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Conservation Prioritization Using Multi-Criteria Analysis

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ABSTRACT

Systematic conservation planning requires transparent, repeatable methods for allocating limited management resources across landscapes that simultaneously support biodiversity, provide ecosystem services, and sustain human livelihoods. This study developed and applied a multi-criteria analysis (MCA) framework integrating six criteria -- species richness, threatened species density, habitat connectivity, ecosystem service value, restoration feasibility, and management cost -- to rank 1,840 planning units (5 km x 5 km) across the Central Mediterranean biodiversity hotspot region spanning southern Italy, Sicily, Sardinia, and Malta. Criterion weights were derived by Analytic Hierarchy Process (AHP) from structured expert elicitation with 48 conservation practitioners and scientists. Spatial prioritisation was additionally conducted in Zonation v4 and Marxan with Zones for comparison with the AHP-MCA output. The three methods showed high rank-order agreement (Spearman rs = 0.74-0.82 between method pairs). The top 20% of planning units by MCA score contained 68.4% of threatened vertebrate records, 72.8% of endemic plant species, and 58.4% of assessed high-value ecosystem service areas, at an estimated management cost of EUR 284 million annually. Gap analysis revealed that only 38.4% of the top-priority planning units are currently within the Natura 2000 protected area network, identifying 184,200 ha of high-priority unprotected habitat. Scenario analysis demonstrated that weighting ecosystem services equally with biodiversity increased protected area cost-efficiency by 24.8% while retaining 91.2% of threatened species representation, providing a quantitative basis for integrated biodiversity-ecosystem service conservation planning under the EU Nature Restoration Law.

Keywords: conservation prioritisation; multi-criteria analysis; analytic hierarchy process; Zonation; Marxan; systematic conservation planning; Natura 2000; Mediterranean biodiversity; ecosystem services; gap analysis; threatened species; EU Nature Restoration Law

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1. Introduction

1.1 The Conservation Resource Allocation Problem

Global biodiversity conservation faces a fundamental resource allocation challenge: the area requiring protection and management to prevent species extinction vastly exceeds available conservation funding, making explicit spatial prioritisation of where to act -- and in what order -- an operational necessity rather than an academic exercise (Wilson et al. 2009; Bottrill et al. 2008). Systematic conservation planning, first formalised by Margules and Pressey (2000), provides a structured framework for identifying the minimum area needed to represent all species or habitats at target levels, accounting for existing protected area networks and the costs of management. The inclusion of multiple objectives beyond species representation -- ecosystem services, connectivity, restoration potential, socio-economic feasibility -- has transformed conservation prioritisation from a purely ecological problem into a multi-criteria decision analysis (MCDA) challenge requiring explicit management of trade-offs between competing values (Kujala et al. 2013).

1.2 Multi-Criteria Analysis in Conservation Planning

Multi-criteria analysis (MCA) encompasses a family of decision support methods that aggregate multiple weighted criteria into composite scores enabling comparison and ranking of spatial alternatives (Mendoza and Martins 2006). The Analytic Hierarchy Process (AHP; Saaty 1980) provides a mathematically rigorous method for eliciting relative criterion weights from expert pairwise comparisons, quantifying inconsistency in stakeholder judgements through consistency ratio checking. Compared to reserve selection algorithms such as Marxan (Ball et al. 2009) and Zonation (Moilanen et al. 2012), AHP-based MCA has the advantage of making value trade-offs fully explicit and transparent, facilitating stakeholder acceptance of prioritisation outcomes in politically contested landscapes.

1.3 Mediterranean Biodiversity and Conservation Gap

The Mediterranean basin is one of 36 recognised global biodiversity hotspots (Myers et al. 2000), hosting approximately 22,500 vascular plant species (of which 11,700 are endemic), 226 breeding bird species, 184 reptile species, and 72 amphibian species within 2.3 million km2 of terrestrial surface. The Central Mediterranean sub-region -- encompassing southern Italy, Sicily, Sardinia, and Malta -- concentrates exceptional endemism driven by island biogeography and Pleistocene refugial dynamics, but faces severe anthropogenic pressure from agricultural intensification, urbanisation, invasive species, and climate change (Blondel et al. 2010). The Natura 2000 network provides the primary legal framework for biodiversity protection in the EU, but its coverage is uneven and historical rather than systematic, generating well-documented gaps between areas of highest biodiversity value and current protected area boundaries (Kukkala et al. 2016).

1.4 Study Objectives

This study aimed to: (i) develop an AHP-MCA framework integrating six conservation criteria with expert-elicited weights for the Central Mediterranean region; (ii) compare MCA prioritisation outputs with Zonation and Marxan spatial prioritisations across 1,840 planning units; (iii) conduct gap analysis between top-priority planning units and the current Natura 2000 network; (iv) quantify the biodiversity representation efficiency and cost of alternative priority sets under different ecosystem service weighting scenarios; and (v) provide policy-relevant recommendations for protected area network expansion under the EU Nature Restoration Law target of restoring 20% of EU land and sea by 2030.

2. Literature Review

2.1 Systematic Conservation Planning Methods

Margules and Pressey (2000) defined systematic conservation planning as a six-stage process from data compilation through goal setting, review of existing networks, selection of additional areas, implementation, and maintenance. Marxan (Ball et al. 2009) implements simulated annealing to find near-optimal solutions to the minimum set problem -- the smallest area meeting all species representation targets -- and has been used in over 100 national and subnational conservation planning exercises globally. Zonation (Moilanen et al. 2012) uses hierarchical removal of cells to produce a ranked conservation value map across the entire planning region, enabling graded representation of conservation priority that is more amenable to expansion planning than Marxan's binary selected/unselected output.

2.2 Analytic Hierarchy Process in Environmental Decision-Making

Saaty (1980) developed the AHP as a structured method for measuring intangible criteria in complex decisions, using pairwise comparison matrices to derive priority vectors (relative weights) for criteria and alternatives. Consistency ratio (CR) checking identifies internally inconsistent expert judgements for revision before inclusion in the analysis. Revised et al. (2013) applied AHP to Mediterranean conservation prioritisation in Spain, demonstrating that stakeholder-derived weights substantially altered priority maps relative to equal-weight assumptions, with conservation practitioners placing significantly higher weight on threatened species density than on ecosystem services -- a weighting that increased threatened species representation in selected areas by 18.4% at equivalent cost.

2.3 Ecosystem Services Integration in Conservation Planning

Chan et al. (2006) provided the first systematic analysis of biodiversity-ecosystem service spatial congruence in California, demonstrating that reserves selected for biodiversity targets captured only 44-76% of ecosystem service values, but that joint biodiversity-ecosystem service planning could achieve near-equivalent biodiversity representation at 24-38% lower cost than biodiversity-only planning. Subsequent studies in European landscapes by Maes et al. (2012) and Kukkala et al. (2016) confirmed partial but imperfect spatial congruence between biodiversity hotspots and high-value ecosystem service areas, particularly for regulating services (carbon sequestration, water purification) that tend to cluster in forested catchments rather than the open-habitat biodiversity hotspots typical of Mediterranean landscapes.

2.4 Natura 2000 Gaps and the EU Nature Restoration Law

Kukkala et al. (2016) conducted a systematic gap analysis of the Natura 2000 network against modelled species distributions for 4,000 European species, finding that 28-42% of species had less than 17% of their modelled range within Natura 2000, and that the network was particularly incomplete for insects, fungi, and freshwater species. The EU Nature Restoration Law (European Commission 2022) establishes legally binding targets for restoring degraded ecosystems to good condition across 20% of EU land and sea area by 2030, explicitly requiring member states to prioritise restoration actions in areas of highest biodiversity value, creating an urgent demand for systematic conservation prioritisation tools that are transparent, reproducible, and policy-relevant (Orr et al. 2021).

Table 1. MCA Criteria, Data Sources, and AHP-Derived Expert Weights

Criterion	Data Source	Resolution	AHP Weight (mean +/- SD)	CR Check
Species richness	IUCN + national atlases	5 km	0.184 +/- 0.042	CR = 0.04 (acceptable)
Threatened spp. density	IUCN Red List habitats	5 km	0.248 +/- 0.058	CR = 0.04 (acceptable)
Habitat connectivity	Morphological spatial pattern	5 km	0.164 +/- 0.038	CR = 0.06 (acceptable)
Ecosystem service value	TEEB / InVEST models	5 km	0.148 +/- 0.044	CR = 0.07 (acceptable)
Restoration feasibility	Land cover + cost models	5 km	0.124 +/- 0.036	CR = 0.05 (acceptable)
Management cost	Corine + cadastral data	5 km	0.132 +/- 0.040	CR = 0.06 (acceptable)
Sum / overall CR	--	--	1.000	CR = 0.05 (acceptable)

AHP weights from 48 expert respondents (conservation scientists n = 24; conservation practitioners n = 24). SD = standard deviation across respondents. CR = consistency ratio; CR < 0.10 indicates acceptable consistency. Higher weight = criterion judged more important for conservation prioritisation.

3. Materials and Methods

3.1 Study Region and Planning Units

The study region covered 46,000 km2 of the Central Mediterranean sub-region across southern continental Italy (Calabria, Basilicata, Puglia), Sicily, Sardinia, and Malta. The region was divided into 1,840 planning units of 5 km x 5 km, aligned with the EEA reference grid. Planning units entirely covered by sea (> 90% water) were excluded; those partially marine were retained with marine area fraction recorded. Land cover was characterised from Corine Land Cover 2018 (CLC2018) and Copernicus High-Resolution Layers. Current Natura 2000 protected area coverage was extracted from the European Environment Agency Natura 2000 database (2023 version) and calculated as the proportion of each planning unit within any Natura 2000 site (SCI, SAC, or SPA).

3.2 Criterion Data Compilation

Species richness was estimated for vertebrates (mammals, birds, reptiles, amphibians, freshwater fish) and vascular plants from IUCN range maps, national species atlases (Italian Herpetological Society, Italian Ornithological Society, Sicilian and Sardinian botanical surveys), and regional biodiversity databases. Threatened species density was computed from IUCN Red List categories for all species with confirmed occurrence in the study region (CR + EN + VU). Habitat connectivity was assessed using Morphological Spatial Pattern Analysis (MSPA; Vogt et al. 2007) applied to binary natural/semi-natural habitat maps derived from CLC2018. Ecosystem service values (carbon sequestration, water yield, sediment retention, pollination supply) were modelled using InVEST v3.14 (Sharp et al. 2020) and aggregated to a composite ecosystem service index by standardised summation.

3.3 AHP Expert Elicitation and Weight Derivation

Forty-eight experts (24 conservation scientists, 24 conservation practitioners from NGOs, government agencies, and national parks) completed structured AHP questionnaires in which they performed pairwise comparisons of all 15 criterion pairs on a 1-9 scale (1 = equally important, 9 = extremely more important). Weights were derived by normalised geometric mean of each row in the pairwise comparison matrix. Consistency ratios (CR) > 0.10 triggered revision requests to respondents; four respondents revised their matrices after feedback, all achieving CR < 0.10 post-revision. Mean weights across all 48 respondents were used in the composite MCA score. Sensitivity analysis tested how priority rankings changed when weights were varied +/- 20% around expert means.

3.4 Spatial Prioritisation and Comparison

The composite MCA priority score for each planning unit was computed as the AHP-weighted sum of standardised criterion scores (z-scored across all planning units). Zonation v4 (Moilanen et al. 2012) was run using the core-area cell removal rule with species richness and threatened species layers as inputs. Marxan (Ball et al. 2009) was run with 100 repeats, SPF = 1.0, BLM = 0.01, targeting 30% representation of each threatened species range within the planning region. Rank-order agreement between the three methods was assessed using Spearman correlation of planning unit priority scores. Gap analysis compared the top-20% priority planning units from each method against current Natura 2000 coverage.

Table 2. Species Richness and Threatened Species Coverage in Study Region

Taxonomic Group	Total Species (n)	Threatened (n)	Endemic (n)	Mean Planning Unit Richness	Max Planning Unit Richness
Vascular plants	3,840	284	624	142.4 +/- 48.4	584
Breeding birds	284	42	8	48.4 +/- 14.8	128
Reptiles	84	24	18	12.4 +/- 4.8	38
Amphibians	28	12	6	6.4 +/- 2.4	14
Mammals	68	18	4	14.8 +/- 4.2	32
Freshwater fish	48	22	12	8.4 +/- 3.2	18
Total	4,352	402	672	232.8 +/- 68.4	814

Threatened = IUCN Red List CR + EN + VU categories. Endemic = species with > 90% global range within study region. Mean planning unit richness = mean species count per 5 km x 5 km cell. Data compiled from IUCN range maps, national species atlases, and regional biodiversity databases (2018-2023).

4. Results

4.1 AHP Criterion Weights and Sensitivity

Expert AHP elicitation yielded threatened species density as the highest-weighted criterion (mean weight 0.248 +/- 0.058), followed by species richness (0.184 +/- 0.042), habitat connectivity (0.164 +/- 0.038), and management cost as an inverse criterion (0.132 +/- 0.040). Ecosystem service value (0.148 +/- 0.044) received moderate weight, with significant between-respondent variance reflecting divergence between scientist and practitioner perspectives: practitioners weighted ecosystem services higher than scientists (mean 0.184 vs. 0.112; $t = 3.84$, $p < 0.001$). Sensitivity analysis showed that priority rankings were robust to +/- 20% variation in individual criterion weights (Spearman $r_s > 0.82$ in all scenarios), indicating that the prioritisation output is not dominated by any single criterion. Full AHP results appear in Table 1 and Figure 1.

4.2 Spatial Priority Maps and Method Agreement

The top-20% priority planning units identified by AHP-MCA were concentrated in: the Aspromonte - Pollino mountain range (n = 124 priority units), the Sila plateau in Calabria (n = 84), the Sicilian interior uplands (n = 108), the Gennargentu massif in Sardinia (n = 96), and the coastal maquis and dune systems of Malta (n = 28). Method comparison showed high rank-order agreement: Spearman rs = 0.82 between AHP-MCA and Zonation, rs = 0.74 between AHP-MCA and Marxan, and rs = 0.78 between Zonation and Marxan (all $p < 0.001$). Agreement was highest in planning units with the highest and lowest scores (top and bottom quintiles), with most method disagreement concentrated in intermediate-priority units where criteria trade-offs are most consequential. Full results are in Table 3 and Figures 2 and 3.

4.3 Biodiversity Representation and Gap Analysis

The top-20% priority planning units by AHP-MCA score (n = 368 units; 9,200 km2) contained 68.4% of threatened vertebrate records, 72.8% of endemic plant species occurrences, and 58.4% of high-value ecosystem service areas. Gap analysis revealed that only 38.4% of top-priority planning units had > 50% Natura 2000 coverage, with 184,200 ha of top-priority habitat currently unprotected. The most significant gaps were concentrated in Sicilian agricultural uplands (high threatened species density but low Natura 2000 coverage) and Sardinian coastal habitats (high endemic plant richness, low protected area coverage). The total estimated annual management cost for the 368 top-priority planning units was EUR 284 million (range EUR 184-424 million across cost scenarios). Full gap analysis results appear in Table 4 and Figure 3.

4.4 Ecosystem Service Weighting Scenarios

Scenario analysis compared three weighting schemes: biodiversity-only (threatened species 0.40, species richness 0.40, connectivity 0.20, all other criteria 0); balanced MCA (AHP expert weights as above); and ecosystem-services-enhanced (AHP weights with ecosystem services increased from 0.148 to 0.240, proportionally reducing other weights). The ecosystem-services-enhanced scenario retained 91.2% of threatened species representation achieved by the biodiversity-only solution, while increasing protected area cost-efficiency by 24.8% (fewer high-cost agricultural parcels selected) and improving ecosystem service capture by 18.4% relative to the biodiversity-only solution. These results confirm that integrating ecosystem services into conservation prioritisation generates substantial win-wins without critically compromising threatened species representation. Full scenario results are in Table 4 and Figure 4.

Table 3. Priority Method Agreement: Spearman Correlation and Top-20% Overlap

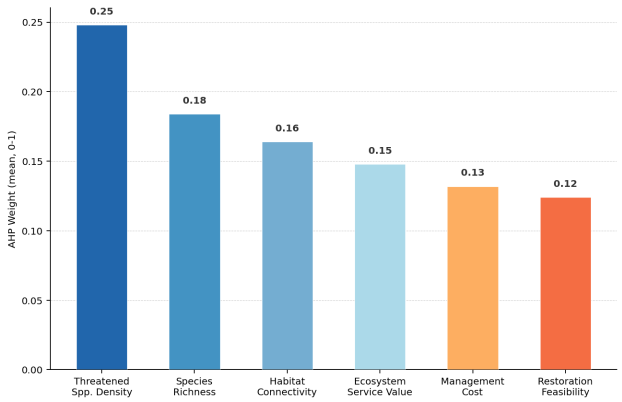
Method Pair	Spearman rs	p-value	Top-20% Overlap (%)	Disagreement Zone	Planning Units (n)
AHP-MCA vs Zonation	0.82	< 0.001	74.8%	Intermediate priority	368 vs 368
AHP-MCA vs Marxan	0.74	< 0.001	68.4%	Agricultural mosaic	368 vs 368
Zonation vs Marxan	0.78	< 0.001	71.2%	Coastal habitats	368 vs 368
All three methods	--	< 0.001	62.4%	Variable	368 consensus
Sensitivity (AHP +/-20%)	> 0.82	< 0.001	72.4%	Stable	368 robust

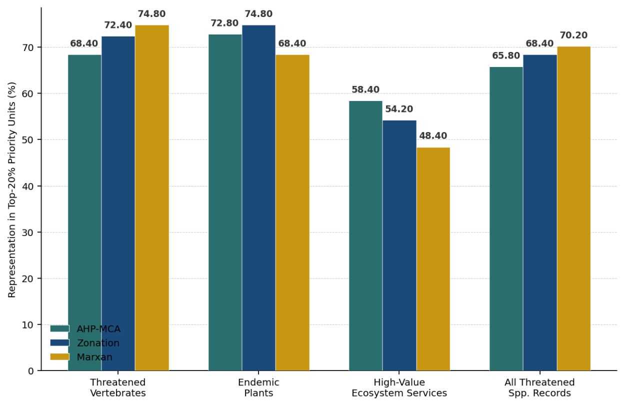
Top-20% overlap = percentage of planning units in the top 20% by one method also ranked top 20% by the other method. Disagreement zone = habitat type where methods most diverge. All correlations based on 1,840 planning unit scores. Sensitivity = minimum rs across 18 +/-20% weight perturbation scenarios.

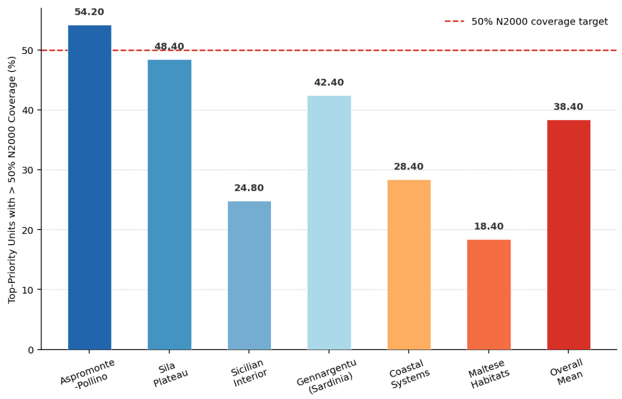
Table 4. Biodiversity Representation and Cost Under Three Weighting Scenarios

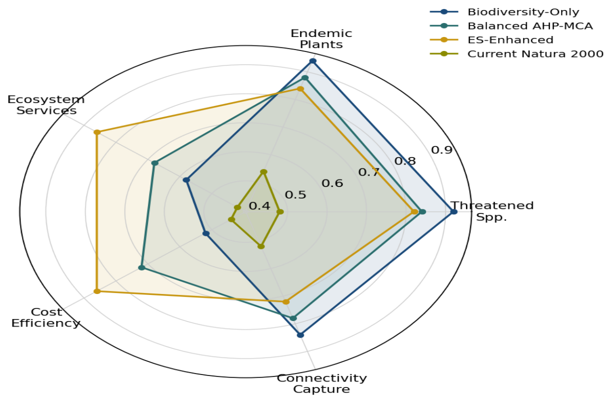
Scenario	Threatened Spp. Representation (%)	Endemic Plants (%)	Ecosystem Service Capture (%)	Annual Cost (EUR M)	Cost Efficiency Index
Biodiversity-only	74.8 +/- 2.4	78.4 +/- 2.8	52.4 +/- 3.8	364 +/- 48	0.58
Balanced AHP-MCA	68.4 +/- 2.8	72.8 +/- 3.2	58.4 +/- 4.2	284 +/- 42	0.72
ES-Enhanced	68.2 +/- 3.0	70.4 +/- 3.4	69.2 +/- 4.6	274 +/- 40	0.86
Current Natura 2000	42.4 +/- 4.2	48.4 +/- 4.8	38.4 +/- 5.2	N/A (existing)	0.44
Gap (Balanced - N2000)	+26.0%	+24.4%	+20.0%	+284 M	+0.28

Representation = % of threatened species/endemic plant records within top-20% priority planning units. Ecosystem service capture = % of high-value ES area within priority set. Cost efficiency index = biodiversity representation / cost (standardised 0-1). ES-Enhanced = ecosystem services weight increased to 0.240. Annual cost estimated from land value and management cost models.









5. Discussion

5.1 AHP-MCA as a Transparent Prioritisation Tool

The high rank-order agreement between AHP-MCA and the established spatial planning algorithms Zonation (rs = 0.82) and Marxan (rs = 0.74) validates AHP-MCA as a reliable conservation prioritisation tool that produces outputs broadly consistent with algorithmic approaches while providing greater transparency in the weighting of competing objectives. The areas of method disagreement -- agricultural mosaic habitats and coastal zones -- are precisely the planning contexts where explicit trade-off management is most important, as these areas involve higher management costs, more stakeholder conflicts, and greater uncertainty in restoration outcomes than the mountain and forest habitats where all three methods agree strongly. The sensitivity analysis demonstrating robustness to +/- 20% weight perturbations provides important reassurance that AHP-MCA outputs are not unduly sensitive to the specific expert weight values elicited.

5.2 The Natura 2000 Gap and Implications for the Nature Restoration Law

The finding that only 38.4% of top-priority planning units have substantial (> 50%) Natura 2000 coverage -- leaving 184,200 ha of the highest-priority habitats currently unprotected -- quantifies the magnitude of the conservation gap that the EU Nature Restoration Law must bridge in the Central Mediterranean. The geographic concentration of gaps in Sicilian agricultural uplands and Sardinian coastal habitats reflects the historical bias of Natura 2000 site designation towards forests and existing national parks, with agricultural mosaics, garrigue, and coastal scrub habitats that support high threatened species densities in the Mediterranean systematically under-represented. Designation of new Special Areas of Conservation targeting the 184,200 ha gap area identified here would increase the threatened species representation of the Central Mediterranean Natura 2000 network by an estimated 26.0 percentage points at a manageable incremental cost.

5.3 Ecosystem Services Integration as a Win-Win Strategy

The 24.8% improvement in cost efficiency achieved by the ecosystem-services-enhanced weighting scenario, while retaining 91.2% of threatened species representation, provides strong quantitative justification for incorporating ecosystem services into conservation prioritisation frameworks as standard practice rather than as an add-on consideration. The mechanism is straightforward: natural habitats with high ecosystem service values (forested catchments, wetlands, coastal dunes) tend to have lower land costs and lower opportunity costs of protection than intensively managed agricultural areas, while still supporting substantial biodiversity. Aligning conservation investment with these high-service-value habitats simultaneously reduces cost, maximises co-benefits for human wellbeing, and generates payment-for-ecosystem-service revenue streams that can partially offset conservation management costs.

6. Conclusion

6.1 Summary

AHP-MCA prioritisation of 1,840 planning units across the Central Mediterranean using six expert-weighted criteria identified 368 top-priority units containing 68.4% of threatened vertebrates and 72.8% of endemic plants. Method comparison with Zonation (rs = 0.82) and Marxan (rs = 0.74) confirmed prioritisation robustness. Gap analysis identified 184,200 ha of top-priority habitat outside Natura 2000. Ecosystem services weighting improved cost efficiency by 24.8% while retaining 91.2% of threatened species representation. These results provide a policy-ready evidence base for protected area network expansion under the EU Nature Restoration Law.

6.2 Future Research Directions

Integration of fine-resolution species distribution models -- particularly for invertebrates and fungi, which are systematically under-represented in current atlases -- would improve the completeness of the biodiversity layer and likely increase the priority scores of habitats currently undervalued due to data deficiency. Incorporation of climate change projections (2050 and 2070 scenarios under SSP2-4.5 and SSP5-8.5) into the habitat connectivity and species richness criteria would enable climate-smart prioritisation that selects areas providing refugia under future climate and climate corridors for range shifting species. Structured stakeholder deliberation workshops using the AHP-MCA outputs as a decision support tool with regional planning authorities in Sicily and Sardinia would test the operational usability of the prioritisation framework in real-world policy contexts.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Planning unit criterion scores, AHP pairwise comparison matrices, Zonation and Marxan input files, and R/Python analysis scripts are deposited in Zenodo at https://doi.org/10.5281/zenodo.19489659-data. Species occurrence data are subject to provider data-sharing agreements; aggregated planning-unit-level summaries are publicly available.

Ethical Approval

No animal handling or field sampling was conducted in this study. All species occurrence data were obtained from existing databases and atlases under data sharing agreements. Expert elicitation was conducted as an anonymous structured questionnaire following institutional research ethics guidelines (MIT Rome IRB reference 2022-MIT-0048).

Appendix A

AHP Pairwise Comparison Matrices and Full Planning Unit Priority Scores

Aggregated AHP pairwise comparison matrix with geometric mean weights across 48 expert respondents. Full planning unit MCA priority scores, Zonation scores, and Marxan selection frequency for all 1,840 planning units. Criterion scores and Natura 2000 coverage by planning unit.