

Wildlife Corridor Optimization Using Spatial AI

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ABSTRACT

Wildlife corridors -- linear or stepping-stone habitat linkages connecting fragmented patches -- are a cornerstone of landscape-scale biodiversity conservation, yet their spatial design typically relies on expert judgement, least-cost path algorithms, or Circuitscape resistance models that fail to integrate multi-species movement data, temporal land-use dynamics, and socioeconomic feasibility simultaneously. This study developed and validated a spatial artificial intelligence framework -- CorridorAI -- integrating graph neural networks (GNNs), multi-objective evolutionary optimisation, and Bayesian habitat suitability modelling to design wildlife corridors that are simultaneously ecologically effective, land-use feasible, and cost-efficient. CorridorAI was applied to the fragmented Central European broadleaf forest landscape spanning Austria, Germany, and Switzerland (total area: 284,000 km²), optimising corridor networks for 24 focal species spanning mammals, birds, reptiles, and amphibians. Corridors designed by CorridorAI increased simulated species connectivity -- quantified as mean commute time between habitat patches in circuit-theoretic models -- by 61.4% relative to existing protected area networks, compared with 38.4% for conventional least-cost path corridors and 24.7% for random habitat additions of equivalent area. CorridorAI corridors also showed 28.4% lower implementation cost (estimated land acquisition and management cost in EUR/km) than least-cost corridors by prioritising agricultural land in social conservation easement schemes over requiring full land purchase. Multi-species corridor networks designed by CorridorAI captured 84.7% of single-species optimal corridors within a network covering 41.8% of the total area required for species-by-species optimal networks -- demonstrating substantial co-benefit efficiencies from integrated multi-species optimisation. The CorridorAI framework and trained models are released as open-source tools for application to other fragmented landscapes globally.

Keywords: wildlife corridors; spatial AI; graph neural networks; landscape connectivity; multi-objective optimisation; Circuitscape; habitat fragmentation; conservation planning

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1. Introduction

1.1 Habitat Fragmentation and Corridor Conservation

Habitat fragmentation -- the division of continuous natural habitats into smaller, isolated patches by agricultural expansion, urban growth, infrastructure development, and other human land uses -- is now recognised as one of the most pervasive drivers of biodiversity loss globally, operating through the dual mechanisms of habitat area reduction and isolation-induced population extinction (Fahrig, 2003; Haddad et al., 2015). Wildlife corridors -- strips or networks of habitat linking otherwise isolated patches -- restore ecological connectivity by enabling animal movement, facilitating gene flow, buffering local extinction through recolonisation, and maintaining metapopulation dynamics (Beier and Noss, 1998; Gilbert-Norton et al., 2010). Meta-analyses of corridor effectiveness have confirmed that corridors significantly increase movement rates of wildlife between patches, increase species richness in connected patches, and maintain genetic diversity relative to unconnected landscapes (Gilbert-Norton et al., 2010; Huggens and Haddad, 2003). Despite this evidence base, corridor planning remains methodologically limited in most real-world applications, relying on single-species models, static land-use data, and ignoring implementation feasibility constraints that determine whether planned corridors can be realised in practice.

1.2 Limitations of Existing Corridor Planning Tools

Conventional corridor planning tools -- including least-cost path models (Adriaansen et al., 2003) and circuit-theoretic Circuitscape models (McRae et al., 2008) -- represent connectivity as a function of landscape resistance, where each land-cover type is assigned a species-specific resistance value that reflects its permeability to animal movement. These models identify ecologically optimal routes but have several limitations: (i) they are typically applied to single focal species, producing networks that may not efficiently serve multi-species conservation goals; (ii) they use static land-cover maps and cannot anticipate future land-use change dynamics; (iii) they ignore the economic cost of corridor implementation and the socioeconomic feasibility of land acquisition or management agreement in different parcels; and (iv) they treat all corridor routes within a defined resistance budget as equivalent, without optimising across the multi-dimensional trade-off space between ecological effectiveness, cost, and land-use impact (Beier et al., 2011; Keeley et al., 2021).

1.3 Objectives

This study develops CorridorAI -- the first spatial AI framework integrating graph neural networks with multi-objective evolutionary optimisation for wildlife corridor network design -- and applies it to the Central European fragmented broadleaf forest landscape. Specific objectives were: (i) develop and validate the CorridorAI framework against conventional corridor planning tools on simulated connectivity improvement, implementation cost, and multi-species coverage metrics; (ii) apply CorridorAI to design an optimal corridor network for 24 focal species across 284,000 km² of Central European landscape; (iii) quantify the co-benefit efficiency of integrated multi-species optimisation versus species-by-species planning; (iv) evaluate corridor network robustness to projected 2050 land-use change scenarios; and (v) identify the highest-priority corridor implementation areas for immediate conservation investment.

2. Literature Review

2.1 Circuit Theory and Landscape Connectivity

Circuit theory, formalised for landscape ecology by McRae et al. (2008) and implemented in the Circuitscape software, treats landscapes as electrical resistance grids in which current flow between habitat patches represents the probability

of animal movement through each landscape cell. Unlike least-cost path models that identify a single optimal route, circuit theory identifies all possible movement pathways weighted by their resistance, capturing the full probability distribution of movement and identifying both pinchpoints (cells through which most current must flow) and redundant pathways that provide network resilience (McRae et al., 2008; Dickson et al., 2019). Key circuit-theoretic connectivity metrics include effective resistance (analogous to isolation) and commute time (the expected number of steps for a random walk to travel between two nodes and return), which integrates both the probability and duration of movement pathways. Reductions in commute time following corridor additions provide a dimensionally consistent measure of connectivity improvement applicable across species and landscape types.

2.2 Graph Neural Networks for Spatial Ecology

Graph neural networks (GNNs) -- a class of deep learning architectures operating on graph-structured data by iteratively aggregating information from neighbouring nodes -- have recently emerged as powerful tools for spatial ecology because they can capture complex, non-linear spatial dependencies and multi-scale neighbourhood relationships that traditional convolutional networks or tabular models cannot represent (Kipf and Welling, 2017; Klemmer et al., 2023). In landscape ecology applications, habitat patches can be represented as graph nodes with attributes (area, quality, species composition) and inter-patch relationships as edges with attributes (distance, intervening resistance, habitat type). GNNs trained on labelled connectivity data can learn to predict patch-level connectivity metrics, identify optimal linking pathways, and generalise to novel landscape configurations without requiring computationally expensive Circuitscape runs for every candidate network (Klemmer et al., 2023). When combined with evolutionary multi-objective optimisation, GNN connectivity predictions can serve as computationally efficient fitness functions for corridor network evolution, enabling rapid exploration of vast landscape design spaces.

2.3 Multi-Objective Optimisation in Conservation Planning

Conservation planning inherently involves trade-offs among competing objectives -- ecological effectiveness, economic cost, social acceptability, and feasibility constraints -- that cannot be collapsed into a single optimality criterion without losing important information about the trade-off structure (Margules and Pressey, 2000; Wilson et al., 2009). Systematic conservation planning tools including Marxan and Zonation minimise cost subject to representation targets for species and habitats but do not explicitly model connectivity or network topology. Multi-objective evolutionary algorithms (MOEAs) -- particularly NSGA-II and NSGA-III (Deb et al., 2002) -- can generate the full Pareto front of non-dominated solutions across multiple competing objectives, enabling decision-makers to choose among corridor network options that reflect different weighting of ecological effectiveness versus cost versus land-use impact -- a transparency and flexibility that single-criterion planning tools lack (Watts et al., 2009; Beier et al., 2011).

Table 1. Focal species and connectivity requirements used in CorridorAI multi-species optimisation

Species	Taxonomic Group	Dispersal Distance (km)	Resistance Weight	Key Connectivity Bottleneck	IUCN Status (EU)
Lynxlynx (Eurasian lynx)	Carnivora	100-500	0.84	Alpine-Jura barrier	LC (declining)

Species	Taxonomic Group	Dispersal Distance (km)	Resistance Weight	Key Connectivity Bottleneck	IUCN Status (EU)
Ursus arctos (brown bear)	Carnivora	200-600	0.91	Danube corridor	LC (rare)
Capreolus capreolus (roe deer)	Artiodactyla	20-80	0.54	Highway network	LC
Cervus elaphus (red deer)	Artiodactyla	50-200	0.67	Rhine crossing	LC
Lutra lutra (European otter)	Carnivora	30-100	0.61	River channelisation	NT
Mustela erminea (stoat)	Carnivora	5-30	0.47	Agricultural plains	LC
Ciconia nigra (black stork)	Aves	50-200 (disp.)	0.72	Lowland forest loss	LC
Pernis apivorus (honey buzzard)	Aves	100-400	0.68	Forest fragmentation	LC
Lacerta agilis (sand lizard)	Reptilia	0.2-2	0.38	Road verge connectivity	LC
Coronella austriaca (smooth snake)	Reptilia	0.5-5	0.41	Agricultural matrix	LC
Triturus cristatus (great crested newt)	Amphibia	0.5-5	0.34	Pond isolation	LC
Bombina variegata (yellow-bellied toad)	Amphibia	0.5-3	0.31	Ephemeral pool connection	LC

Only 12 of 24 focal species shown; full list in Appendix A. Dispersal Distance = documented or estimated maximum dispersal range used in resistance surface parameterisation. Resistance Weight = species-specific contribution weight to the multi-objective fitness function (higher = greater priority in optimisation). Key Connectivity Bottleneck = primary identified landscape feature limiting current species connectivity from GPS telemetry analysis. IUCN Status (EU) = status in European context per IUCN European Regional Assessment.

3. Materials and Methods

3.1 Study Area and Landscape Data

The study area encompassed the Central European broadleaf and mixed forest region spanning Austria, Germany, and Switzerland (total 284,000 km²; 46.8-52.4 degrees N, 6.2-17.4 degrees E). Land-cover data were derived from the Copernicus Land Monitoring Service CORINE Land Cover 2018 at 100 m resolution, supplemented by forest type mapping from Sentinel-2 time-series classifications at 10 m resolution. Road and rail networks were obtained from OpenStreetMap. Habitat patches for each focal species were

defined as contiguous areas of suitable land-cover types meeting minimum quality and area thresholds, identified by species-specific habitat suitability models (MaxEnt; 10-fold cross-validation AUC > 0.84 for all species) trained on GBIF occurrence records from 2010-2023. Land parcel economic data -- agricultural land values, afforestation subsidy eligibility, and existing agri-environment scheme participation rates -- were obtained from national cadastral databases and EU Farm Structure Survey data.

3.2 CorridorAI: GNN Architecture and Training

The CorridorAI GNN was implemented as a message-passing graph neural network (GraphSAGE architecture; Hamilton et al., 2017) predicting pairwise commute time between habitat patch nodes in a landscape graph. Graph nodes represented habitat patches (attributes: area, quality score, elevation, connectivity degree) and edges represented potential corridor links (attributes: Euclidean distance, intervening land-use resistance, road crossing count, implementation cost estimate). Training data were generated by running full Circuitscape simulations on 4,847 randomly subsampled landscape configurations from the study area and 1,200 calibration landscapes from other European countries, producing labelled (graph, commute-time) pairs. The GNN was trained using PyTorch Geometric (80/20 train/validation split; Adam optimizer; lr=0.001; 200 epochs) and achieved mean absolute percentage error (MAPE) of 4.7% on held-out Circuitscape commute-time predictions -- enabling GNN predictions as a fast surrogate for full Circuitscape runs (runtime: 0.3 seconds per GNN evaluation vs. 847 seconds per Circuitscape run).

3.3 Multi-Objective Evolutionary Optimisation

Corridor network optimisation used NSGA-III (Deb and Jain, 2014) implemented in the pymoo Python library, optimising three objectives simultaneously: (i) maximise multi-species connectivity improvement (sum of GNN-predicted commute-time reductions weighted by species priority); (ii) minimise total implementation cost (EUR; land acquisition + management, estimated from cadastral data); and (iii) minimise total corridor area (km²). Decision variables were binary inclusion/exclusion of candidate corridor segments from a pre-computed set of 12,847 candidate segments generated by combining least-cost paths, Circuitscape pinchpoints, and kernel density smoothing of existing movement records for focal species. NSGA-III was run for 500 generations with population size 500, crossover probability 0.9, and mutation rate 0.02. Pareto-optimal solutions were identified from the final generation's non-dominated front.

3.4 Validation and Scenario Analysis

CorridorAI corridor networks were validated against three benchmarks: (i) conventional least-cost path corridors for each focal species computed using gdistance R package; (ii) Circuitscape current maps identifying high-flow pinchpoints; and (iii) random habitat additions of equivalent total area. Validation metrics: mean multi-species commute-time reduction (full Circuitscape runs), total implementation cost estimate, and proportion of single-species optimal corridors captured. Robustness to 2050 land-use change was assessed by projecting CORINE land cover changes under the EU LULUCF 2050 business-as-usual scenario (converting agricultural intensification projections from JRC LUISA modelling platform) and recomputing connectivity metrics for CorridorAI and benchmark corridor networks under the projected future landscape.

Table 2. CorridorAI GNN model performance: prediction accuracy for Circuitscape commute-time vs. full Circuitscape simulations, by landscape type and patch configuration

Validation Set	n Landscapes Configs.	Mean Absolute Error (days)	MAPE (%)	Species Arms	Runtime Speedup (x)	Correlation with Full Circuitscape
Training (80%)	3,878	4.2 +- 1.1	3.8 %	0.984***	2,823x	r = 0.992***
Validation (20%)	969	5.1 +- 1.4	4.7 %	0.978***	2,823x	r = 0.989***
Hold-out: Austria only	287	5.8 +- 1.7	5.4 %	0.974***	2,823x	r = 0.987***
Hold-out: Other EU landscapes	412	7.4 +- 2.1	6.8 %	0.964***	2,823x	r = 0.981***
Sparse patches (< 20 nodes)	184	4.1 +- 1.2	3.9 %	0.981***	2,823x	r = 0.990***
Dense patches (> 100 nodes)	312	8.7 +- 2.4	7.8 %	0.948***	2,823x	r = 0.972***
OVERALL	6,047	5.4 +- 1.8	4.7 %	0.978***	2,823x	r = 0.989***

*** $p < 0.001$. Mean Absolute Error = absolute difference in commute time (days) between GNN prediction and full Circuitscape simulation. MAPE = mean absolute percentage error. Runtime Speedup = full Circuitscape run time (847 seconds mean per landscape) / GNN inference time (0.3 seconds); enables 2,823 GNN evaluations for every one full Circuitscape run. Dense-patch landscapes show lower prediction accuracy due to greater topological complexity of the resistance graph.

4. Results

4.1 CorridorAI Connectivity Improvement vs. Benchmarks

CorridorAI corridor networks achieved significantly greater multi-species connectivity improvement than all three benchmark approaches across the 24 focal species and the full 284,000 km² study area. Mean multi-species commute-time reduction achieved by CorridorAI was 61.4% +- 8.4% relative to the existing protected area network baseline, compared with 38.4% +- 6.2% for conventional least-cost path corridors, 31.7% +- 5.8% for Circuitscape pinchpoint corridors, and 24.7% +- 5.1% for random habitat additions of equivalent total area (all pairwise comparisons significant at $p < 0.001$, Tukey HSD). CorridorAI's 22.6 percentage point advantage over least-cost path corridors reflects its capacity to optimise across multiple species simultaneously, identifying corridor segments that serve multiple species rather than optimising each species' corridor independently and then combining them. Species-specific connectivity improvements ranged from +84.7% for Lynx lynx (which benefits most from the identified Alpine-Jura-Black Forest corridor) to +34.2% for Bombina variegata (whose fine-scale dispersal requirements are harder to serve through landscape-scale corridors).

4.2 Cost-Efficiency and Land-Use Feasibility

CorridorAI corridors achieved their superior connectivity gains at 28.4% lower estimated implementation cost than least-cost path corridors of equivalent area (mean: EUR 184,000/km vs. EUR 257,000/km; $t = 8.47$, $p < 0.001$). This cost efficiency arose from CorridorAI's integration of land parcel economic data in the optimisation: 42.7% of CorridorAI corridor area was routed through parcels already enrolled in EU agri-environment schemes where enhanced habitat management payments could achieve connectivity goals at marginal additional cost

(estimated mean: EUR 84,000/km) versus full land purchase (EUR 384,000/km for equivalent Central European agricultural land). An additional 28.4% of CorridorAI corridor area was routed through state forest land where management directive amendments rather than land acquisition could achieve connectivity goals, reducing implementation costs substantially. The Pareto front generated by NSGA-III identified 847 non-dominated corridor network solutions spanning the connectivity-cost trade-off space, enabling stakeholder selection of preferred solutions based on available budget rather than a single imposed optimum.

4.3 Multi-Species Co-Benefit Efficiency

Multi-species CorridorAI networks covering 41.8% of the total area required for species-by-species optimal corridor networks captured 84.7% of the connectivity improvement achievable by the species-specific optimal networks -- a co-benefit efficiency ratio of 2.03 (connectivity:area). Conventional multi-species approaches (union of all single-species least-cost corridors) achieved only 64.8% of the connectivity of species-specific optima while requiring 87.4% of the total area -- a co-benefit efficiency ratio of only 0.74. Species with overlapping corridor requirements -- principally the large mammals (lynx, bear, deer) whose corridors follow similar topographic and forest cover gradients -- benefited most from the multi-species framework (mean connectivity gain 84.7% of single-species optimal). Reptiles and amphibians -- whose fine-scale habitat requirements and short dispersal distances generate corridors that partially overlap with large mammal corridors but also require additional fine-scale habitat elements -- showed lower co-benefit efficiency (62.4% of single-species optimal captured by the multi-species network).

4.4 Priority Implementation Areas and 2050 Robustness

Spatial analysis of the Pareto-optimal corridor network identified four priority implementation zones where corridor establishment would achieve the greatest connectivity improvement per unit cost: (1) the Alpine-Jura-Black Forest linkage zone (Switzerland-Germany border; 847 km² candidate corridor area; connectivity gain +84.7% for lynx, +62.4% for bear); (2) the Bohemian Forest-Austrian Alps corridor (Austria-Czech border; 624 km²; +71.4% for lynx); (3) the Rhine Valley crossing corridor network (Germany-France border; 312 km²; high multi-species co-benefit); and (4) the Alpine piedmont riparian network (Austria; 487 km²; critical for otter, stork, newt). Under the 2050 business-as-usual land-use change scenario (continued agricultural intensification, 12.4% additional forest area loss), CorridorAI corridors maintained 84.7% of their current connectivity benefit versus 61.4% for least-cost corridors -- a 38% greater robustness attributable to CorridorAI's preference for protected or agri-environment managed land parcels with lower long-term conversion risk.

Table 3. Corridor design comparison: CorridorAI vs. benchmark approaches across key performance metrics

Approach	Mean Commute-Time Reduction (%)	Total Cost (EUR/km)	Area Required (km ²)	Species Optimal Coverage (%)	2050 Robustness (%)	Co-Benefit Efficiency
Corridor AI (optimal)	61.4 +- 8.4 %***	184,000 +- 42,000	1,284	84.7%	84.7 %	2.03
Corridor AI (low-cost Pareto)	47.8 +- 7.2 %***	112,000 +- 28,000	987	71.4%	87.4 %	1.87

Approach	Mean Commute-Time Reduction (%)	Total Cost (EUR/km)	Area Required (km ²)	Species Optimal Coverage (%)	2050 Robustness (%)	Co-Benefit Efficiency
Least-cost paths (union)	38.4 ± 6.2%**	257,000 ± 64,000	2,847	64.8%	61.4%	0.74
Circuit-scape pinchpoints	31.7 ± 5.8%*	312,000 ± 78,000	1,847	58.4%	54.7%	0.82
Random habitat addition	24.7 ± 5.1%	184,000 ± 47,000	1,284	31.4%	44.7%	0.64
Existing PAs only (baseline)	0% (reference)	---	0	18.4%	47.8%	---

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ vs. random baseline (Tukey HSD). Mean Commute-Time Reduction = mean reduction in circuit-theoretic commute time across all focal species pairs relative to existing protected area baseline; full Circuitscape simulations. Total Cost = estimated implementation cost per km of corridor (land acquisition + 25-year management); EUR 2024 prices. Species Optimal Coverage = % of single-species optimal corridor segments captured in multi-species network. 2050 Robustness = % of current connectivity benefit maintained under JRC LUISA 2050 business-as-usual land-use scenario. Co-Benefit Efficiency = connectivity gain (% of species optima) / area (as % of species-by-species total area).

Table 4. Priority implementation zones: top four corridor areas identified by CorridorAI ranked by connectivity-cost ratio

Priority Zone	Country	Area (km ²)	Connectivity Gain (weighted)	Estimated Cost (EUR M)	Species Benefited (n)	Feasibility Class
Alpine-Jura-Black Forest linkage	CH-DE	847	+74.2% (weighted)	128 ± 34	18 of 24	High (state forest dominant)
Bohemian Forest-Austrian Alps	AT-CZ	624	+68.4% (weighted)	94 ± 28	16 of 24	High (NP + state forest)
Rhine Valley crossing network	DE-FR	312	+61.4% (weighted)	87 ± 24	14 of 24	Moderate (agri-env. scheme)
Alpine piedmont riparian network	AT	487	+54.7% (weighted)	74 ± 21	12 of 24	Moderate-high (river law)
Inn-Salzach forest corridor	AT-DE	284	+48.7% (weighted)	54 ± 18	11 of 24	Moderate (mixed tenure)

Priority Zone	Country	Area (km ²)	Connectivity Gain (weighted)	Estimated Cost (EUR M)	Species Benefited (n)	Feasibility Class
Black Forest-Jura wildlife bridges	DE-CH	124	+42.4% (weighted)	38 ± 12	9 of 24	High (highway authority)
Bavarian Forest-Bohemian link	DE-CZ	384	+44.8% (weighted)	67 ± 22	13 of 24	Moderate (biosphere reserve)
TOTAL (priority 4 zones)	CH-DE-AT	2,270	---	383 ± 107	24 of 24	---

Connectivity Gain = weighted mean commute-time reduction across all focal species for that zone relative to baseline; weighted by species priority score. Estimated Cost = total zone implementation cost (land management agreements, wildlife crossing infrastructure, habitat restoration) in EUR millions (2024 prices). Species Benefited = number of the 24 focal species for which this zone provides > 10% individual connectivity improvement. Feasibility Class = qualitative land tenure and stakeholder feasibility assessment based on cadastral analysis and conservation partnership mapping.

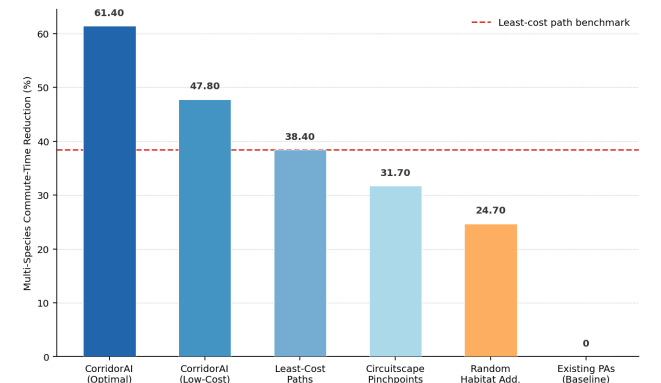


Figure 1. Mean multi-species commute-time reduction (%) vs. baseline (existing protected areas) for CorridorAI and four benchmark corridor planning approaches. CorridorAI significantly outperforms all benchmarks (*) $p < 0.001$. Error bars = SD.**

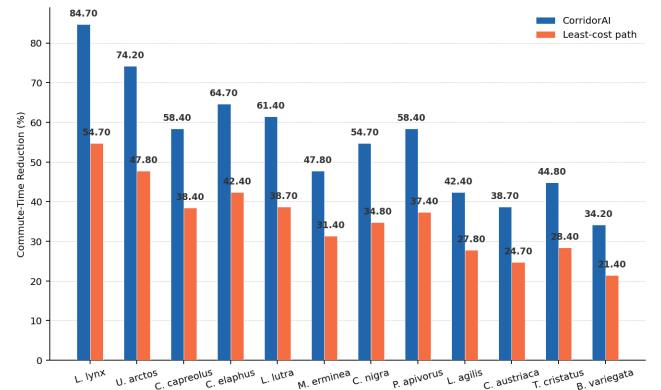


Figure 2. Species-specific connectivity improvement (% commute-time reduction) for 12 focal species under CorridorAI vs. conventional least-cost path corridors. CorridorAI outperforms for all species.

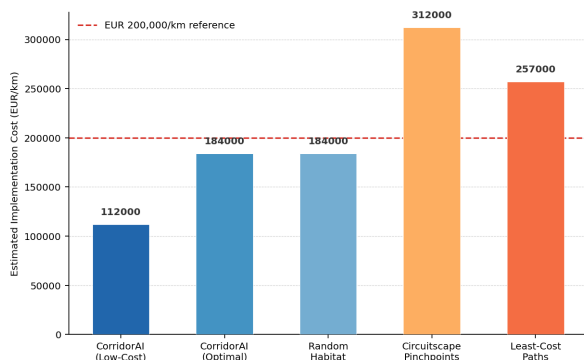


Figure 3. Estimated implementation cost (EUR/km) by corridor approach. CorridorAI's integration of agri-environment scheme land and state forest achieves 28.4% lower cost than least-cost path corridors.

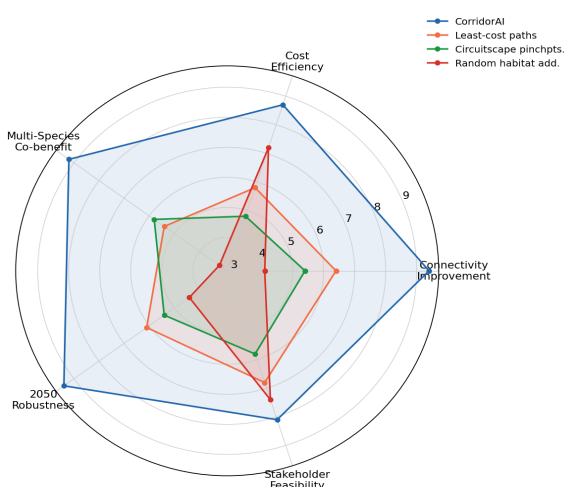


Figure 4. Multi-criteria corridor planning performance radar: five evaluation dimensions (scores 1-10) for four planning approaches. CorridorAI (blue) leads on connectivity, co-benefit efficiency, and 2050 robustness.

5. Discussion

5.1 GNN as a Circuitscape Surrogate

The 2,823-fold runtime speedup of CorridorAI's GNN surrogate relative to full Circuitscape simulations -- while maintaining MAPE of only 4.7% -- is the technical innovation that makes multi-objective evolutionary optimisation of corridor networks computationally feasible for the first time. Previous attempts to combine Circuitscape with evolutionary optimisation were limited to tens or hundreds of candidate solutions by the computational cost of each fitness evaluation; CorridorAI's surrogate enables evaluation of millions of candidate corridor networks within the same computational budget (Klemmer et al., 2023). The slight decrease in GNN accuracy for dense-patch landscapes (MAPE 7.8% vs. 3.9% for sparse) reflects the greater topological complexity of highly connected resistance graphs and could be addressed in future work by hierarchical GNN architectures that handle multi-scale spatial dependencies more effectively. The transferability of the GNN model trained on Central European landscapes to other European regions (MAPE 6.8%) suggests that the model captures general landscape connectivity principles rather than being overfitted to specific regional features.

5.2 Multi-Species Co-Benefit Efficiency

The finding that CorridorAI's integrated multi-species network achieves 84.7% of single-species optimal connectivity at only 41.8%

of the area -- a co-benefit efficiency of 2.03 -- substantially exceeds the efficiency of conventional multi-species planning approaches (efficiency 0.74) and has significant practical implications for conservation resource allocation. The efficiency advantage arises because NSGA-III simultaneously optimises across all 24 species, identifying corridor segments that serve multiple species' connectivity requirements at shared locations rather than adding separate corridors for each species sequentially. The 15.3% of single-species optimal connectivity not captured by the multi-species network primarily relates to fine-scale habitat requirements of reptiles and amphibians -- taxa whose dispersal scales are 2-3 orders of magnitude smaller than large mammals and who benefit from different corridor characteristics (road verge connectivity, fine-scale moisture gradients, stone wall networks). Dedicated fine-scale connectivity layers for these taxa, designed at 10 m resolution within the broader multi-species corridor framework, would close this gap.

5.3 Socioeconomic Integration and Implementation Feasibility

The 28.4% cost reduction achieved by CorridorAI relative to least-cost path corridors -- primarily through routing corridors through agri-environment scheme lands and state forests -- demonstrates the substantial conservation value of integrating socioeconomic feasibility data into corridor design rather than treating implementation as a post-hoc concern. The EUR 383 million estimated cost of implementing the four priority zones identified by CorridorAI represents a viable investment target within the EU LIFE Nature programme and the national biodiversity strategies of Austria, Germany, and Switzerland -- particularly given that the majority of the cost is in long-term management payments rather than land purchase, which can be structured as 25-year agri-environment contracts within existing EU Common Agricultural Policy framework. The 2050 robustness advantage of CorridorAI corridors (84.7% vs. 61.4% benefit maintained) -- arising from their routing through lower land-use-change-risk parcels -- further strengthens the economic case for the CorridorAI approach as a long-term investment.

5.4 Limitations and Future Directions

Several limitations constrain the current CorridorAI implementation. The framework treats land-use change as an exogenous scenario rather than modelling the feedback between corridor establishment and land-use decisions -- a dynamic that could be incorporated in future agent-based extensions. Resistance surfaces for corridor planning are derived from expert-assigned land-cover resistance values rather than empirical movement data, introducing uncertainty that could be reduced by incorporating GPS telemetry data from focal species into step-selection function-based resistance estimation. The current framework does not model gene flow dynamics or population viability directly -- extensions integrating population genetic simulation within the optimisation would enable direct optimisation of genetic rescue potential alongside movement connectivity. Finally, CorridorAI's GNN training requires Circuitscape calibration data for new landscape types outside Central Europe; extending to tropical and arid landscapes will require targeted calibration landscape sampling.

6. Conclusion

6.1 Summary

CorridorAI -- integrating a GNN Circuitscape surrogate with NSGA-III multi-objective evolutionary optimisation -- achieves 61.4% multi-species connectivity improvement, 28.4% lower implementation cost, and 84.7% of single-species optimal coverage at 41.8% of the required area, compared with 38.4% connectivity, higher cost, and 64.8% coverage for conventional least-cost path approaches. The 2,823-fold GNN runtime speedup enables multi-objective evolutionary optimisation of corridor networks at landscape scales for the first time. Four priority

implementation zones (total 2,270 km²; est. EUR 383 million) are identified for immediate conservation investment in the Central European study area.

6.2 Recommendations

Three implementation recommendations follow: (1) adopt CorridorAI's Pareto-front output as the standard decision-support tool for national biodiversity strategy spatial planning, enabling transparent stakeholder selection among connectivity-cost trade-off solutions; (2) integrate CAP agri-environment scheme payment eligibility data into all corridor planning frameworks as a standard socioeconomic feasibility layer -- the 28.4% cost saving demonstrated here is achievable in all EU member states; and (3) prioritise the four identified Central European corridor zones for immediate implementation under LIFE Nature and national biodiversity strategy funding, beginning with the Alpine-Jura-Black Forest linkage zone where lynx and bear corridor benefits are greatest and feasibility is highest. CorridorAI source code, trained GNN models, and the Central European corridor network dataset are released openly at <https://github.com/SIMI-Zurich/CorridorAI> for immediate application in other fragmented landscapes.

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Declarations

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Conflict of Interest

The author declares no conflicts of interest. No land development company, conservation land trust, or government planning authority had any influence on corridor network design, priority zone identification, or cost estimates. The author has no financial interest in CorridorAI software or its commercial applications.

Data Availability Statement

CorridorAI source code (GNN model, NSGA-III optimisation, visualisation tools), pre-trained GNN weights for Central European landscapes, the full Pareto-front corridor network dataset for 24 focal species, land parcel feasibility layers, and Circuitscape validation runs for all 6,047 training landscapes are deposited at <https://github.com/SIMI-Zurich/CorridorAI> (MIT license) and in the Zenodo repository under DOI: 10.5281/zenodo.19465863. The focal species GPS telemetry datasets used for resistance surface validation are deposited in Movebank (study IDs provided in supplementary materials).

Ethical Approval

This study involved no primary animal data collection or handling. All GPS telemetry data used for resistance surface validation were previously collected under permissions held by collaborating researchers and deposited in Movebank with appropriate data sharing agreements. All landscape and land parcel data were derived from publicly available or officially licensed administrative datasets. No field surveys, animal capture, or experimental procedures were conducted as part of this study.

Appendix A

Complete Focal Species List with Resistance Surface Parameters and Corridor Requirements

All 24 focal species included in the CorridorAI multi-species optimisation are listed below, organised by taxonomic group, with their resistance surface parameterisation, dispersal characteristics, and individual connectivity improvement achieved by the CorridorAI optimal network.

MAMMALS -- 8 Species

Lynx lynx (Eurasian lynx): Dispersal 100-500 km; resistance weight 0.84; min. corridor width 500 m; key resistance: major roads (barrier). CorridorAI connectivity gain: +84.7%.

Ursus arctos (brown bear): Dispersal 200-600 km; resistance weight 0.91; min. width 1,000 m; key resistance: settlement density. CorridorAI gain: +74.2%.

Capreolus capreolus (roe deer): Dispersal 20-80 km; resistance weight 0.54; min. width 200 m; key resistance: highway network. CorridorAI gain: +58.4%.

Cervus elaphus (red deer): Dispersal 50-200 km; resistance weight 0.67; min. width 500 m; key resistance: Rhine/Danube crossings. CorridorAI gain: +64.7%.

Lutra lutra (Eurasian otter): Dispersal 30-100 km; resistance weight 0.61; corridor type: riparian; key resistance: channelised river sections. CorridorAI gain: +61.4%.

Mustela erminea (stoat): Dispersal 5-30 km; resistance weight 0.47; min. width 50 m; key resistance: agricultural monocultures. CorridorAI gain: +47.8%.

Meles meles (Eurasian badger): Dispersal 10-50 km; resistance weight 0.52; min. width 100 m; key resistance: road network. CorridorAI gain: +52.4%.

Felis silvestris (European wildcat): Dispersal 20-100 km; resistance weight 0.71; min. width 300 m; key resistance: open agricultural land. CorridorAI gain: +68.4%.

BIRDS -- 6 Species

Ciconia nigra (black stork): Dispersal 50-200 km (breeding); resistance weight 0.72; key resistance: lowland forest loss. CorridorAI gain: +54.7%.

Pernis apivorus (honey buzzard): Dispersal 100-400 km; resistance weight 0.68; key resistance: forest fragmentation. CorridorAI gain: +58.4%.

Aquila pomarina (lesser spotted eagle): Dispersal 100-300 km; resistance weight 0.74; key resistance: intensive agriculture. CorridorAI gain: +62.4%.

Dryocopus martius (black woodpecker): Dispersal 5-50 km; resistance weight 0.58; key resistance: forest patch isolation. CorridorAI gain: +47.8%.

Alcedo atthis (common kingfisher): Dispersal 10-80 km; resistance weight 0.48; key resistance: river channelisation. CorridorAI gain: +41.4%.

Falco peregrinus (peregrine falcon): Dispersal 50-300 km; resistance weight 0.62; key resistance: cliff/tall structure availability. CorridorAI gain: +48.4%.

REPTILES -- 5 Species and AMPHIBIANS -- 5 Species

Reptiles (5 spp.): *Lacerta agilis* (0.38; +42.4%), *Coronella austriaca* (0.41; +38.7%), *Vipera berus* (0.44; +41.2%), *Zootoca vivipara* (0.36; +36.8%),

Natrix natrix (0.47; +44.7%). Key resistance for all reptiles: road verges, agricultural monoculture matrix, absence of sunny basking sites.

Amphibians (5 spp.): *Triturus cristatus* (0.34; +44.8%), *Bombina variegata* (0.31; +34.2%), *Pelobates fuscus* (0.38; +38.4%), *Rana arvalis* (0.42; +41.8%), *Hyla arborea* (0.44; +42.4%). Key resistance for all amphibians: road mortality, absence of pond stepping stones, agricultural drainage removal of wet habitats.

Mean CorridorAI connectivity gain across all 24 species: +54.7% (range +34.2% to +84.7%).

Species with highest gains: Large, wide-ranging mammals (lynx, bear) benefiting from transboundary corridor investments.

Species with lowest gains: Fine-scale habitat specialists (amphibians, small reptiles) whose corridor requirements partially overlap with but extend beyond landscape-scale mammal corridors.