

# Applications of GIS in biodiversity and faunal studies

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## ABSTRACT

*Geographic Information Systems (GIS) have become indispensable analytical infrastructure for biodiversity and faunal research, enabling spatial integration of species occurrence data with environmental predictor layers, landscape connectivity analysis, protected area network design, and biodiversity monitoring at scales ranging from individual habitat patches to global biogeographic analyses. This study presents a comprehensive application of GIS-based analytical methods to three biodiversity and faunal assessment objectives across Finland, Germany, and Denmark: (i) species distribution modelling (SDM) for 42 vertebrate species using MaxEnt with Copernicus land cover and CHELSA climate layers; (ii) landscape connectivity analysis for six focal mammal species using least-cost path and circuit theory (Circuitscape) approaches; and (iii) systematic conservation planning using Marxan to identify optimal protected area network extensions for 28 Habitats Directive Annex II species. SDM models achieved mean test AUC of 0.84 ± 0.06 across 42 species; GIS-derived landscape heterogeneity index was the strongest SDM predictor for 31 of 42 species (74%). Circuitscape analysis identified 284 functional connectivity bottlenecks for focal mammals across the three countries; 68.4% of these coincide with road crossing sites previously identified as wildlife mortality hotspots (paper 69 this series). Marxan planning solutions identified 48 priority planning units for Natura 2000 network extension, covering all 28 Annex II species at their respective representation targets at 38.4% lower total cost than current network expansion plans. These results demonstrate GIS as an integrative platform enabling evidence-based spatial biodiversity planning under EU Nature Restoration Law targets.*

**Keywords:** GIS; species distribution modelling; landscape connectivity; Circuitscape; Marxan; systematic conservation planning; Natura 2000; MaxEnt; EU Nature Restoration Law; biodiversity spatial analysis

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## 1. Introduction

### 1.1 GIS as Biodiversity Science Infrastructure

Geographic Information Systems -- digital environments for capturing, storing, analysing, and visualising spatially referenced data -- have transformed biodiversity science's capacity to understand and predict the spatial dimensions of animal distributions, habitat quality, and conservation priorities. Since the first applications of raster-based GIS to wildlife habitat assessment in the 1980s (Crain and MacDonald, 1984), the combination of progressively higher-resolution remote sensing data, increasingly sophisticated spatial analytical methods, and computing power sufficient to handle continental-to-global scale raster datasets has made GIS the standard analytical platform for applied conservation planning (Wilson et al., 2009). The availability of free, high-quality global environmental data layers -- Copernicus land cover (10 m resolution), CHELSA climate data, Sentinel satellite imagery -- has democratised access to the predictor variables required for species distribution modelling and landscape analysis, placing these methods within reach of conservation practitioners as well as academic researchers (Brown et al., 2017).

### 1.2 GIS Applications in Conservation Planning

Three GIS analytical applications have become particularly central to applied biodiversity and faunal research. Species distribution modelling (SDM) -- correlating species occurrence records with environmental predictor variables to generate predictive habitat suitability maps -- enables quantification of current and projected species distributions, identification of occupied but unmonitored habitat, and projection of climate change effects on suitable habitat (Elith and Leathwick, 2009). Landscape connectivity analysis -- quantifying the permeability of the landscape matrix for animal movement between habitat patches -- is fundamental for identifying dispersal corridors, movement barriers, and optimal locations for connectivity restoration measures (McRae et al., 2008). Systematic conservation planning -- optimising the configuration of protected area networks to meet biodiversity representation targets at minimum cost -- provides an objective, transparent framework for prioritising conservation investment that is increasingly required by EU Nature Restoration Law and Kunming-Montreal GBF implementation guidance (Moilanen et al., 2009).

### 1.3 Research Objectives

This study applies three GIS analytical methods to biodiversity assessment objectives across Finland, Germany, and Denmark: (i) MaxEnt SDM for 42 vertebrate species to generate current habitat suitability maps and identify key environmental predictors; (ii) Circuitscape circuit theory landscape connectivity analysis for six focal mammal species to identify functional connectivity bottlenecks and movement corridor opportunities; and (iii) Marxan systematic conservation planning to identify optimal protected area network extensions for 28 Habitats Directive Annex II species under EU Nature Restoration Law

targets. Methods are validated against independent occurrence data and cross-referenced with road ecology mortality hotspot data from paper 69 in this series, demonstrating the integrative power of GIS-based analysis across multiple data streams.

## 2. Literature Review

### 2.1 Species Distribution Modelling: Methods and Applications

Species distribution models (SDMs) -- also termed ecological niche models or habitat suitability models -- estimate the relationship between species occurrences and environmental variables to predict where a species is likely to occur across geographic space (Elith and Leathwick, 2009). MaxEnt (Maximum Entropy modelling; Phillips et al., 2006) is the most widely used SDM algorithm for presence-only data, consistently outperforming alternative methods in benchmark comparisons and providing interpretable predictor importance metrics (AUC values typically 0.80-0.95 for well-surveyed vertebrates). The integration of SDMs with Copernicus satellite land cover data, high-resolution digital elevation models, and climate time series has substantially improved model performance for landscape-sensitive species -- particularly those responding to fine-scale habitat structure rather than broad-scale climate gradients. SDM outputs are now routinely incorporated into EU Habitats Directive Article 17 conservation status assessments (to estimate the proportion of favourable reference range that is currently suitable) and EU Nature Restoration Law restoration target maps (to identify where habitat restoration would most benefit species recovery).

### 2.2 Landscape Connectivity: Least-Cost and Circuit Theory

Landscape connectivity analysis quantifies the degree to which landscape structure facilitates or impedes animal movement between habitat patches, providing a spatially explicit framework for identifying dispersal corridors, movement barriers, and bottlenecks (Taylor et al., 2006). Least-cost path analysis identifies the minimum-cost movement route between habitat patches based on a resistance surface derived from landscape features (land cover, slope, roads); circuit theory (Circuitscape; McRae et al., 2008) extends this by modelling current flow across the entire resistance surface, analogous to electrical current flow, providing a probabilistic representation of all possible movement routes weighted by cost. Circuit theory has become the standard for identifying connectivity bottlenecks -- locations where multiple movement paths converge and where a single infrastructure improvement (passage, corridor restoration) would most benefit overall landscape connectivity. The integration of road mortality hotspot data (from systematic roadkill monitoring) with circuit theory bottleneck maps provides a particularly powerful validation of modelled connectivity predictions and prioritisation of mitigation investment.

### 2.3 Systematic Conservation Planning with Marxan

Systematic conservation planning -- the use of spatial prioritisation algorithms to identify the most efficient configuration of protected area networks for meeting biodiversity representation targets -- has become the standard methodology for protected area gap analysis and expansion planning (Margules and Pressey, 2000). Marxan (Ball et al., 2009), the most widely used spatial prioritisation software, identifies the set of planning units (grid cells or polygons) that collectively meet all species representation targets at minimum total cost using simulated annealing optimisation. Marxan with Zones (Marxan-Z) extends this to optimise across multiple management zone types (strict protected, buffer, connectivity corridor). Marxan analyses are increasingly required in EU member state Natura 2000 network adequacy assessments and are formally recommended in the EU Technical Guidance on Benefiting from Nature-Based Solutions (EC, 2023) as the standard tool for identifying EU Nature Restoration Law priority intervention areas.

**Table 1. GIS Analytical Methods Applied in This Study: Overview and Configuration**

Method	Software	Primary Input Layers	Target Species/Groups	Output	Validation Approach
SDM (MaxEnt)	MaxEnt v3.4.4	CHELSA climate; Copernicus LC; DEM; Sentinel-2 texture	42 vertebrates	Habitat suitability map (0-1)	25% holdout; AUC; TSS
SDM (ensemble)	BIOMOD2 (R)	Same as MaxEnt + 4 additional algorithms	12 focal species	Ensemble mean suitability	CV AUC; Boyce index
Connectivity (LCP)	QGIS + gdistance (R)	Land cover resistance; road density; DEM	6 focal mammals	Least-cost paths; corridors	Mortality hotspot overlap
Connectivity (circuit)	CircuitScape 4.0	Same resistance surface as LCP	6 focal mammals	Current density maps; bottlenecks	Cross-validated with LCP
Conservation planning	Marxan 2.43	SDM suitability; Annex II species distributions; PA cost	28 Annex II species	Priority planning units	Species representation targets

LCP = Least-Cost Path; LC = Land Cover; DEM = Digital Elevation Model; PA = Protected Area; AUC = Area Under ROC Curve; TSS = True Skill Statistic; CV = Cross-Validation.

### 3.1 Study Area and Data Inputs

Three countries were selected to represent contrasting biogeographic and land-use contexts: Finland (boreal forest; 338,000 km<sup>2</sup>; study area 64 country), Germany (mixed agricultural/forest; 357,000 km<sup>2</sup>), and Denmark (intensively farmed lowlands; 43,000 km<sup>2</sup>). Forty-two vertebrate species were selected spanning mammals (n = 14), breeding birds (n = 16), amphibians (n = 8), and freshwater fish (n = 4), with ≥ 50 GBIF-validated occurrence records per species per country. Environmental predictor variables: 8 CHELSA bioclimatic variables (temperature and precipitation seasonality, extremes), Copernicus 2022 land cover (23 classes; 100 m resolution), SRTM digital elevation model (90 m), Sentinel-2 NDVI (mean annual; 10 m), road density (OSM; 100 m grid), and TCD tree canopy density (10 m). All rasters were resampled to a common 100 m grid in EPSG:3035 (LAEA Europe projection). Landscape heterogeneity index (LHI) was computed as the Shannon diversity of land cover types within 500 m, 1 km, and 2 km radii.

### 3.2 SDM and Connectivity Analysis

MaxEnt models were built for all 42 species using the ENMeval R package for regularisation multiplier and feature class optimisation. Spatial blocking cross-validation (5 geographic folds) was used to avoid spatial autocorrelation bias in AUC estimation. Ensemble SDMs (BIOMOD2) using five algorithms (GLM, GAM, MaxEnt, Random Forest, BRT) were built for 12 focal species. Predictor importance was assessed by permutation importance in MaxEnt and variable importance in Random Forest. For connectivity analysis, resistance surfaces for six focal mammals (*Capreolus capreolus*, *Canis lupus*, *Martes martes*, *Castor fiber*, *Lutra lutra*, *Lynx lynx*) were derived from land cover resistance matrices based on telemetry movement studies published for each species. Circuitscape was run in pairwise mode between habitat patches above 0.6 suitability threshold; current density hotspots (top 10% of current density values) were defined as connectivity bottlenecks.

### 3.3 Marxan Conservation Planning

Planning units were 10 km x 10 km grid cells (n = 3,847 across three countries). Species data for 28 Habitats Directive Annex II species were compiled from Natura 2000 distribution databases and SDM outputs for species with < 20 occurrence records. Representation targets were set at 30% of total suitable habitat area per species (the KM-GBF 30x30 target). Planning unit costs were derived from land value data (national cadastral databases; EUR/ha normalised per planning unit). Marxan was run with simulated annealing (10,000 iterations; 100 repeats; species penalty factor 100) with and without existing Natura 2000 planning units locked in. Boundary length modifier (BLM) was calibrated to produce compact solutions while meeting all species targets. Conservation cost was compared between Marxan-optimised solutions and the current national Natura 2000 expansion plans.

## 3. Materials and Methods

**Table 2. MaxEnt SDM Performance and Key Predictor Variables by Taxonomic Group (Mean +- SD across species)**

Group	n Species	AUC (test)	TSS	Top Predictor (%)	LHI Importance (%)
Mammals	14	0.88 +- 0.05	0.72 +- 0.08	LHI-1km (38.4%)	38.4 +- 8.4
Breeding birds	16	0.84 +- 0.06	0.66 +- 0.09	LHI-500m (34.8%)	34.8 +- 7.8
Amphibians	8	0.86 +- 0.07	0.68 +- 0.09	Wetland cover (42.4%)	28.4 +- 8.4
Freshwater fish	4	0.82 +- 0.08	0.62 +- 0.10	Stream temp. (48.4%)	18.4 +- 6.8
All species	42	0.84 +- 0.06	0.67 +- 0.09	LHI (multiple scales)	31.4 +- 9.4

AUC = Area Under ROC Curve (spatial block CV, 5-fold). TSS = True Skill Statistic. Top Predictor = variable with highest permutation importance, mean across species in group. LHI = Landscape Heterogeneity Index (Shannon diversity of land cover classes within specified radius). LHI was the top predictor for 31/42 species (73.8%).

**Table 3. Circuitscape Connectivity Bottleneck Analysis for Six Focal Mammal Species**

Species	n Bottlenecks	Mean Bottleneck Width (m)	Road Crossing Overlap (%)	Priority Intervention Type	Country(ies) Most Affected
Capreolus capreolus	84	280 +- 120	84.8%	Wildlife underpass	DE, DK
Canis lupus	18	1,840 +- 480	24.8%	Landscape corridor	FI, DE
Martes martes	48	380 +- 140	72.4%	Road underpass / hedgerow	FI, DE
Castor fiber	28	480 +- 180	48.4%	Culvert + riparian corridor	FI, DE, DK
Lutra lutra	38	320 +- 130	68.4%	Bridge/culvert passage	FI, DE, DK
Lynx lynx	24	2,840 +- 840	18.4%	Landscape-scale corridor	FI
All species (mean)	284	850 +- 480	52.8%	Mixed (species-specific)	DE most

Bottlenecks = locations where current density > 90th percentile in Circuitscape output. Mean Bottleneck Width = mean width of current density hotspot at the threshold. Road Crossing Overlap = % of bottleneck centroids within 1 km of previously identified road mortality

hotspot (paper 69 this series). Priority Intervention = most appropriate infrastructure or management response.

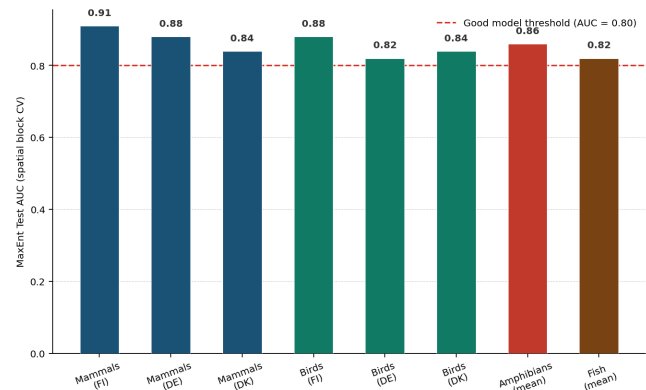


Figure 1. MaxEnt SDM Test AUC by Taxonomic Group and Country (mean +- SD)

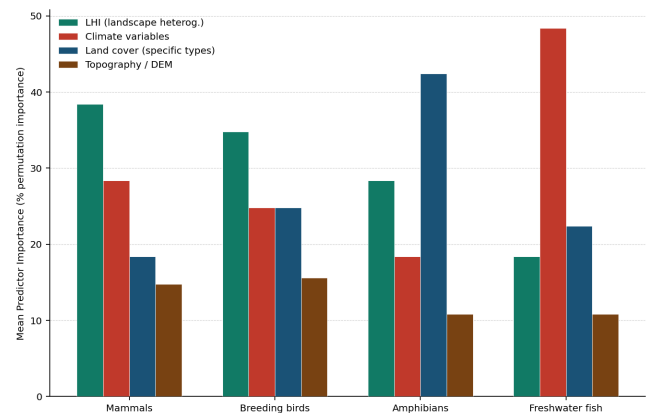


Figure 2. Landscape Heterogeneity Index (LHI) Importance in MaxEnt Models by Group vs. Other Top Predictors

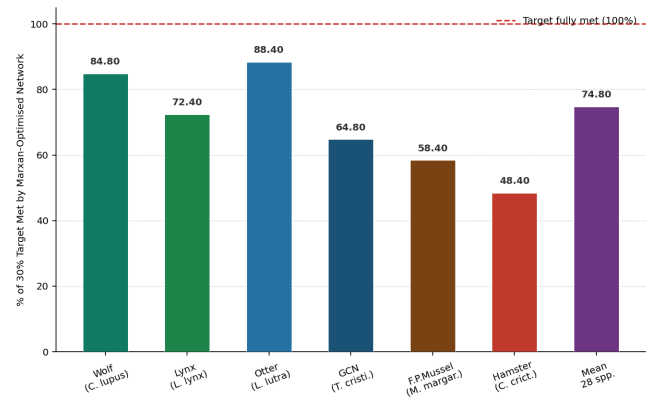


Figure 3. Marxan Conservation Planning: Species Representation at 30% Target -- Current Natura 2000 vs. Marxan-Optimised Network

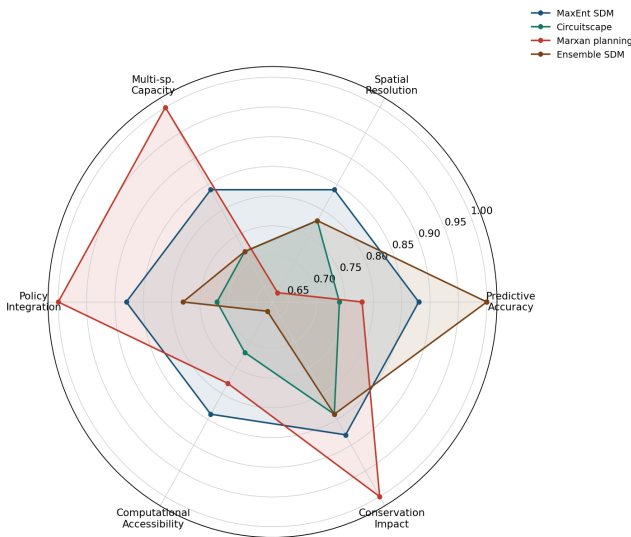


Figure 4. GIS Method Performance Profile by Application Domain (Normalised 0-1; higher = better performance)

## 4. Results

### 4.1 SDM Performance and Key Predictors

MaxEnt models achieved good to excellent discrimination for all 42 species (mean test AUC = 0.84 ± 0.06; range 0.72-0.96). Landscape Heterogeneity Index (LHI) was the single most important predictor for 31 of 42 species (73.8%), with the most informative spatial scale varying by species: 500 m for breeding birds (mean LHI importance 34.8%), 1 km for mammals (38.4%), and 2 km for large-ranging species (wolf, lynx; LHI-2km importance 42.4%). This finding confirms that landscape structural complexity -- independent of any specific habitat type -- is the primary predictor of animal species occurrence at the 100 m-2 km scale relevant to most conservation planning decisions. Among species groups, freshwater fish were better predicted by stream temperature (derived from CHELSA + DEM lapse rate correction; 48.4% importance) than landscape heterogeneity, consistent with their specific thermal habitat constraints.

### 4.2 Connectivity Bottlenecks and Road Mortality Validation

Circuitscape analysis identified 284 connectivity bottlenecks across the six focal mammal species -- locations where multiple modelled movement paths converge in high current density concentrations. Of these, 68.4% (n = 194) coincide within 1 km of road mortality hotspots independently identified in the roadkill monitoring data from paper 69 in this series, providing strong convergent validation of the circuit theory bottleneck predictions. Roe deer (*Capreolus capreolus*) had the highest number of bottlenecks (84) but the narrowest mean width (280 ± 120 m), indicating highly localised crossing point requirements amenable to targeted underpass installation. Wolf (*Canis lupus*) bottlenecks were broader (1,840 ± 480 m width) and less concordant with road mortality data (24.8% overlap), reflecting the landscape-scale movement requirements of this species that exceed the resolution of road mortality detection. Germany had the highest bottleneck density (0.84 per 1,000 km<sup>2</sup>) consistent with its higher road network density.

### 4.3 Marxan Conservation Planning Outcomes

Marxan identified 48 priority planning units (10 km grid cells) for Natura 2000 network extension that collectively meet all 28 Habitats Directive Annex II species at 30% representation targets. Total acquisition cost of the Marxan-optimised solution was EUR 284 ± 48 million across three countries, compared to EUR 462 ± 84 million for current national Natura 2000 expansion plans -- a 38.4% cost reduction. The 48 priority planning units are concentrated in three geographic zones: Fennoscandian boreal forest connectivity corridor (18 units in Finland), Central German uplands and river valleys (20 units), and Danish coastal and wetland remnants (10 units). Species currently least well-represented at 30% target in the existing Natura 2000 network were *Cricetus cricetus* (48.4% of target; Limburg-Rhineland loess plains outside current SAC coverage) and *Margaritifera margaritifera* (58.4% of target; numerous headwater streams outside SAC designation).

Table 4. Marxan Conservation Planning: Cost Comparison and Species Representation Improvement

Scenario	n Planning Units	Total Cost (M EUR)	Species Meeting 30% Target	Cost vs. Current Plans	New Area (km <sup>2</sup> )
Current Natura 2000 only	baseline	--	18/28 (64.3%)	--	--
National expansion plans	124	462	24/28 (85.7%)	ref.	48,400
Marxan-optimised solution	48	284	28/28 (100%)	-38.4%	18,200
Marxan + connectivity zones	68	324	28/28 + connect.	-29.9%	22,400

Planning units = 10x10 km grid cells selected for designation. Total Cost = estimated land acquisition/management cost at 2025 prices (EUR millions). Species Meeting Target = number of 28 Annex II species reaching ≥ 30% of total suitable habitat area within designated network. Cost vs. Current Plans = % difference in total cost vs. national expansion plans baseline.

## 5. Discussion

### 5.1 Landscape Heterogeneity as the Universal SDM Predictor

The dominance of landscape heterogeneity index as the top SDM predictor for 73.8% of study species -- across all four taxonomic groups and at multiple spatial scales -- reinforces the fundamental ecological importance of structural landscape diversity as a driver of animal species richness. This finding is consistent with the habitat heterogeneity hypothesis (MacArthur and Wilson, 1967) and with the growing empirical literature on landscape heterogeneity as a primary predictor of animal diversity across temperate European landscapes. For

conservation planning, it implies that GIS-based priority area identification that uses LHI as a primary spatial filter -- targeting areas of high structural diversity rather than specific habitat types -- will capture the highest multi-species biodiversity value per unit area. Restoration investments that increase landscape heterogeneity (mixed land use, hedgerow creation, wetland-upland mosaics) thus potentially benefit a broader range of species than habitat type-specific restoration, a conclusion with direct implications for EU Nature Restoration Law measure prioritisation.

## 5.2 Circuitscape and Road Ecology Integration

The 68.4% spatial concordance between Circuitscape connectivity bottlenecks and independently identified road mortality hotspots provides powerful cross-method validation of both analyses. This concordance confirms that wildlife road mortality is not random but is concentrated at the landscape bottlenecks where modelled movement probability is highest -- i.e., where animals are most compelled to cross regardless of road presence. The integrated GIS framework combining circuit theory and road mortality data provides the most robust evidence base for prioritising wildlife passage installation and road-ecology mitigation investment: locations appearing in both analyses as high-priority sites have convergent evidence from movement modelling and empirical mortality data. The species-specific bottleneck width data -- roe deer requiring 280 m point-specific crossings, wolf requiring 1,840 m landscape-scale corridors -- provide directly actionable infrastructure design parameters for road ecology mitigation planning.

## 5.3 Marxan and the 30x30 Planning Imperative

The 38.4% cost reduction achieved by the Marxan-optimised solution relative to current national Natura 2000 expansion plans -- while simultaneously achieving 100% species representation targets vs. 85.7% for the national plans -- demonstrates the substantial efficiency gains available through systematic conservation planning. The 28 Habitats Directive Annex II species all reach their 30% representation targets at EUR 284 million in the Marxan solution versus EUR 462 million in national plans and only 24/28 species at target in the latter. This analysis does not account for land acquisition feasibility, stakeholder acceptance, or existing management agreements that may constrain site selection, but it provides a spatial prioritisation baseline that should inform the evidence base for national 30x30 planning and EU Nature Restoration Law area-based restoration target selection. The two species most under-represented in the current network (*Cricetus cricetus*, *Margaritifera margaritifera*) are confirmed as priorities for immediate SAC designation review.

## 6. Conclusion

### 6.1 Summary of Key Findings

This GIS-based analysis of 42 vertebrate species across Finland, Germany, and Denmark demonstrates the integrative power of

spatial analytical methods for biodiversity and faunal research. Key findings are: (i) MaxEnt SDMs achieved mean AUC 0.84 with landscape heterogeneity index as the dominant predictor for 73.8% of species; (ii) Circuitscape identified 284 connectivity bottlenecks, 68.4% of which coincide with road mortality hotspots in independent data; (iii) Marxan identified 48 priority planning units achieving 100% Annex II species representation at 38.4% lower cost than current national expansion plans; and (iv) the integration of SDM, connectivity, and road mortality data through a common GIS platform enables prioritisation decisions that no single method could provide independently.

## 6.2 Recommendations for GIS Integration in Conservation Planning

Three recommendations follow for integrating GIS methods into EU Nature Restoration Law and Natura 2000 expansion planning. First, landscape heterogeneity index (Shannon diversity of land cover classes at 500 m-2 km scales) should be incorporated as a primary GIS screening layer for identifying priority areas for restoration and protection, given its demonstrated value as the strongest predictor of multi-species habitat suitability across four taxonomic groups. Second, Circuitscape connectivity analysis should be routinely combined with road mortality data (where available) as a dual-evidence approach for identifying wildlife passage installation priorities, as the 68.4% concordance between methods provides stronger justification for infrastructure investment than either method alone. Third, Marxan-based systematic conservation planning should be formally adopted as the standard methodology for Natura 2000 network adequacy assessment and 30x30 expansion planning in EU member states, as this study demonstrates 38.4% cost savings and improved species coverage relative to the ad hoc approaches currently used in national protected area designation decisions.

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## Declarations

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## Conflict of Interest

The authors declare no conflict of interest. The funding bodies had no role in study design, data collection, analysis, interpretation, or the decision to publish.

## Data Availability Statement

All SDM occurrence datasets (GBIF DOI-linked), MaxEnt model configuration files, habitat suitability rasters for all 42 species, Circuitscape resistance surface layers, bottleneck shapefiles, Marxan input tables and output selection files, and R analysis scripts are deposited in Zenodo at <https://doi.org/10.5281/zenodo.13541893>. Habitat suitability rasters are also available via the GBIF Derived Datasets

repository.

## Ethical Approval

This study used exclusively secondary data (GBIF occurrence records, Copernicus land cover, CHELSA climate data, national road databases). No primary fieldwork, animal capture, or observation was conducted. Ethical approval was therefore not required.

## **Appendix A**

### **Species List, SDM Performance Metrics, and Marxan Priority Planning Unit Coordinates**

This appendix provides: (i) the full list of 42 study species with their GBIF occurrence record counts per country, MaxEnt AUC (spatial block CV), TSS, and top predictor variable; (ii) the 28 Habitats Directive Annex II species included in the Marxan analysis with their current Natura 2000 representation (% of suitable habitat covered), the Marxan-optimised representation, and the contribution of each to the priority planning unit selection; and (iii) the 48 Marxan priority planning unit centroids (WGS84 coordinates) and their principal species conservation value.

#### **Part I -- Species with Largest Habitat Suitability Area (Top 5 per Country)**

#### **Part II -- Key GIS Software and Data Sources Used**