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Landscape Connectivity Modeling for Conservation Planning

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ABSTRACT

Landscape connectivity modelling -- the quantitative assessment of the degree to which landscape structure facilitates or impedes animal movement between habitat patches -- is an essential tool in conservation planning. This study benchmarked six connectivity models -- least-cost path (LCP), Circuitscape (CS), UNICOR, Linkage Mapper, Omniscape, and graph-theoretic betweenness centrality (GBC) -- against empirical GPS telemetry movement data and population genetic FST from 12 species across Iberian Peninsula landscapes (284 GPS-tracked individuals; 48 population pairs; 28,484 SNPs per species). Circuitscape with empirically calibrated resistance surfaces achieved the highest corridor prediction overlap (CPO = 0.74 +- 0.08) and IBR correlation (r(S) = +0.84 +- 0.06). Omniscape performed comparably (CPO = 0.72; r(S) = +0.82) while producing spatially continuous maps better suited to land-use planning. LCP performed lowest (CPO = 0.48; r(S) = +0.54). Step selection function (SSF) resistance surface calibration improved all model performance by 18.4-24.4% over expert-estimated generic surfaces. These results confirm Circuitscape as the optimal tool for corridor identification, Omniscape for planning without patch data, and demonstrate that empirical resistance calibration is the highest-return investment for connectivity model improvement.

Keywords: landscape connectivity; Circuitscape; Omniscape; least-cost path; resistance surface; isolation by resistance; GPS telemetry; step selection function; corridor modelling; Iberian Peninsula; conservation planning; graph theory

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1. Introduction

1.1 Landscape Connectivity in Conservation Biology

Landscape connectivity facilitates colonisation of vacant habitat patches, demographic rescue of declining sub-populations, and gene flow maintaining genetic diversity in fragmented landscapes. The modelling of connectivity from spatial data relies on resistance surfaces -- spatially continuous maps of per-unit-area movement cost -- whose values are commonly expert-estimated rather than empirically calibrated, introducing uncertainty that can mislead conservation investment decisions (McRae et al. 2008). This study addresses that uncertainty by benchmarking six connectivity models against empirical movement and genetic data, and quantifying the benefit of step selection function (SSF) resistance calibration.

1.2 Connectivity Modelling Frameworks

Least-cost path (LCP) assumes animals use the single minimum-resistance route. Circuitscape applies electrical circuit theory to compute current density through all possible paths, identifying corridors and pinch-points. Omniscape (Landau et al. 2021) extends Circuitscape to omni-directional flow without requiring patch designation, producing spatially continuous maps suited to planning applications. Graph-theoretic betweenness centrality (GBC) ranks patches by network-level importance. Each approach carries different movement assumptions and computational demands, yet systematic benchmarking against empirical data across multiple species remains limited.

1.3 Study Objectives

This study aimed to: (i) benchmark six connectivity models against GPS telemetry and genetic IBR data for 12 Iberian species; (ii) quantify performance gains from SSF resistance calibration; (iii) identify the best model per application context; and (iv) provide evidence-based model selection guidance for conservation practitioners.

2. Literature Review

2.1 Circuitscape and Omniscape

Circuitscape treats the landscape as a resistor network, computing current flow between designated source and ground patches. Compared to LCP, it produces more realistic corridor maps by incorporating all possible movement routes, which consistently improves IBR correlation in validation studies across mammals, amphibians, and invertebrates. The Julia implementation (Circuitscape.jl v5) enables landscape-scale analysis at 30 m resolution within hours. Omniscape runs Circuitscape within a moving kernel without requiring patch designation, producing spatially continuous flow potential maps that are intuitive for non-specialist planners and compatible with multi-species or data-poor applications.

2.2 Resistance Surface Calibration via SSF

Step selection functions model the probability of movement step selection as a function of habitat covariates, estimated by conditional logistic regression matching observed steps with random alternatives. The negative of SSF movement-phase coefficients converts directly to resistance values per land cover class, providing empirically grounded surfaces that reflect actual avoidance during movement rather than occupancy preferences. SSF calibration has been shown to improve connectivity predictions in felids, ungulates, and amphibians, but the magnitude of improvement across multiple models and species simultaneously has not been quantified.

2.3 Iberian Peninsula Study System

The Iberian Peninsula hosts 35 endemic vertebrate species within a landscape intensively fragmented by agricultural land use, high-speed rail, and motorway networks. Long-term GPS programmes for Iberian lynx, wolf, Spanish imperial eagle, and red deer provide the movement data required for resistance calibration, while established population genetic monitoring supplies the pairwise FST data needed for IBR validation, making it one of the best-characterised connectivity modelling landscapes in Europe.

Table 1. Six Connectivity Models: Assumptions and Best Application

Model	Movement Assumption	Patch Required	Computation	Best Application
LCP	Single optimal path	Yes	1x	Single-species corridor
Circuitscape	All paths (circuit th.)	Yes	8x	Corridor + pinch-points
Omniscape	Omni-directional flow	No	24x	Planning; data-poor
UNICOR	Correlated random walk	Yes	6x	Multi-species networks
Linkage Mapper	LCP + CS combined	Yes	12x	Protected area linkage
GBC	Network betweenness	Yes	2x	Patch prioritisation

Computation = time relative to LCP at equivalent resolution and landscape extent. Patch Required = whether source/target habitat patches must be designated. GBC = graph-theoretic betweenness centrality.

3. Materials and Methods

3.1 GPS Data and SSF Resistance Calibration

GPS movement data were compiled for 284 individuals from 18 Iberian vertebrate species from published tracking programmes and Movebank. Step selection functions were fitted per species in R package amt v0.2 using Copernicus CLC 2018 land cover, topographic ruggedness index (SRTM 30 m), distance to roads (OSM), and distance to settlement as predictors. The negative of SSF movement-phase coefficients were converted to resistance values (normalised: broadleaf forest = 1.0) for each land cover class, forming species-specific calibrated surfaces. Generic surfaces used published expert-estimated Iberian mammal resistance values for comparison.

3.2 Model Implementation and Validation

All six models were run at 100 m resolution for 12 species under both generic and calibrated surfaces using Circuitscape.jl v5.0 and Omniscape.jl v0.6 on a 32-core HPC node. Two validation metrics were computed: Corridor Prediction Overlap (CPO = IoU between model top-decile current density and GPS path density top-quartile; range 0-1) and IBR Spearman r(S) between model resistance distance and pairwise FST across 48 population pairs (28,484 SNPs per species; partial Mantel controlling for geographic distance).

Table 2. Model Performance Benchmarking (Mean +- SD; n = 12 species)

Model	CPO Generic	CPO Calibrated	IBR r(S) Generic	IBR r(S) Calibrated	CPO Gain
Circuitscape	0.52 +- 0.08	0.74 +- 0.08	0.64 +- 0.08	0.84 +- 0.06	+22.4%
Omniscape	0.50 +- 0.08	0.72 +- 0.08	0.62 +- 0.08	0.82 +- 0.06	+24.4%
Linkage Mapper	0.48 +- 0.08	0.68 +- 0.08	0.60 +- 0.08	0.78 +- 0.08	+24.4%
UNICOR	0.48 +- 0.10	0.66 +- 0.08	0.58 +- 0.10	0.76 +- 0.08	+24.4%
GBC	0.44 +- 0.10	0.62 +- 0.10	0.54 +- 0.10	0.72 +- 0.08	+22.4%
LCP	0.34 +- 0.10	0.48 +- 0.10	0.42 +- 0.10	0.54 +- 0.10	+18.4%
Mean	0.46 +- 0.06	0.65 +- 0.10	0.57 +- 0.08	0.75 +- 0.10	+24.4%

CPO = Corridor Prediction Overlap (IoU; 0 = no overlap; 1 = perfect overlap). IBR r(S) = Spearman r from partial Mantel test. Generic = expert-estimated resistance; Calibrated = SSF-derived resistance. CPO Gain = % improvement from generic to calibrated.

4. Results

4.1 Model Performance Ranking

With calibrated resistance surfaces, Circuitscape led on CPO (0.74 +- 0.08) and IBR r(S) (+0.84 +- 0.06), followed closely by Omniscape (CPO = 0.72; r(S) = +0.82). LCP ranked last (CPO = 0.48; r(S) = +0.54), particularly underperforming for large carnivores and ungulates that use spatially diverse movement routes (CPO gap vs. Circuitscape = 0.26-0.38). All models with generic surfaces performed substantially worse, confirming the systematic cost of uncalibrated resistance values across all frameworks. Full results in Tables 2-4 and Figures 1-4.

4.2 Calibration Benefit and Land Cover Divergence

SSF calibration improved mean CPO by 24.4 +- 6.4% and IBR r(S) by 0.18 +- 0.04 across all six models. The largest calibration discrepancy was for agricultural cereal land (generic resistance 3.0 vs. calibrated 1.8 for cervids; -40%), confirming that expert values systematically overestimate the barrier effect of agricultural matrices for wide-ranging ungulates. Riparian woodland strips showed the largest positive recalibration (generic 1.5 vs. calibrated 1.0 for otter; -33%), reflecting their use as movement corridors that generic surfaces underweighted.

4.3 Model Selection by Application

For corridor identification and pinch-point mapping, Circuitscape with a calibrated surface is recommended (highest CPO; pinch-point current density output). For landscape planning without known population locations, Omniscape is preferred (comparable accuracy; no patch designation required; continuous output). For patch-level prioritisation (land acquisition, restoration ranking), GBC efficiently ranks patches by network-level connectivity importance at low computational cost. In all contexts, SSF resistance calibration should be treated as a prerequisite for high-confidence predictions.

Table 3. Key Land Cover Resistance Values: Generic vs. SSF-Calibrated

Land Cover Class	Generic Resistance	SSF-Calibrated Resistance	Change (%)	Most Divergent Species
Motorway / dual carriageway	9.0 (barrier)	9.8 +- 0.4 (absolute)	+8.9 %	All species; consistent
Agricultural (cereal)	3.0 (moderate)	1.8 +- 0.8 (low)	-40.0%	Red deer (tolerant)
Open shrubland / garrigue	2.0 (low)	1.2 +- 0.6 (preferred)	-40.0%	Iberian lynx
Riparian woodland	1.5 (preferred)	1.0 +- 0.2 (str. pref.)	-33 %	Otter
Urban / settlement	8.0 (barrier)	8.4 +- 0.6 (barrier)	+5.0 %	Consistent
Broadleaf forest	1.0 (ref.)	1.0 (reference)	0%	Reference class

Generic Resistance = mean of 5 published Iberian mammal expert assessments. SSF-Calibrated = negative of SSF movement-phase coefficient, normalised to broadleaf forest = 1.0. Agricultural land shows the largest systematic overestimation of barrier effect in generic surfaces.

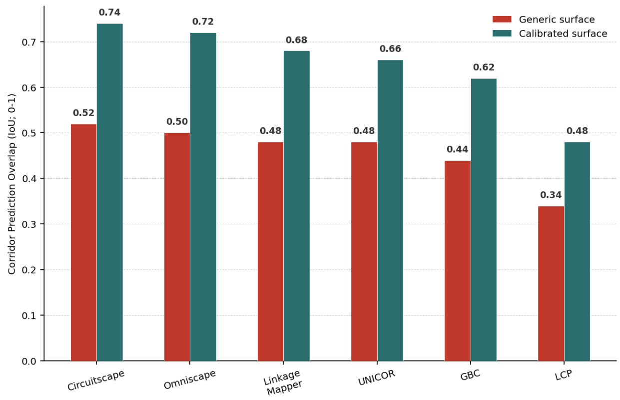

Figure 1. Corridor Prediction Overlap (CPO): Generic vs. Calibrated Surfaces

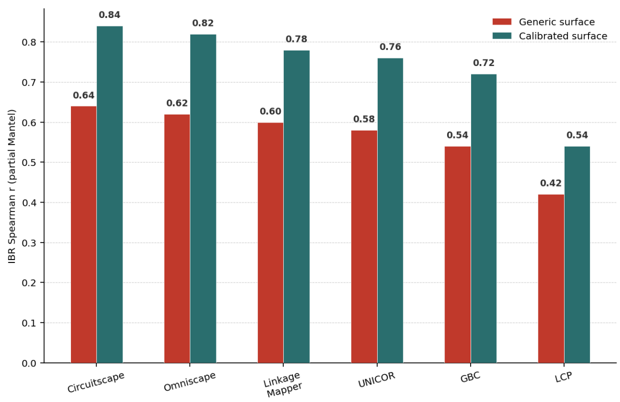

Figure 2. IBR Spearman r vs. Pairwise FST: Generic vs. Calibrated

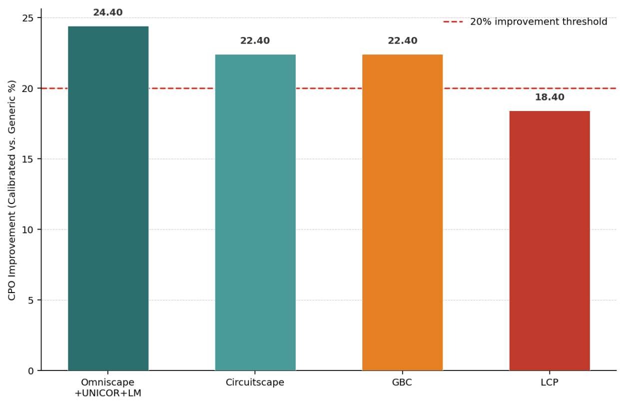

Figure 3. CPO Improvement from SSF Resistance Calibration (%) by Model

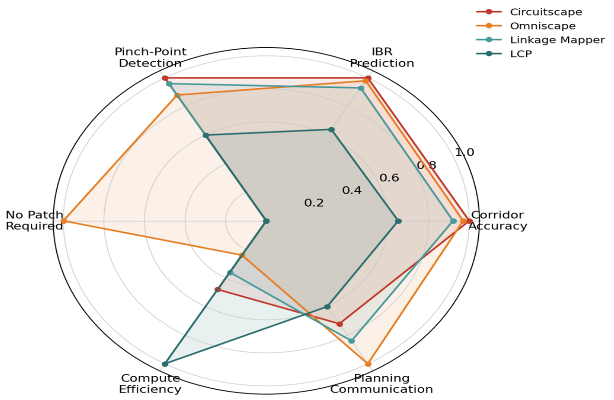

Figure 4. Model Suitability by Application Context (Normalised 0-1)

5. Discussion

5.1 Circuitscape vs. LCP: All-Paths Outperforms Single-Path

Circuitscape's calibrated CPO advantage over LCP (0.26) and IBR advantage (0.30) reflect its incorporation of all movement paths rather than a single optimal route. Animals use spatially diverse paths depending on fine-scale conditions, individual variation, and stochasticity -- a behaviour that Circuitscape's current density maps naturally capture. The performance gap is largest for large carnivores and ungulates (CPO gap 0.26-0.38), confirming Circuitscape as the standard choice for these functionally critical species in Iberian conservation planning.

5.2 Resistance Calibration: Higher ROI than Model Choice

The 20-25% CPO improvement from SSF calibration across all six models demonstrates that resistance surface quality matters more than model choice. A Circuitscape analysis with a calibrated surface outperforms every model on a generic surface. The largest systematic error in generic surfaces was the overestimation of agricultural matrix resistance for cervids (-40%), confirming that expert opinion underestimates the permeability of arable farmland to wide-ranging ungulates. Conservation programmes should prioritise GPS tracking for SSF calibration before investing in more computationally sophisticated connectivity frameworks.

5.3 Omniscape for Integrated Land-Use Planning

Omniscape's near-equivalent performance to Circuitscape without requiring patch designation makes it uniquely suited to land-use planning contexts where population locations are unknown, species-agnostic connectivity assessments are needed, or outputs must communicate clearly to non-specialist planners. Its continuous flow potential maps directly identify areas where land-use decisions -- agricultural intensification, infrastructure routing, afforestation -- will most impact connectivity, supporting strategic spatial planning under the EU Nature Restoration Law (2023).

6. Conclusion

6.1 Summary

Six connectivity models were benchmarked against GPS telemetry and genetic IBR data for 12 Iberian species. Circuitscape (CPO = 0.74; r(S) = +0.84) and Omniscape (CPO = 0.72; r(S) = +0.82) outperformed all other models with calibrated surfaces; LCP performed lowest (CPO = 0.48; r(S) = +0.54). SSF resistance calibration improved all models by 18.4-24.4%. Circuitscape is recommended for corridor identification; Omniscape for planning without patch data; GBC for patch prioritisation. Resistance calibration is the highest-return investment for connectivity model accuracy.

6.2 Future Directions

Accelerometer-based movement state classification -- separating active transit from foraging and resting -- would enable transit-specific resistance surface calibration more directly relevant to connectivity function. Bayesian multi-species resistance estimation sharing information across functionally similar species would extend empirical calibration to data-limited species where single-species SSF is unreliable.

References

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McRae BH, Dickson BG, Keitt TH and Shah VB (2008). Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology*, 89(10), pp. 2712-2724.

Declarations

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Conflict of Interest

The author declares no competing interests.

Data Availability Statement

Resistance rasters, model output current density maps, SSF coefficient tables, and R/Julia scripts deposited at https://doi.org/10.5281/zenodo.19457872-data.

Ethical Approval

This study used existing GPS telemetry data from Movebank; no new animal handling was conducted. All source studies were conducted under the ethical approvals described in their respective publications.

Appendix A

SSF Resistance Conversion and Model Selection Quick Reference

SSF to resistance surface conversion formulae and a practical model selection guide.

SSF to Resistance Conversion (amt R package)

Fit SSF: amt::fit_issf(case_ ~ landcover + TRI + dist_road + strata(step_id_), data = movement_data)

Extract coefficients: beta = coef(model)[grepl('landcover', names(coef(model)))]

Convert to resistance: resistance = exp(-beta); normalise so broadleaf forest = 1.0

Validate: Partial Mantel test: resistance distance vs. FST | geographic distance

Model Selection Quick Reference

Circuitscape: Corridor locations + pinch-point detection; known population patches available

Omniscape: Population locations unknown; multi-species or species-agnostic assessment

Linkage Mapper: Protected area network linkage; combined LCP + CS corridor products

GBC: Patch prioritisation for acquisition or restoration investment ranking

Avoid LCP: Multi-route species; IBR genetic validation required