and 90th percentile categories. Restoration priorities were determined with data from all seven scenarios. A pixel was selected as priority for this map if it appeared in greater than 50% of scenarios as either a persistent or emerging hotspot. Higher or lower resistance groups were determined by using a moving window average of surrounding resistance separating pixels at the 50th percentile of resistance values within persistent or emerging sites.

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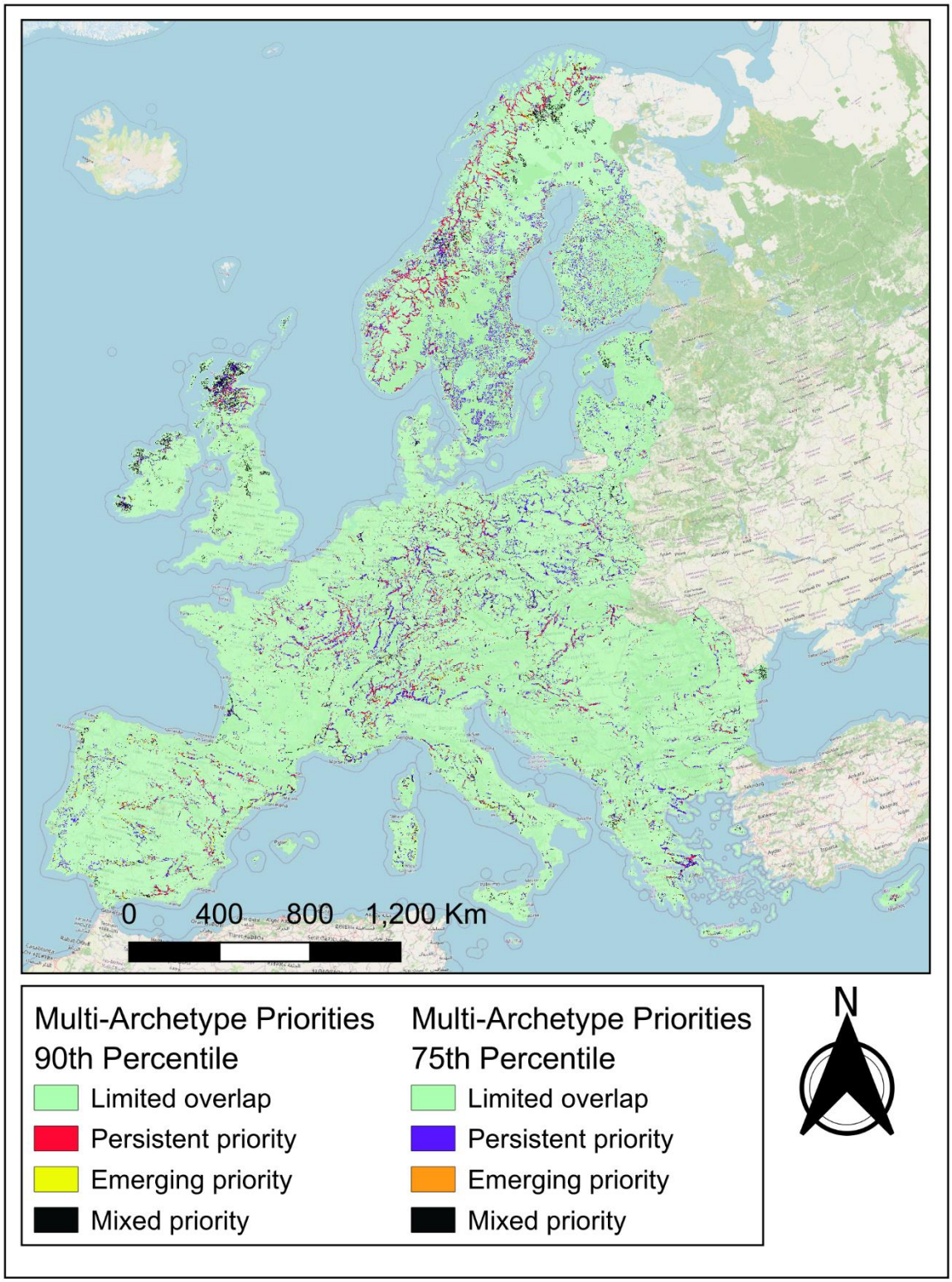

Figure 9: Multi-archetype restoration priorities for high resistance site at two different connectivity percentiles. Persistent and emerging priority pixels are the overlap of 2 or more archetypes matching those categories. The mixed priority category was the conflicting overlap of at least 1 or more persistent and emerging priorities.

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3. Interpretation and Application

3.1. Key Findings

We analysed how different land-use and nature future scenarios influenced spatial priorities of connectivity conservation and restoration. Our results highlight both major persistence of key connectivity areas and differential areas of shifting priorities depending on the future makeup of global climate and European land planning. The two analytical approaches, based on graph and circuit theory, provided distinct but complementary information on vertebrate connectivity. The PC and dPC graph analyses captured the contribution of discrete protected areas and the effective links among them, thereby identifying the overall network resilience to different scenarios and the distribution of protected areas. Omniscape circuit analyses characterised continuous connectivity patterns across the landscape, revealing broad movement zones, alternative pathways, and localized bottlenecks not restricted to any predefined protected area configuration. Together, these approaches allowed future scenarios to be assessed in terms of the importance of the current and future protected-area network and changes in the landscape space supporting movement within and between protected areas.

The NFF scenarios highlighted improvements in landscape connectivity potential especially for the large bat and large mammalian carnivore archetypes. The significant reduction in cost distance within corridors connecting protected areas highlighted that there was much broader improvement in overall landscape permeability under the three biodiversity-centric NFF scenarios. In contrast, the increase of archetype cost distance in SSP2 and SSP3 demonstrated the impact of land-use change patterns that follow “Middle of the Road” and “Regional Rivalry” scenario projections of higher carbon emissions and relaxing environmental governance. Both SSP2 and SSP3 scenarios enhanced the aggregation of high-density urban areas, high-intensity agriculture and high-intensity forestry (Tita et al. 2025). SSP2 in particular resulted in reduced mosaic habitat as compared to the other two SSP projections and showed the highest cost distance increase for all archetypes (Figure 4).

Persistent and emerging bottlenecks demonstrated how consolidated close-to-nature and mixed forest expansion, as well as an expanded TEN-N, may relieve pressures on several key connectivity bottlenecks across Europe (Figure 7). N4N and NaC scenarios especially showed high turnover in the level of emerging corridor spaces (Table 2) indicating shifting priorities to newer emerging corridors made possible through increased protection and habitat restoration. As previously noted, these scenarios had a strong focus on efficiency of land uses and consolidation into single-use land systems following a land sparing approach (N4N) or land sharing with a strong focus on reconnecting human to natural systems (NaC). The N4N scenario added nearly 1 million ha forests of either low or medium management intensity, which could be part of the explanation for the large reduction in cost distance magnitude in large carnivores, frogs and bats (Hackbarth et al. 2026). Simultaneously, the forest expansion and land-use homogenization could explain the modest decrease in landscape permeability for the lizard archetype as these species show preference for more heterogeneous and open vegetation (Figure 4). Overall, our results indicate that any of the three different NFF strategies for future landscape management significantly enhance ecological connections across Europe.

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3.2. Applications

The analysis of connectivity projections provides a rare opportunity to explore how future configurations of a continental-scale landscape could determine important connectivity conservation areas and bottleneck locations. This information is key to assist conservation planning and policy. Projected forest expansions and increases in close-to-nature forest cover are major drivers of connectivity increase across most future land use scenarios. So too was the expansion of forest/shrub mosaic habitats more prevalent in SSP1 and SSP3 which we specified *a priori* to be lower resistance than homogenous croplands or grasslands (Table A1). The reduction of these mosaics under SSP2 and large expansions of arable cropland in the Continental and Pannonian biogeographic regions will potentially drive major barriers to future wildlife movement. This is revealed through a reduction in dPC values for protected areas throughout these two regions, signifying potential degradation in the PA connections (Figure 6).

Our results build on scenario projections determining the spatial configuration of continental land uses, thus, there is inherent uncertainty in interpreting any individual future connectivity scenario as a probable future. However, the scenarios provide a wide range of plausible transitions affecting changes in connectivity, which makes taking information from this dataset, especially maps that consolidate overlapping persistent and emerging corridors, as better sources for on-the-ground application purposes. The resulting maps provide practitioners and policymakers with a valuable large-scale perspective for identifying where local-scale conservation and restoration actions can contribute most effectively to maintaining and enhancing connectivity under environmental change, and for guiding the conservation and restoration of complementary ecological corridors.

A key factor in interpreting these connectivity datasets is to be mindful of how timescales of connectivity vary between the different archetypes. As some of the corridors could be traversed by an individual large carnivore or bat in one day, the same corridor would require the gradual shift of an amphibian or reptile metapopulation over multiple generations. The dispersal distances for the amphibian and reptile archetypes in the study were not much more than the width of an individual pixel (1 km). Therefore, we chose to model potential ecological connections and bottlenecks far beyond the maximum individual dispersal distance for these archetypes to be able to incorporate a wider breadth of species groups in future connectivity projections and thus recommendations. Likewise, we adopted a heuristic approach to modelling the four different archetypes. drawing on natural history data and expert assessment to characterize the relative associations of each archetype with different habitat classes. This was due in part for the versatility this provided for projecting across the continental scale for 25 years into the future and not be hindered or biased by the current species distributions.

Management of future multifunctional corridors must take into consideration varying species-habitat relationships and temporal scales operating on the different archetypes. The establishment of stepping stones for smaller-bodied and limited dispersal species is thus vital to enable the long-term conditions necessary for generational species movement across land-use transitions. The success of a corridor for these species is therefore not just the ability to move through the landscape but to permanently reside and breed within the ecological continuity. This can be achieved for ectothermic (i.e., cold-blooded) species through the restoration of multiple habitat stepping stones to allow for successful survival and

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reproduction. This is particularly necessary if corridors are to assist with climate change adaptation or are in highly modified or arid regions.

3.3. Utilization of Datasets

The different connectivity data products derived from future land use scenarios can be used by practitioners and policymakers separately or congruently when making conservation and spatial planning decisions. The use of specialized GIS and spatial analysis software is necessary to exploit the full potential of the data produced; however, Omniscape connectivity maps can be visualized in the EBV Data Portal:

- Omniscape cumulative current results allow for identifying regional areas of high connectivity that potentially require specific examination and, eventually, protection. The normalized current rasters can directly assist in identifying and prioritizing strong movement bottlenecks. Normalized values >1.7 are generally seen as the highest priority or "channelized" group. Also, these results are not influenced by protected area distribution so both cumulative and normalized results can assist with inter and intra protected area planning.
- Change in the probability of connectivity (*dPC*) metrics can be isolated for each of the protected areas and protected area groups, as well as the changes in *dPC* between baseline and future scenarios. This approach, for example, could be applied for smaller sub-regions to help ranking local protected areas and for supporting conservation planning at multiple scales.
- Persistence/Emerging connectivity and restoration maps can be directly applied to inform management and land use designations. Areas where persistent bottlenecks overlap for multiple archetypes or across multiple scenarios are a higher priority for conservation. Local information should be used when making these decisions, with the addition of these future connectivity data, thereby harnessing the complementarity between large-scale and local-scale perspectives.

Connectivity maps and associated statistics from this analysis can offer extensive insights for practitioners and policymakers as they implement measures to conserve and restore terrestrial connectivity. With this collection of future scenario connectivity maps and spatial data, along with functional and structural terrestrial and freshwater connectivity from previous deliverables we, have provided an expansive analysis of the current and future state of ecological connectivity in the EU and beyond. Altogether these represent a unique collection of connectivity data for supporting implementation of protected area and restoration policies. Below are examples of stakeholder groups and potential means in which they could utilise these results:

National authorities – individual scenario cumulative current or normalized density maps can assist national-level authorities in long-term conservation planning especially in regard to meeting goals for the TEN-N and the goals of the Nature Restoration Regulation (NRR). Scenario-based connectivity results, coupled with comprehensive current-state connectivity datasets (Dertien et al. 2025), are valuable resources for identifying key conservation and restoration areas to best meet 30% protection goals.

Protected area managers – the connectivity results including inside protected areas boundaries. Protected area managers can use these maps to prioritize important areas within their PA or determine which areas may be the most multifunctional for protecting long-term

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connectivity for the most species. These maps could also be useful, in combination with other factors, in determining areas of that may need stricter protection.

Regional and local authorities – similar to the analyses on present-day connectivity, these future scenario results are especially useful for regional spatial planning including for transportation, green and blue infrastructure placement, energy production and urban expansion. These results can assist with planning wildlife passages, trans-national corridor conservation, expansion of protected areas in and around urban areas, potential expansion areas for protected species

Non-governmental Organisations (NGOs) – organisations with a focus on large landscape conservation or conservation science can use these data to assist with compliance monitoring, systematic conservation planning, engaging with policymakers, rewilding management plans and decisions surrounding land acquisition. For all NGOs these results can be used for justifications in grant-writing, when acquiring additional resources or identifying future areas to concentrate initiatives.

Private land use sector – future planning, sound investments and the minimization of risk is vital for private sector operations. Future scenario connectivity data could assist those in the private sector when joining the burgeoning markets surrounding conservation investments and nature credits. Scenario projections can assist the private sector in the production of products that carry a green premium or avoiding major land alteration where the impact on biodiversity could be costly.

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5. Data availability

Omniscape data including cumulative and normalized connectivity rasters will available and visualizable on the EBV portal (link).

All data will be made available on the Zenodo NaturaConnect community page (link). In the immediate short-term data access is restricted and only available on request.

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6. Annexes

Annex 1: Resistance and Source Values for Connectivity Models

***Table A1.1**. Resistance values assigned to the four species archetype groups. Bats were assigned the lowest overall resistance values given their flight ability. The frog archetype was given very high values for human landscapes and other areas that were a major threat of desiccation. Though permanent water is highly important for frogs, at the 1km2 scale of our land cover rasters this included large lakes and other areas of low habitat suitability for frogs. The lizard archetype was similar in human settlement and agriculture, with lower resistance in mosaic and other potentially more arid landscapes.*

ID	Land Cover Class	Bat	Frog	Lizard	Mammal
0	Low intensity settlement	220	500	350	250
1	Medium intensity settlement	450	850	700	650
2	High intensity settlement	900	1000	1000	1000
3	Wetlands	70	1	750	250
4	Forest/shrub + cropland mosaic	25	450	120	360
5	Forest/shrub + grassland mosaic	10	250	60	150
6	Low intensity arable cropland	100	300	300	270
7	Medium intensity arable cropland	280	600	600	480
8	High intensity arable cropland	600	900	850	700
9	Low intensity grassland	20	350	200	150
10	Medium intensity grassland	120	600	450	350
11	High intensity grassland	240	850	650	600
12	Permanent cropland	450	900	800	700
13	Primary-close to nature forest	1	60	100	50
14	Combined objective forest	20	100	200	150
15	Intensive-very intensive forest	100	350	300	250
16	Permanent water/snowpack	250	700	1000	1000
17	Bare rock and shrub	300	800	10	600

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***Table A1.2**. Source values assigned to the different land use/land cover classes utilized in the Omniscape analysis at 1km resolution. High source values were given to habitats that were more likely to maintain breeding or shelter habitat for the different archetypes. Moderate levels were given to more mosaic habitats that had the potential to maintain partial habitat areas. Low to zero source value was given to high intensity settlement, grassland and permanent cropland.*

ID	Land Cover Class	Bat	Frog	Lizard	Mammal
0	Low intensity settlement	0.30	0.30	0.30	0.30
1	Medium intensity settlement	0.20	0.00	0.20	0.00
2	High intensity settlement	0.00	0.00	0.00	0.00
3	Wetlands	0.80	1.00	0.20	0.70
4	Forest/shrub and cropland mosaic	0.50	0.40	0.40	0.50
5	Forest/shrub and grassland mosaic	0.65	0.50	0.65	0.65
6	Low intensity arable cropland	0.50	0.40	0.50	0.50
7	Medium intensity arable cropland	0.30	0.00	0.30	0.30
8	High intensity arable cropland	0.00	0.00	0.00	0.00
9	Low intensity grassland	0.50	0.40	0.40	0.50
10	Medium intensity grassland	0.00	0.00	0.27	0.27
11	High intensity grassland	0.00	0.00	0.00	0.00
12	Permanent cropland	0.00	0.00	0.00	0.30
13	Primary-close to nature forest	0.95	0.95	0.95	0.95
14	Combined objective forest	0.90	0.90	0.90	0.90
15	Intensive-very intensive forest	0.75	0.60	0.70	0.75
16	Permanent water/snowpack	0.00	0.00	0.00	0.00
17	Bare rock and shrub	0.40	0.00	0.40	0.40

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***Table A1.3**. Literature referenced during the construction of resistance source values.*

Archetype	Reference	DOI or ISBN
Bat	Altringham, J.D. 2011. Bats: From Evolution to Conservation, 2nd ed. Oxford University Press.	9780199207121
Large Carnivore / Mammal	Boitani, L., & Powell, R.A. (eds.). 2012. Carnivore Ecology and Conservation: A Handbook of Techniques. Oxford University Press.	978-0-19-955852-0
Lizard	Bowles, P., Doronin, I.V., Carretero, M.A., et al. (2025). Measuring the Pulse of European Biodiversity: European Red List of Reptiles. Brussels, Belgium. European Commission.	https://doi.org/10.2779/5108
Bat	Browning, E., Barlow, K.E., Burns, F., Hawkins, C., & Boughey, K. 2021. Drivers of European bat population change: a review reveals evidence gaps. Mammal Review, 51, 353–368.	https://doi.org/10.1111/mam.12239
Large Carnivore/ Mammal	Chapron, G., Kaczensky, P., Linnell, J.D.C., et al. 2014. Recovery of large carnivores in Europe's modern human-dominated landscapes. Science, 346, 1517–1519.	10.1126/science.125755
Large Carnivore / Mammal	Cimatti, M., Ranc, N., Benítez-López, A., et al. (2021). Large carnivore expansion in Europe is associated with human population density and land cover changes. Diversity and Distributions, 27, 602–617.	https://doi.org/10.1111/ddi.13219
Large Carnivore / Mammal	Cretois, B., Linnell, J.D.C., Van Moorter, B., Kaczensky, P., Nilsen, E.B., Parada, J., & Rød, J.K. 2021. Coexistence of large mammals and humans is possible in Europe's anthropogenic landscapes. iScience, 24, 103083.	10.1016/j.isci.2021.103083
Frog	Covarrubias, S., González, C., & Gutiérrez-Rodríguez, C. 2021. Effects of natural and anthropogenic features on functional connectivity of anurans: a review of landscape genetics studies. Journal of Zoology, 313, 159–171.	https://doi.org/10.1111/jzo.12851
Frog	Cushman, S.A. 2006. Effects of habitat loss and fragmentation on amphibians: A review and prospectus. Biological Conservation, 128, 231–240.	https://doi.org/10.1016/j.biocon.2005.09.031
Lizard	Dent, S., & Spellerberg, I.F. 1987. Habitats of the lizards Lacerta agilis and Lacerta vivipara on forest ride verges in Britain. Biological Conservation, 42, 273–286.	https://doi.org/10.1016/0006-3207(87)90072-3
Lizard	Doherty, T.S., Balouch, S., Bell, K., et al. 2020. Reptile responses to anthropogenic habitat modification: A global meta-analysis. Global Ecology and Biogeography, 29, 1265–1279.	https://doi.org/10.1111/geb.13091
Bat	Frey-Ehrenbold, A., Bontadina, F., Arlettaz, R. and Obrist, M.K. (2013), Landscape connectivity, habitat structure and activity of bat guilds in farmland-	https://doi.org/10.1111/1365-2664.12034

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	dominated matrices. Journal of Applied Ecology. 50: 252-261.	
Bats, Frogs, Lizards, Large Carnivores	Garriga, N., Santos, X., Montori, A. et al. 2012. Are protected areas truly protected? The impact of road traffic on vertebrate fauna. Biodivers Conserv 21, 2761–2774.	https://doi.org/10.1007/s10531-012-0332-0
Frog	Hamer, A.J., & McDonnell, M.J. 2008. Amphibian ecology and conservation in the urbanising world: A review. Biological Conservation, 141, 2432–2449.	https://doi.org/10.1016/j.biocon.2008.07.020
Large Carnivore / Mammal	Jędrzejewski, W., Jędrzejewska, B., Zawadzka, B., Borowik, T., Nowak, S., & Mysłajek, R.W. 2008. Habitat suitability model for Polish wolves based on long-term national census. Animal Conservation, 11, 377–390.	https://doi.org/10.1111/j.1469-1795.2008.00193.x
Bat	Jung, K., Threlfall, C.G. 2016. Urbanisation and Its Effects on Bats—A Global Meta-Analysis. In: Voigt, C., Kingston, T. (eds) Bats in the Anthropocene: Conservation of Bats in a Changing World. Pp. 13-33 Springer, Cham.	https://doi.org/10.1007/978-3-319-25220-9_2
Large Carnivore / Mammal	Kramer-Schadt, S., Revilla, E., Wiegand, T., & Breitenmoser, U. 2004. Fragmented landscapes, road mortality and patch connectivity: modelling influences on the dispersal of Eurasian lynx. Journal of Applied Ecology, 41, 711–723.	https://doi.org/10.1111/j.0021-8901.2004.00933.x
Bat	Law, B., Park, K.J., Lacki, M.J. 2016. Insectivorous Bats and Silviculture: Balancing Timber Production and Bat Conservation. In: Voigt, C., Kingston, T. (eds) Bats in the Anthropocene: Conservation of Bats in a Changing World. pp 105–150 Springer, Cham.	https://doi.org/10.1007/978-3-319-25220-9_5
Bat	O'Shea, T.J., Cryan, P.M., Hayman, D.T.S., Plowright, R.K. and Streicker, D.G. 2016. Multiple mortality events in bats. Mammal Review, 46: 175-190.	https://doi.org/10.1111/mam.12064
Lizard	Rugiero, L., Capula, M., Di Vittorio, M., Dendi, D., Meek, R., & Luiselli, L. 2021. Ontogenetic habitat use and density of the green lizard (Lacerta bilineata) in contrasted landscapes in France and Italy. Conservation, 1, 1–16.	https://doi.org/10.3390/conservation1010001
Frog	Semlitsch, R. 2008 Differentiating migration and dispersal processes for pond-breeding amphibians. Journal of Wildlife Management. 72: 260-267	https://doi.org/10.2193/2007-082
Frog	Wells, K.D. (2007). The Ecology and Behavior of Amphibians. pp. 557-855. University of Chicago Press.	9780226893334
Bat	Williams-Guillén, K., Olimpi, E., Maas, B., Taylor, P.J., & Arlettaz, R. 2016. Bats in the Anthropogenic Matrix: Challenges and Opportunities for the Conservation of Chiroptera and Their Ecosystem Services in Agricultural Landscapes. In: Voigt, C., Kingston, T. (eds) Bats in the Anthropocene: Conservation of Bats in a Changing World. pp151-186, Springer, Cham.	https://doi.org/10.1007/978-3-319-25220-9_6

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Annex 2: Cost Distance Statistics

Cost-distance values were compared across the archetype-land use scenario combinations in order to better evaluate the influence of different futures on landscape permeability. We used linear mixed-effects models with a response variable of normalized cost distance which was the accumulated cost distance between a pair of protected areas divided by the Euclidean distance between those pair of protected areas. This normalization controlled for differences in the lengths of corridors, allowing the response to be interpreted as the average landscape resistance encountered per unit of straight-line distance. Lower normalized cost-distance values represented more permeable landscapes and therefore greater potential functional connectivity, whereas higher values represented increased resistance to movement. Linear mixed models and the estimation of marginal means completed using the “lme4” and “emmeans” R package.

The combined dataset contained 63,910 corridor observations from seven land-use scenarios and four vertebrate archetypes. Land-use scenario and archetype were included as categorical predictor variables. A unique corridor identifier was included as a random effect to account for repeated measurements of the same connection across archetypes. The interaction model tested whether the effect of future land-use change differed among the four species archetypes.

Estimated marginal means were calculated for every land-use scenario separately within each archetype. These model-adjusted means represented the expected normalized cost distance for a scenario after accounting for the repeated observations associated with individual corridor–archetype combinations. Estimated marginal means and their 95% confidence intervals were used when summarizing scenario-level cost distance.

Because the study was designed around specific baseline/future scenario comparisons, hypothesis tests were conducted using planned contrasts rather than all possible pairwise comparisons. For each archetype, the three Shared Socioeconomic Pathway scenarios were compared with Current conditions:

$$SSP1 - Current, \qquad SSP2 - Current, \qquad SSP3 - Current$$

The Nature Futures scenarios were constructed from SSP1 and were therefore compared with SSP1 rather than Current conditions:

$$Nature\ for\ Nature - SSP1,$$

$$Nature\ for\ Society - SSP1,$$

$$Nature\ as\ Culture - SSP1.$$

Each contrast estimated the model-adjusted difference in normalized cost distance between a future scenario and its appropriate reference scenario. Negative contrast estimates indicated that the future scenario reduced landscape movement costs relative to its baseline and therefore increased potential connectivity. Positive estimates indicated increased movement costs and reduced potential connectivity. Statistical significance was evaluated using asymptotic z tests.

To improve the ecological interpretability of the contrast estimates, scenario effects were expressed as percentage changes in model-estimated normalized cost distance. Percentage changes were calculated from the estimated marginal means as:

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$$\%\Delta = 100 \times \frac{\hat{\mu}_{future} - \hat{\mu}_{reference}}{\hat{\mu}_{reference}}$$

where ($\hat{\mu}_{future}$) was the estimated marginal mean for the future scenario and $(\hat{\mu}_{reference})$ was the estimated marginal mean for Current or SSP1, depending on the comparison.

$$\Delta_{SSP1} = \hat{\mu}_{SSP1} - \hat{\mu}_{Current}$$

The percentage changes were descriptive transformations of the model-estimated marginal means rather than separate statistical tests. Statistical significance labels displayed with the percentage changes were therefore obtained from the corresponding mixed-model planned contrasts and not from tests performed directly on the calculated percentages. Results were visualized as horizontal bar plots separated into two comparison groups: Current-to-SSP comparisons and SSP1-to-Nature Futures comparisons. Bars represented model-estimated percentage changes for each archetype and scenario, while annotations reported the magnitude and statistical significance of the associated planned contrast.

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Annex 3: Protected Area Processing and Functional Connectivity Workflows

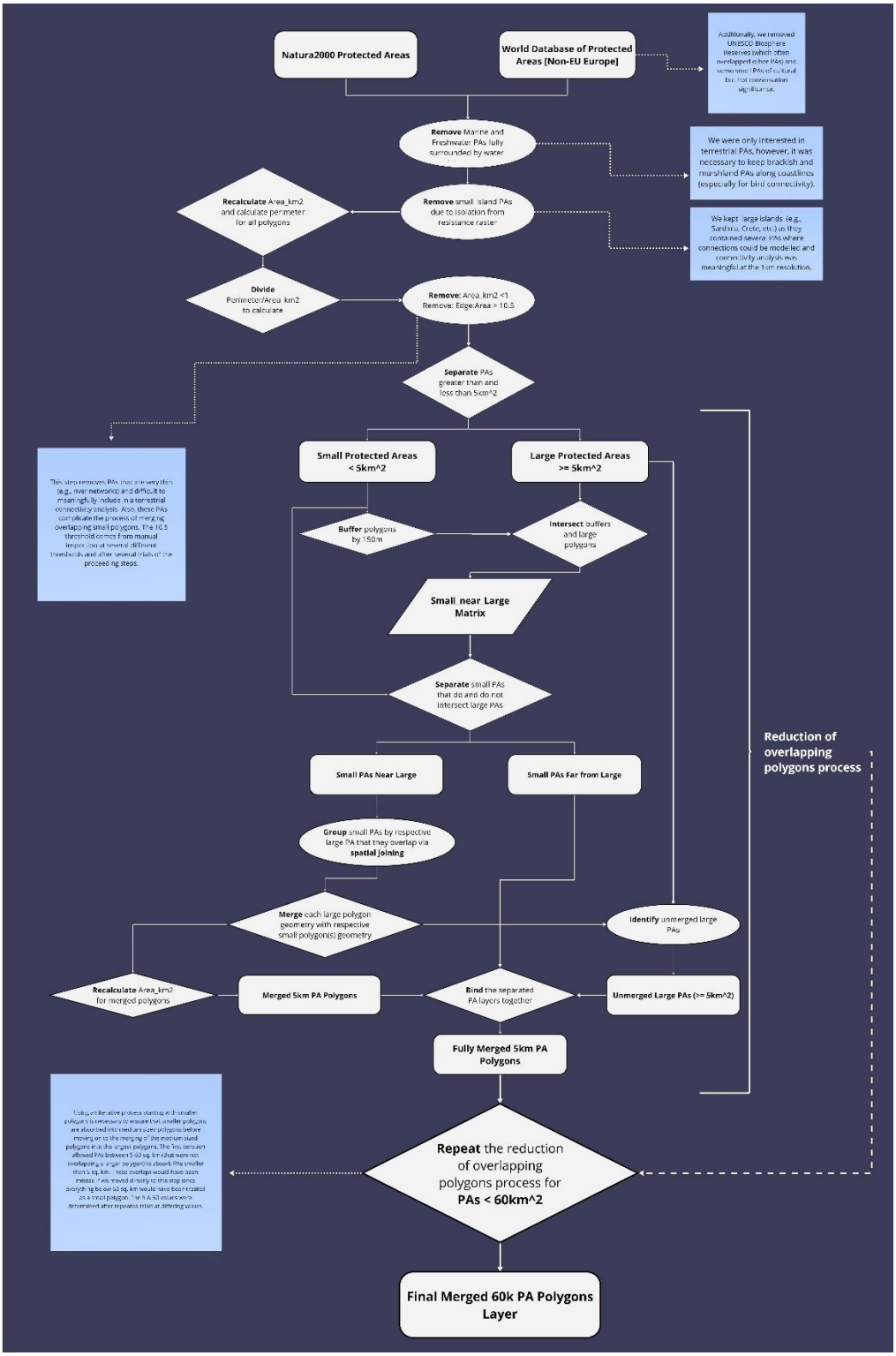

Figure A3.1: *The protected areas (PA) spatial data for Europe provided unique challenges given the varying overlapping classifications for the same piece of land. To combine neighboring protected areas that share boundaries we created a workflow that iteratively combined smaller PAs that were in close proximity to larger PAs*

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Annex 4: Comparison and Restoration Priority Maps

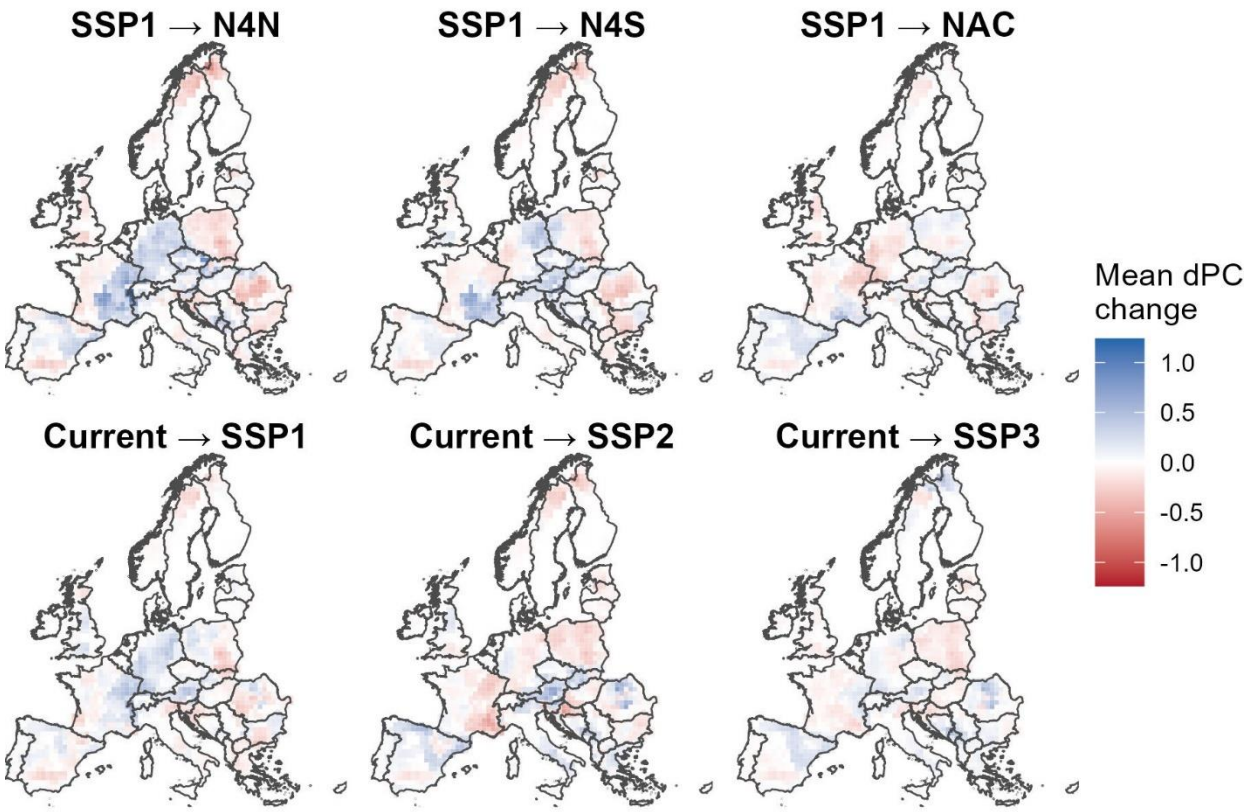

Figure A4.1. *Mean dPC change between the different baseline and future scenarios. Protected areas of southern France and within mountain ranges such as the Alps and Pyrenees increased in their importance for maintaining connectivity in the European protected area network. Several landscapes, mostly flatter topographically, such as central Poland, northern Sweden and the Transylvania Plateau either decreased in dPC values either due to greater disconnection from the surrounding protected area network and/or other protected areas becoming higher priorities.*

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Annex 5: Comparison and Restoration Priority Maps

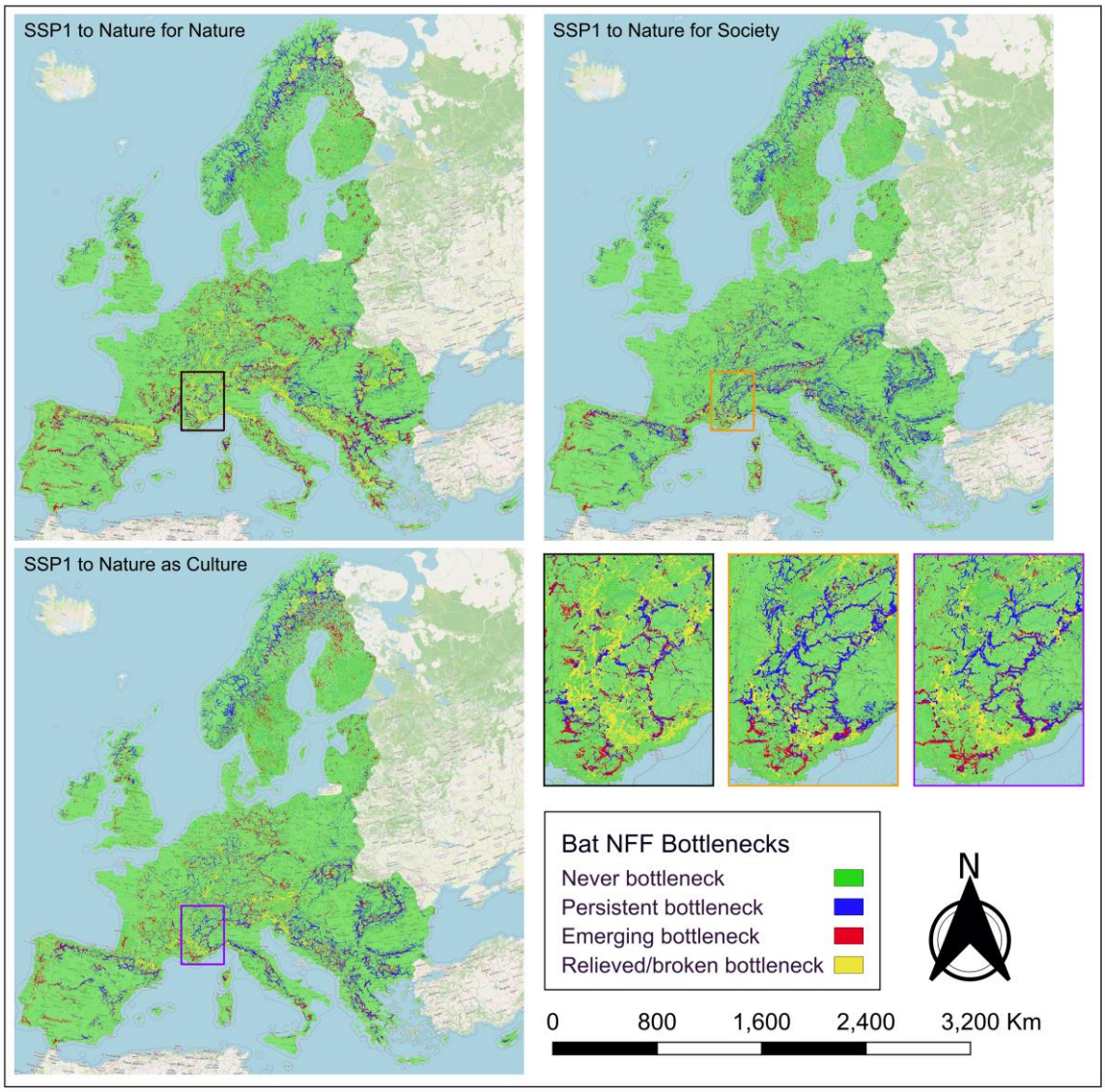

***Figure A5.1**. Overlap of different NFF scenarios with the baseline SSP1 scenario for the bat archetype.*

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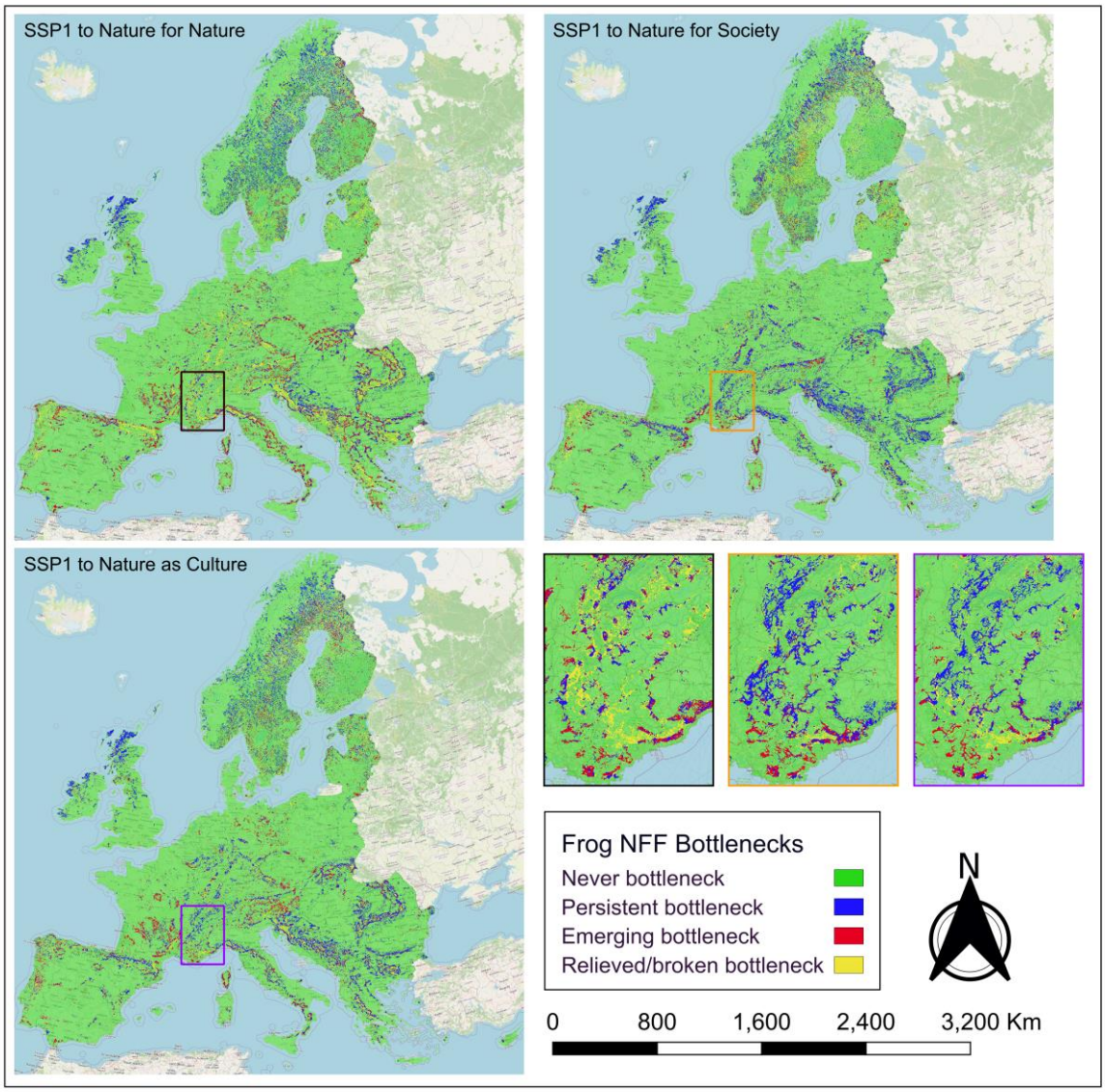

***Figure A5.2**. Overlap of different NFF scenarios with the baseline SSP1 scenario for the frog archetype.*

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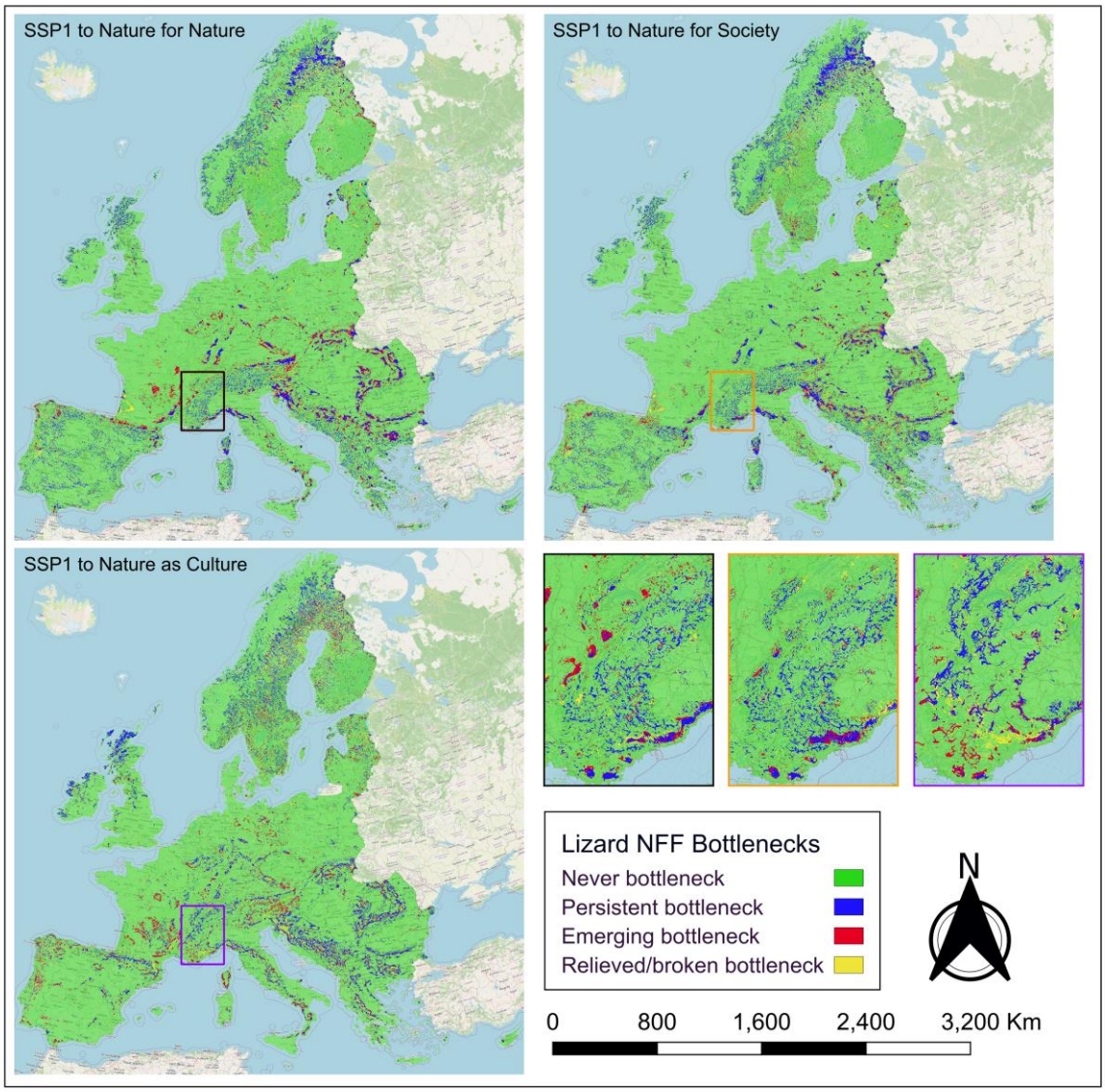

Figure A5.3. *Overlap of different NFF scenarios with the baseline SSP1 scenario for the lizard archetype.*

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***Table A5.1**. Land area within the different restoration priority categories. Persistent areas with high resistance were considered those of highest priority for restoration or conservation as they were maintained as the same sites were maintained throughout multiple scenarios and under pressure from highly resistant habitat.*

Archetype	Category	Area (km^2)
bat	Lower priority	4505982.02
frog	Lower priority	4508815.04
lizard	Lower priority	4515684.07
mammal	Lower priority	4493153.96
bat	Persistent + lower resistance	376623.84
frog	Persistent + lower resistance	389674.90
lizard	Persistent + lower resistance	401049.96
mammal	Persistent + lower resistance	391689.91
bat	Persistent + higher resistance	1843.01
frog	Persistent + higher resistance	864.00
lizard	Persistent + higher resistance	531.00
mammal	Persistent + higher resistance	4385.02
bat	Emerging + lower resistance	85747.42
frog	Emerging + lower resistance	71131.35
lizard	Emerging + lower resistance	52278.26
mammal	Emerging + lower resistance	80471.39
bat	Emerging + higher resistance	316.00
frog	Emerging + higher resistance	39.00
lizard	Emerging + higher resistance	188.00
mammal	Emerging + higher resistance	805.00
bat	Mixed + higher resistance	18.00
frog	Mixed + higher resistance	6.00
lizard	Mixed + higher resistance	799.00
mammal	Mixed + higher resistance	25.00

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More information about the project:

NaturaConnect has 22 partner institutions: International Institute for Applied System Analysis (project lead; Austria); German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig (project co-lead; Germany); Associacao Biopolis (Portugal); BirdLife Europe (Netherlands); Birdlife International (United Kingdom); Centre National De La Recherche Scientifique (France); Doñana Research Station - Agencia Estatal Consejo Superior De Ivestigaciones Cientificas (Spain); Europarc Federation (Germany); Finnish Environment Institute (Finland); Humboldt-University of Berlin (Germany); Institute for European Environmental Policy (Belgium); Netherlands Environmental Assessment Agency (Netherlands); Rewilding Europe (Netherlands); University of Evora (Portugal); University of Helsinki (Finland); University of Natural Resources and Life Sciences, Vienna (Austria); University of Rome La Sapienza (Italy); University of Warsaw (Poland); Vrie University of Amsterdam (Netherlands); WWF Central and Eastern Europe (Austria); WWF Romania and WWF Hungary.

NaturaConnect aims to design and develop a blueprint for a truly coherent **Trans-European Nature Network** (TEN-N) of conserved areas that protect at least 30% of land in the European Union, with at least one third of it under strict protection. Our project unites universities and research institutes, government bodies and non-governmental organizations, working together with key stakeholders to create targeted knowledge and tools, and build the capacity needed to support European Union Member States in realizing an ecologically representative, resilient and well-connected network of conserved areas across Europe.

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