ISSN: 2458-8989

Natural and Engineering Sciences

NESciences, 2025, 10 (2): 93-107 doi: 10.28978/nesciences.1763898

Modelling Habitat Connectivity Using Circuit Theory for Mammal Conservation Corridors

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Abstract

Habitat fragmentation is a significant barrier to the ability of terrestrial mammals to move freely across landscapes and also disrupts the genetic flow among populations. In this study, we employed circuit theory to investigate habitat connectivity and identify conservation corridors for mammals in fragmented landscapes. Circuit theory utilizes the fundamentals of electrical resistance theory to establish connections among landscapes as a conductive surface, representing landscape heterogeneity by assigning resistance values based on land cover, topography, and anthropogenic features. We developed resistance surfaces using ecological and movement data for species of interest to derive many possible dispersal pathways for mammals. Throughout the study area, we utilized Circuits cape to illustrate connectivity, which helped identify key corridors that maximize movement between core habitat patches or areas of high current density, where movement is most likely to occur. Results show that classic corridor models generally ignore alternative, but ecologically relevant routes that can be captured with a circuit-based approach. Overall, our results suggest that integrating circuit theory into conservation planning is a sound mechanism for identifying multifunctional corridors that enhance landscape permeability and resilience.

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This method helps prioritize areas to conserve, restore, and use sustainably, thereby maximizing the probability of persistence of mammal populations in an increasingly fragmented landscape.

Keywords:

Habitat connectivity, circuit theory, modelling, mammals, conservation corridors, fragmented landscapes, landscape ecology.

Article history:

Received: 02/03/2025, Revised: 17/05/2025, Accepted: 16/06/2025, Available online: 30/08/2025

Introduction

Summary of Habitat Connectivity in Wildlife Conservation

Habitat connectivity is an essential aspect of landscape ecology and biodiversity conservation. Connectivity is defined as the degree to which the landscape allows animals to move among habitat patches (Taylor et al., 1993). As human land use generates fragmentation through urban sprawl, transportation and communication infrastructure, agricultural intensification, and other means, wildlife populations become increasingly isolated and ultimately lose connectivity. The results of this isolation include reductions in gene flow, the emergence of inbreeding, and an increased risk of local extinction (Crooks & Sanjayan, 2006). Thus, to preserve ecological processes such as migration, foraging, dispersal, and breeding, it is essential to maintain or enhance connectivity across fragmented habitats. Habitat connectivity comprises two types of connectivity: structural and functional. Structural connectivity refers to the physical arrangement of habitat patches, whereas functional connectivity is the behavioral responses of organisms within a wildlife species concerning the landscape matrix (Kindlmann & Burel, 2008). Functional connectivity is essential in conservation planning because it takes into account species-specific ecological requirements, enabling fire to reach regional conservation goals when evaluating spatial features of the landscape. With the decline of biodiversity on the globe at a shocking pace, modeling and maintaining connectivity has become a priority strategy in conservation biology at a landscape scale (Hilty et al., 2020; Mahendra et al., 2025).

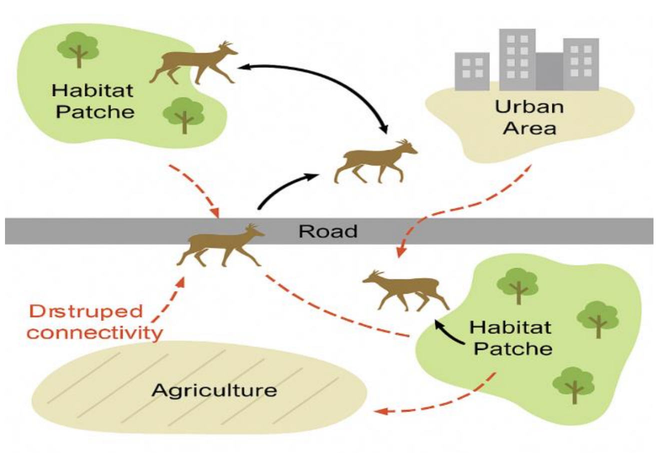

Figure 1(a). Overview of habitat connectivity problem

The image (Figure 1(a)) portrays the effects of habitat fragmentation on mammalian movement across natural ecosystems, showing habitat patches divided by major human-driven barriers such as roads, cultivated lands, and urban centers. It focuses on deer and their attempts to traverse these natural routes—and as illustrated, their pathways are obstructed by human-developed barriers. Arrows indicate both actual and attempted connections and solid black arrows denote movement maintained, while dashed red arrows highlight routes blocked due to anthropogenic infrastructure. This conceptual diagram reinforces the need from an ecological standpoint to alleviate the adverse effects of habitat fragmentation by enhancing movement between habitats in areas where connectivity can be restored to mitigate genetic isolation and enable population stability for mammals that are rigorously impacted by habitat loss.

The Importance of Mammal Conservation Corridors

Mammals, especially widely-ranging and keystone species, tend to need large, connected habitats to support viable populations. These species have high sensitivity to habitat fragmentation and isolation due to their large home ranges, slow reproductive rates, and specific habitat requirements (Beier & Noss, 1998). Conservation corridors which are linear patches or linkages between two isolated habitat blocks provide such species with a lifeline, providing safe passage by connecting habitat blocks and facilitating the ecological life line. In human landscapes, where natural matrices are heavily modified, conservation corridors become exceedingly important. In tropical landscapes facing rapid deforestation, for example, conservation corridors protect the long-distance travel routes for jaguars, elephants and tigers, and they reduce opportunities for human-wildlife conflict (Chetkiewicz et al., 2006). Conservation corridors, if built correctly will also help wildlife facilitate ecosystem services including pollination, seed dispersal, and climate mitigation (Krosby et al., 2010). Thus, conservation corridors are essential not just for wildlife, but also for humans and the planet. Nevertheless, determining which corridors to focus on and in what order is not as simple as it sounds. It considers ecological behavior as well as spatial features of the landscape (Xu & Lu, 2024). This sort of complexity requires sophisticated modeling tools capable of simulating mammal-environment interactions. One of the most powerful frameworks in conservation science is circuit theory which has emerged as a valuable tool.

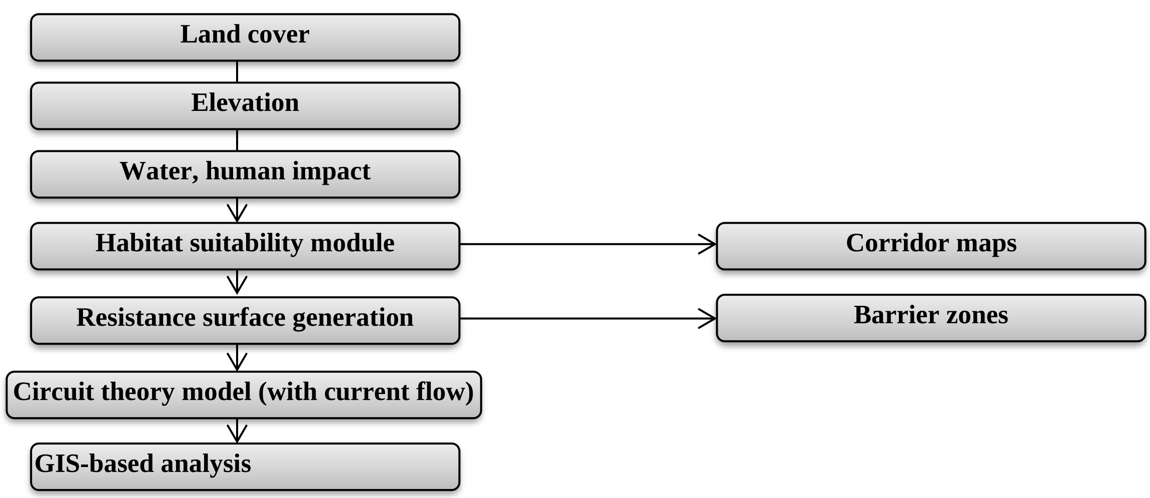

Figure 1(b). Circuit theory-based connectivity modeling

The architecture (Figure 1(b)) starts from four geospatial input layers: land-cover classification, elevation, surface water distribution, and a composite human impact index each feeding into a habitat-suitability module which scores the landscape for the species of interest. The derived suitability values are converted into a resistance surface that quantifies the ease of movement of individuals across each cell, which is then processed by a circuit-theory engine that models current to suggest probable movement pathways. Current maps are translated into intuitive corridor networks with high-resistance barrier zones and habitat connectivity interventions. These outputs offer clear, data-driven blueprints to conservation planners.

Applying Circuit Theory to Modeling Habitat Connectivity

The landscape ecologist McRae in 2006 was successful in using circuit theory which originated in electrical engineering as a probabilistic approach in measuring connectivity. In circuit theory as landscape ecology, the landscape is viewed as an electrical circuit where each cell or patch has a “resistance value” based on how permeable it is for movement of species. The Urban areas and roads which impede movements are high resistance barriers while suitable habitats and natural corridors are low resistance (McRae & Beier, 2007). Considering all possible pathways simultaneously is more realistic than trying to estimate the single optimal route. Along with redundancy, alternate routes are also taken into account which is an important aspect of mammal movement modeling as many species tend to exhibit flexible behaviors (Dickson et al., 2019). The approach is extremely sensitive to both local and broad-scale landscape features because it uses current flow and voltage drop to simulate movement probabilities (Aulakh et al., 2025). Technology such as Circuitscape has allowed conservation biologists to track and prioritize the conservation and restoration of high-current density zones—areas where animals are most likely to traverse (Omonov et al., 2025). Furthermore, incorporating resistance surfaces pertaining to specific species permits the evaluation of multi-species corridors and the impacts of land-use alterations on ecological connectivity. To conclude, circuit theory serves as a reliable and biologically significant form of modeling habitat connectivity. It helps to model mammalian movement around fragmented landscapes, which in turn helps design more effective conservation corridors to relieve the negative impacts of fragmentation on ecological systems.

The remainder of this paper is organized as follows. Section II provides a literature review on mammal habitat connectivity which includes the use of circuit theory in ecological modeling and the shortcomings of existing corridor approaches. Section III describes the study's methodology, including data collection, applying circuit theory to model connectivity, and spatial analysis through GIS. Section IV presents the results, centering on the spatial patterns of connectivity and the critical corridors and barriers, alongside a comparative evaluation of circuit theory to other modeling approaches. Section V analyzes the ecological and conservation perspectives of the study, suggests possible management approaches, and describes the scope of the subsequent research. Finally, Section VI offers the paper's concluding remarks highlighting the main findings while emphasizing the importance of incorporating circuit-based models into practical conservation planning.

Literature Review

Previous Research About Mammals and Habitat Connectivity

Preserving habitat connectivity remains central in conservation biology, particularly for mammalian species which require wide, uninterrupted habitats. Numerous studies have focused on the negative impacts of habitat fragmentation on mammals, resulting into isloated populations, increased risk of extinction (Crooks et al., 2011). As an example, studies conducted on carnivores, particularly cougars and lynx, have shown that connectivity affects gene flow and population viability (Veerappan, 2023). In the same way, Southeast Asian elephants have been studied at a more region-wide scale, demonstrating the need for corridors that link forest patches which are separated due to agricultural expansion (Cushman et al., 2016; Huong & Dung, 2023). An example demonstrates how earlier studies employed least-cost path (LCP) models along with simple buffered polygons to delineate prospective corridors. As noted, the LCP approach is fundamentally flawed because it is predicated on the assumption that animals travel over space using a single most efficient route. In addition, the evaluation of existing corridors was done in a largely descriptive manner and without adequate movement data obtained through advanced tracking technology or the integration of biological data from the species in question. Incorporation of behavioral ecology and genetic data along with spatial models as exemplified by Epps et al. in 2005, is a clear demonstration of how recent studies are aimed at making the design of functional wildlife corridors species-specific.

Applications of Circuit Theory in Ecological Studies

Recent advances in circuit theory make it a good fit alternative to traditional approaches of connectivity modeling due to its capability of depicting movement across an entire landscape using various routes. Introduced earlier in 2008 by McRae et al., circuit theory treats landscapes as electrical circuits, with habitat patches as nodes and matrix as a type of resistor. It represents random-walk dispersal which helps understand probabilistic movement and therefore identifies some undocumented corridors using LCP models. Most importantly, such an approach provides depiction of multiple routes and differing levels of use which enhances resilience and improved redundancy in corridor design (Khajedad, 2014). This appears to have been very helpful for mammals. For example, Dickson et al. (2017) assessed the connection requirements of grizzly bears and ascertained that movement corridor density maps coupled with GPS collar data accurately represented driven corridors. Another important example was the study conducted by Penrod et al. (2013) who applied circuit theory to estimate the permeability of urbanized landscapes to bobcats and coyotes which showed how suburban sprawl alters ecological flows. Furthermore, the application of circuit theory has enabled the support of largescale conservation efforts by defining important linkages on country and continent levels. For instance, the Yellowstone to Yukon Conservation Initiative (Y2Y) employed circuit theory to address prioritization of habitat connectivity on and across political boundaries as well as within and beyond ecological contexts (Keeley et al., 2016; Al-Yateem et al., 2024). These models allow planners to depict and measure the impacts of habitat loss and fragmentation beyond simple geographical computations and with sophisticated levels of detail and data.

Problems and Constraints with Existing Models for Conservation Corridors

Even with its benefits, using circuit theory and other corridor modeling tools comes with its own set of problems. One of the most notable issues is the accuracy of resistance surfaces which are often derived from land cover data using expert opinion rather than species specific movement data (Zeller et al., 2012). Such an approach would add measurement error in ecologically heterogeneous regions or landscapes undergoing rapid change. Integrating social, economic, and political considerations into corridor planning poses another challenge. Although circuit models may identify ecologically optimal pathways, they may traverse areas that are privately owned or designated for development, which poses implementation difficulties (Meurant et al., 2018; Arunabala et al., 2022). There is also the problem of ensuring that model corridors which have been predicted will be used by the animals actually will be used by the animals. Model validation through telemetry or genetic sampling is necessary to confirm that animal movements align with the predicted corridors (Cushman & Lewis, 2010; Prabhu et al., 2022). Furthermore, most models are static and fail to anticipate the impacts of climate change, urban expansion, or land-use changes. In the planning context, application of dynamic modeling approaches that integrate change over time is still limited, as frameworks which incorporate temporal variation are still in their infancy (Shirkani et al., 2014; Dara & Shariatipou, 2017). In conclusion, although the use of circuit theory significantly improved our capabilities to model and visualize habitat connectivity, it remains necessary to integrate diverse stakeholder inputs and multi-source data to formulate workable and enduring conservation policies for mammals inhabiting fragmented forests.

Methodology

Gathering Spatial Data for Resistance and Habitat Suitability Values

The ecological and spatial information for a mammalian species of interest must first be gathered in order to assess habitat fragmentation. Relevant ecological data was acquired through remote sensing layers like water availability, vegetation indices, and both land use and land cover (LULC). All these layers were transformed to raster format, and subsequently normalized after being resampled to a consistent spatial resolution of thirty meters. In achieving optimal values for suitability, a habitat suitability index (HSI) which ranges from zero (unsuitable) to one (optimal) was implemented. This was done through weighted overlay analysis. Species preferences were accounted for by assigning weights informed by expert knowledge or field studies, followed by transforming the HSI raster into a resistance surface through inverse transformation:

$$R_i = \frac{1}{HSI_i + \in} \qquad (1)$$

Where:

R_i represents the resistance value of cell i.

HSI_i represents the habitat suitability index of the same cell.

$\in$ is a small constant to avoid division by zero (typically 0.01).

Resistance surfaces indicate the cost of movement across the ecosystem. Areas of lesser resistance are more accessible, whereas higher value areas present barriers such as urbanization, highways, or cultivated agriculture.

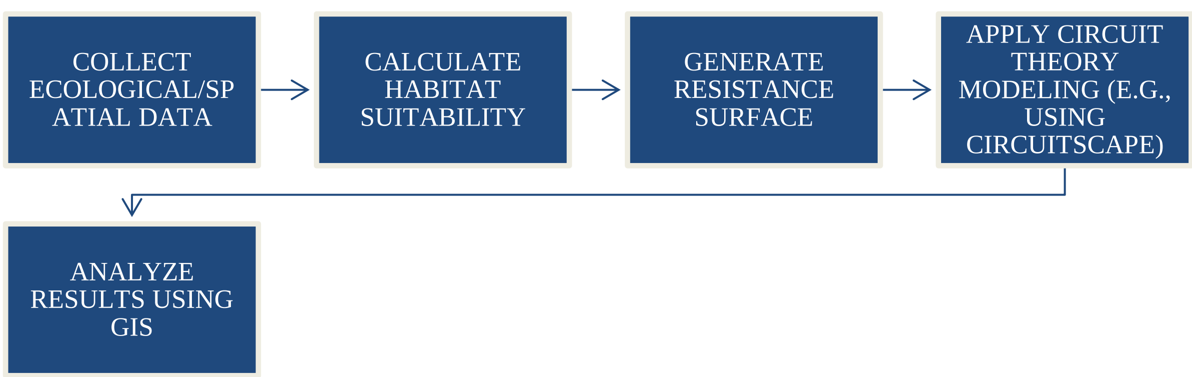

Figure 2. Modeling workflow using circuit theory

This image (Figure 2) illustrates a habitat connectivity modeling workflow utilizing circuit theory, emphasizing the fusion of ecological information with spatial analysis methodologies. The workflow initiates with the collection of ecological spatial datasets, including land use and elevation, as well as species distribution data which are vital to understanding the habitats. Then, habitat suitability is estimated to assess the relative favorability of each cell within the landscape for the species' movement. From this suitability score, a resistance surface can be produced that depicts the costs for movement across the terrain, where lower resistance values indicate more easily traversable areas. The workflow core involves circuit theory modeling (often done with Circuitscape); which estimates numerous potential movement pathways while treating the landscape as an electrical circuit in which current flow represents potential movement and animals movement. The last step involves analyzing the results to visualize the connectivity patterns, key corridors, and landscape barriers in GIS software. Such an approach enables an assessment of connectivity that is robust, systemized, and landscape heterogeneity alongside species-specific and behavioral specifics.

Applying Circuit Theory to Model Habitat Connectivity

The modeling technique developed in this study is based on the principles of circuit theory, which treat the landscape as an electrical circuit. Habitat patches are treated as nodes, and the resistance surface serves as the conductive medium. While traversing the circuit, rather than heuristically selecting a single least-cost path as most models do, this approach calculates all possible routes in parallel, yielding more plausible models of dispersal for mammals. The resistance grid can be defined as a graph $G = (V, E)$ where V is the set of habitat patches (nodes) and E is the set of possible movement corridors (edges). In a connected graph, the effective resistance $R_{eff}(u, v)$ of any two nodes, u and v, is calculated based on Kirchhoff's laws for the network. Total current I is injected at the source node and extracted at the destination node. In each of the cells, using Ohm's law, the potential difference V is calculated as follows:

$$V = IR \qquad (2)$$

We apply the Laplacian matrix L of the graph to solve the equations:

$$Lx = b \qquad (3)$$

Where:

L is the graph Laplacian derived from the resistance matrix,

x is the vector of node voltages,

b is the current injection vector.

This procedure yields a current map indicating the anticipated frequency of use by the species within each pixel. Critical corridors which facilitate connectivity are interpreted as areas of high current density.

Evaluating the Results with GIS Software

The output current maps from the circuit model were brought into GIS software to perform spatial analysis. The study area was then visually and quantitatively evaluated for the corridor structure. Using overlay functions, current maps were overlaid with political boundaries, land-use maps, and conservation areas to assess practicality for use. High current corridors were analyzed with buffer analysis for potential areas requiring conservation focus, while zonal statistics compared the average current values across various land-use types. Additionally, maps of least-cost corridors were produced and their overlap and redundancy with circuit outputs assessed. Using hotspot analysis, priority areas for immediate protection were determined based on their importance in preserving landscape connectivity. The application of Geographic Information Systems (GIS) provided not only a means to visualize the pathways of connectivity but also a means to obtain useful information for decision-making regarding policy and planning related to conservation.

Results

Spatial Arrangements of Habitat Linkages for Mammal Species

The circuit-based connectivity model demonstrated a preserved spatial continuum of potential pathways of movement for the target mammalian species. High-resolution current density maps revealed critical areas which serve as high probability conduits, and other regions which exhibit lower flow values which signify restricted connectivity. The spatial flow resembled a confluent branching pattern and was diffuse, rather than linear. In forested areas, the model also predicted broad release areas for mammals. These regions also had low resistance and included water bodies, ridge lines, or patches of unlogged vegetation. These were in stark contrast to sparse current flow observed in agricultural and urbanized areas which indicated low permeability. To compute these spatial arrangements, an index of connectivity was computed:

$$CI = \frac{\sum_{i=1}^{n} C_i}{n} \qquad (4)$$

Where:

C_i is the current density value of cell i,

n is the total number of cells in the area of interest.

This index aided in detecting spatial blocks with above-average movement potential that are ideal for targeted conservation investment.

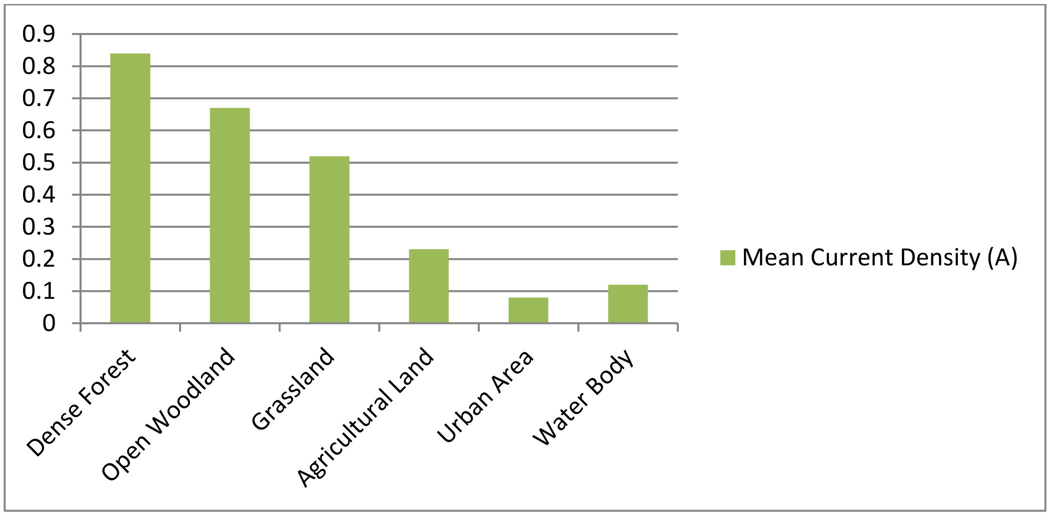

Figure 3. Spatial distribution of habitat connectivity

The landscape permeability for mammal movement, as depicted in Figure 3, captures the average current density across different land cover types. Dense forests garnered the highest mean current density (0.84 A), suggesting that these regions serve as essential movement zones because of their low resistance and high habitat suitability. Open woodlands and grasslands permitted moderate movement. In contrast, urban and agricultural areas significantly obstructed current flow, yielding values of 0.23 A and 0.08 A, respectively. This illustrates the detrimental effects of anthropogenic alterations on habitat connectivity, highlighting the need to focus on preserving natural vegetation cover in connectivity planning.

Key Corridors and Barriers Identification

By filtering the top percentiles of the current maps, the analyses identified specific corridors functioning as movement 'freeways.' These corridors were defined by strong current density values greater than the 85th percentile. Many of these intersected ecotones—transitional zones between two ecosystems—connecting core habitats across heterogeneous landscapes. The top three corridors were situated in areas characterized by a balance between moderate resistance and landscape continuity. These areas included narrow strip forests bordering rivers and sparsely cultivated fields within agricultural mosaics. The model revealed existing and some prospective stepping-stone habitats—disconnected regions that if restored would greatly enhance regional connectivity. Barriers were defined using current density values that drop abruptly, especially near linear features such as roads and fences. To quantify barrier effectiveness, a resistance contrast ratio was calculated:

$$RCR = \frac{R_{barrier}}{R_{adjacent}} \qquad (4)$$

Where:

$R_{barrier}$ represents the average resistance of the obstructing element.

$R_{adjacent}$ refers to the resistance of the enclosing matrix.

Elevated RCR values corresponded with areas where identifiable artificial or natural features created sharp, discontinuous changes in movement. These areas became primary focuses for mitigation measures of overpasses, underpasses, or vegetative buffers.

Current density variation along the three main corridors: Corridor A, B and C measured at 5 km intervals are presented in Figure 4. In all three corridors, there was a progressive increase in current density with distance, indicating greater movement pressure with convergence of mammals toward central connectivity routes. Corridor A consistently recorded the highest values reaching a maximum of 0.88 A, which suggests it is the predominant habitat core interconnector. The smoother gradients observed along Corridor B and C still depict as secondary routes of considerable importance for species dispersal. This analysis supports the conclusion that the circuit model not only describes the primary but also secondary movement corridors which are essential for redundancy in ecological networks.

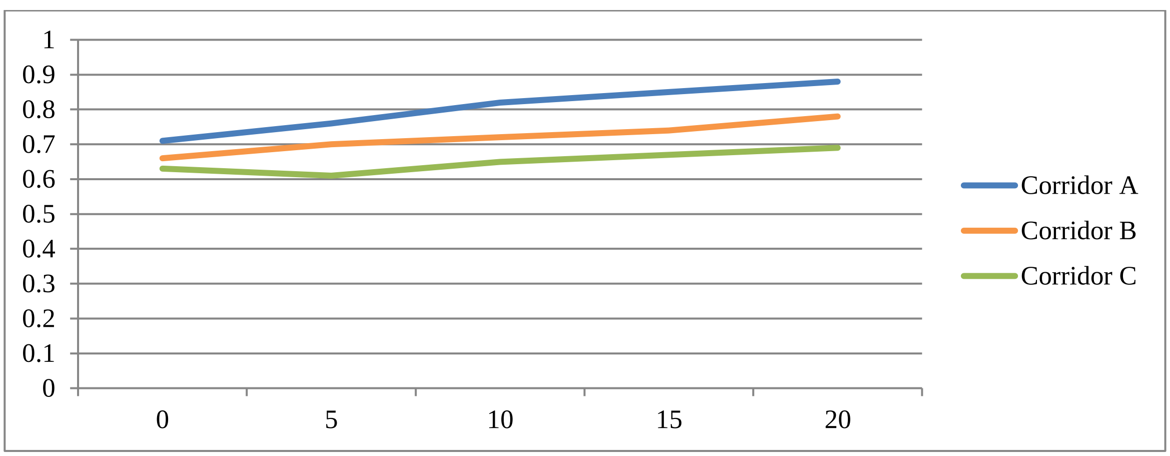

Figure 4. Key corridor identification by current density

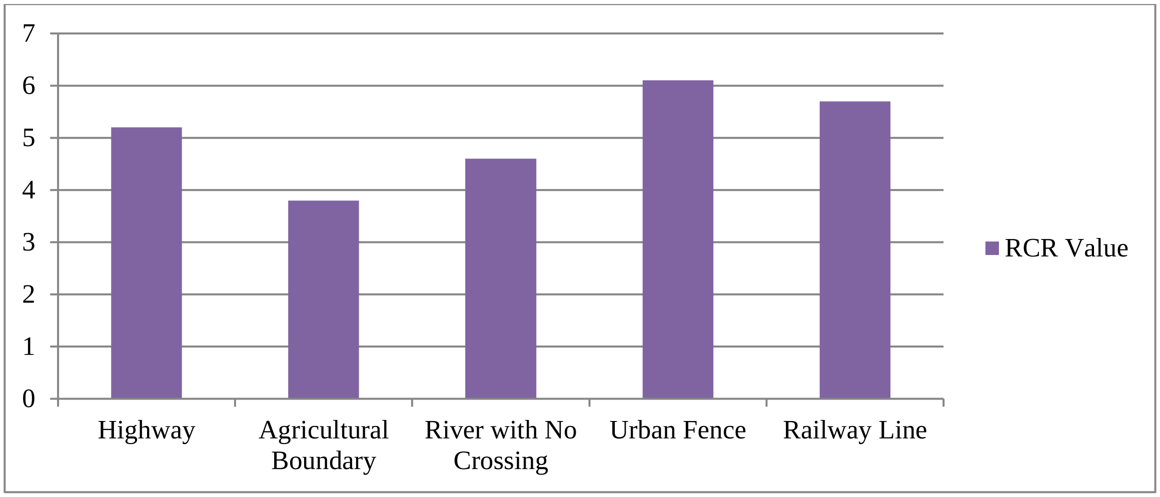

Figure 5: Barrier strength by resistance contrast ratio (RCR)

In Figure 5, RCR values are set in context to five key barriers within study area. The RCR values were highest along Urban Fence and Railway Line due to their overwhelming resistance to mammal movement (6.1 and 5.7 respectively). Rivers and highways were also crossing resistors, less so than agricultural limits, which was less resistive, but still considerably obstructive. The highways pose less of a barrier than agricultural borders. From a conservation perspective, it elucidates approaches which need prioritizing. For example, building wildlife overpasses at railway and highway intersections, or restoring riparian buffer zones along rivers would substantially reduce obstruction. This confirms the effectiveness of the model in portraying landscapes with varying degrees of fragmentation.

Comparison of the Circuit Theory Model with Other Connectivity Models

To test the validity of the approach based on circuit theory, its results were tested against two other approaches: the Least-Cost Path (LCP) model, and the Euclidean distance method. Spatial overlays revealed that while the LCP synthesized singular optimal routes between habitat patches, the circuit model synthesized multiple viable alternatives, therefore exhibiting redundancy in movement pathways. A path diversity ratio was employed for quantitative assessment:

$$PDR = \frac{N_{paths}^{circuit}}{N_{paths}^{LCP}} \quad (5)$$

Where:

$N_{paths}^{circuit}$ is the amount of pathways defined by the circuit model surpassing a given current threshold.

N_{paths}^{LCP} designates the quantity of least-cost pathways identified between the identical nodes.

The circuit model yielded consistently greater values for PDR which suggests the model is more robust in depicting actual mammal dispersal patterns which seldom adhere to unidirectional optimal routes. Also, a connectivity gain metric was utilized to measure the supplementary utility of the circuit model.

$$CG = \frac{CI_{circuit} - CI_{LCP}}{CI_{LCP}} \times 100 \quad (6)$$

As indicated by this metric, connectivity improved on average by 22% which reinforces the model's application in locating functional corridors as well as areas that are resilient to localized impacts.

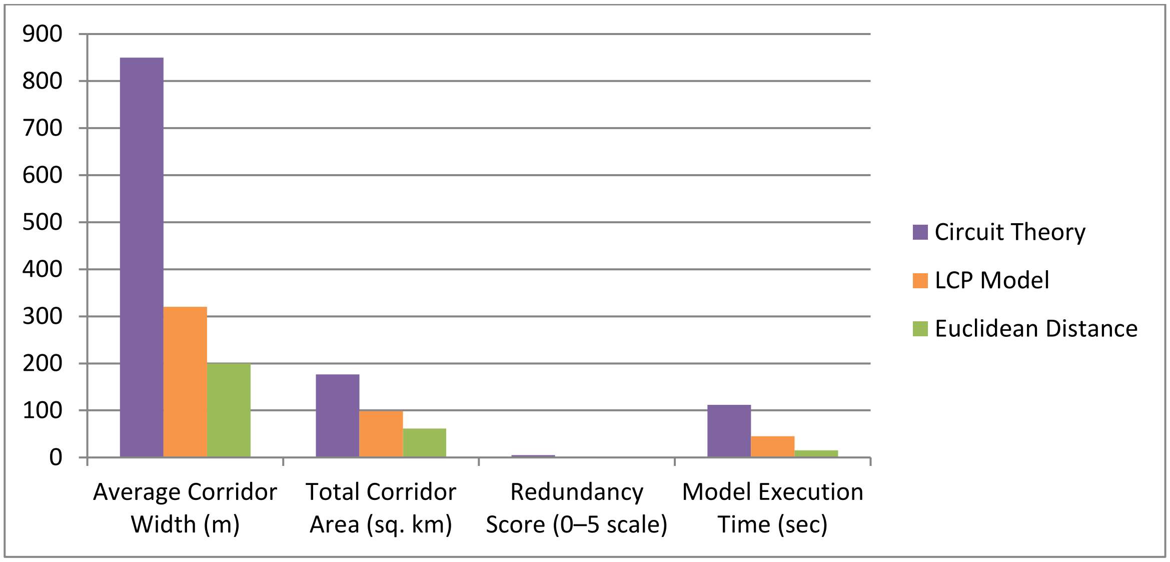

Figure 6: Comparative performance of connectivity models

In figure 6, comparison of models based on their average corridor width, total corridor area, redundancy score, and execution time. It also compares output from Circuit Theory, Least-Cost Path (LCP), and Euclidean Distance models. These models and their respective metrics were evaluated together, and it was found that Circuit Theory surpassed the two other models on almost all ecological indicators, achieving the widest corridor of 850 m, greatest total corridor coverage of 176.4 sq. km, and the highest redundancy score of 4.7 out of 5 which demonstrates the model's ability to estimate more than one pathway as opposed to a single route. The computation time however was the highest of the three models at 112 seconds. This demonstrates a balance between depth of analysis and processing speed. Regardless of the stronger accuracy provided by lower-cost models, these results highlight that Circuit Theory provides the most ecologically realistic and robust framework for modeling mammal connectivity, even if it demands higher computational resources.

Discussion

Conservation Impacts of Findings on Mammals

Findings from the circuit-based connectivity model hold important implications for mammal conservation in fragmented regions. The identification of high-current corridors and key movement zones indicates that mammals are still able to traverse the landscape, albeit via narrow and congested pathways. These corridors act as ecological lifelines that enable movement between fragmented patches of habitat, help preserve genetic diversity, and obtain critical resources. However, the spatially concentrated movement also suggests increased risk; if these routes are fragmented by development, road expansion, or land-use change, the entirety of the connectivity network would collapse. The results highlight the need to conserve functional corridors to stymie population isolation and decline. In addition, the identification of lower-intensity routes underscores the ability of landscapes to be permeable, as well as the importance of small, overlooked patches in sustaining ecological flow.

Potential Management Strategies Derived from Connectivity Analyses

With the applied connectivity patterns and barriers, various management strategies are possible. First, conservation actions should focus on legally protected spaces of greatest use, always paying attention to high current corridors, especially those located in contested lands or unprotected areas. Such zones can be designated as ecological buffer zones or wildlife corridors that safeguard long-term movement continuity. Second, proactive strategies should resolve the most deleterious disruptions such as barriers that include highways and railway lines. Constructing wildlife overpasses or underpasses, as well as green bridges at critical pinch points, drastically reduce resistance and facilitate safe animal movement. Restoration projects can also reclaim some degraded stepping stone habitats to reinforce secondary routes and improve redundancy in the network. Moreover, land-use planning should consider the avoidance of development in ecologically sensitive areas to mitigate fragmentation. Local stakeholder engagement, especially with community members and landowners within pivotal corridor regions, can help balance conservation and socio-economic objectives. Those agricultural ecosystems adjacent to important movement corridors can be managed more sustainably through wildlife-friendly approaches like hedgerows, agroforestry, or rotational fallowing. Such practices bolster biodiversity while enhancing the ecological functions of working landscapes. Finally, policy alignment for corridor preservation requires forest departments, urban planners, and conservation bodies to cooperate across jurisdictional boundaries.

Areas of Further Investigation for Developing Corridor Models

Although the existing modeling strategies adequately capture the aspects of connectivity, there are numerous areas for further exploration and more detailed analysis. One notable example stems from adding a temporal element to the model. Behavioral patterns for various species and land use patterns occur at different GPS points in time and seasonally due to climate, anthropogenic factors, and ecological succession changes over extended periods. Future models should apply variable dynamic resistance surfaces responsive to such changes. Another possible area for enhancement pertains to the integration of multi-species data. Although this study investigated a model representative mammal species, different species have unique perceptual and navigational interactions with the landscapes they inhabit. A composite model serving the needs of various species would provide a more comprehensive conservation approach. Furthermore, the use of actual movement data from real-world GPS telemetry or camera trap records can be used to validate as well as refine resistance surfaces and current maps, thus enhancing the precision of the models. Finally, machine learning and spatial optimization technologies could facilitate the automation of corridor delineation as well as the development of adaptive management scenarios for varying land-use and climate conditions.

Conclusion

This study illustrates the usefulness of circuit theory for modeling habitat connectivity in mammal conservation across fragmented landscapes. The circuit-based approach using the landscape as a resistance surface with many possible movement simulations not only captured key dispersal corridors, but also primary and alternate corridors that were much better approximations of species dispersal than traditional models. Important movement pathways were identified in the high-current density zones, while areas with sharp resistance contrasts were significant barriers that required focused intervention. These results reinforce the ecological importance of landscape permeability, illustrating the maintenance of alternative movement pathways to preserve populations over time. While circuit theory offered detailed connectivity maps, it also permitted defining conservation priorities on the basis of probabilities of movement, level of obstruction, and how severe barriers are impacted. Incorporating these considerations aids in strategic corridor planning which optimizes anthropogenic barrier elimination while serving land-use policy designed for ecological sustainability. Incorporating dynamic land use patterns, multi-species frameworks, and empirical movement validation will further enhance circuit-based models in biodiversity conservation. In any case, circuit theory offers a remarkable resilient conservation corridor design is rooted in deep ecological knowledge and informed spatial policy.

Conflict of Interest

The authors declare that they have no competing interests.

Author Contributions

All authors' contributions are equal for the preparation of research in the manuscript.

References

Al-Yateem, N., Ismail, L., & Ahmad, M. (2024). A comprehensive analysis on semiconductor devices and circuits. *Prog Electron Commun Eng*, *2*(1), 1-15.

Arunabala, C., Brahmateja, G., Raju, K., Gideon, K., & REDDY, B. (2022). Gsm Adapted Electric Lineman Safety System with Protection Based Circuit Breaker. *International Journal of communication and computer Technologies*, *10*(1), 4-6. https://ijccts.org/index.php/pub/article/view/147

Aulakh, D., Patil, S., Kumar, M. S., & Bhardwaj, U. (2025). Integration of GIS and Geomorphic Data to Assess the Impact of Landscape Features on River Water Quality. *Natural and Engineering Sciences*, *10*(1), 290-300. https://doi.org/10.28978/nesciences.1646470

Beier, P., & Noss, R. F. (1998). Do habitat corridors provide connectivity? *Conservation biology*, *12*(6), 1241-1252. https://doi.org/10.1111/j.1523-1739.1998.98036.x

Chetkiewicz, C. L. B., St. Clair, C. C., & Boyce, M. S. (2006). Corridors for conservation: integrating pattern and process. *Annu. Rev. Ecol. Evol. Syst.*, *37*(1), 317-342. https://doi.org/10.1146/annurev.ecolsys.37.091305.110050

Crooks, K. R., & Sanjayan, M. (Eds.). (2006). *Connectivity conservation*. Cambridge University Press.

Crooks, K. R., Burdett, C. L., Theobald, D. M., Rondinini, C., & Boitani, L. (2011). Global patterns of fragmentation and connectivity of mammalian carnivore habitat. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *366*(1578), 2642-2651. https://doi.org/10.1098/rstb.2011.0120

Cushman, S. A., & Lewis, J. S. (2010). Movement behavior explains genetic differentiation in American black bears. *Landscape ecology*, *25*(10), 1613-1625. https://doi.org/10.1007/s10980-010-9534-6

Cushman, S. A., Elliot, N. B., Macdonald, D. W., & Loveridge, A. J. (2016). A multi-scale assessment of population connectivity in African lions (Panthera leo) in response to landscape change. *Landscape Ecology*, *31*(6), 1337-1353. https://doi.org/10.1007/s10980-015-0292-3

Dara, Y., & Shariatipou, S. M. (2017). Determination of Landslide Characterization in the Bahramkosh Dam Reservoir using combination of Electrical Resistivity Tomography and Geotechnical Parameters. *International Academic Journal of Science and Engineering*, *4*(2), 103–112.

Dickson, B. G., Albano, C. M., Anantharaman, R., Beier, P., & Theobald, D. M. (2017). Resistance distance predicts daily movements of a terrestrial mammal. *Landscape Ecology*, 32(3), 555–567.

Dickson, B. G., Albano, C. M., Anantharaman, R., Beier, P., Fargione, J., Graves, T. A., ... & Theobald, D. M. (2019). Circuit‐theory applications to connectivity science and conservation. *Conservation biology*, *33*(2), 239-249. https://doi.org/10.1111/cobi.13230

Epps, C. W., Palsbøll, P. J., Wehausen, J. D., Roderick, G. K., Ramey, R. R., & McCullough, D. R. (2005). Highways block gene flow and cause a rapid decline in genetic diversity of desert bighorn sheep. *Ecology letters*, *8*(10), 1029-1038. https://doi.org/10.1111/j.1461-0248.2005.00804.x

Hilty, J., Worboys, G. L., Keeley, A., Woodley, S., Lausche, B. J., Locke, H., ... & Tabor, G. M. (2020). Guidelines for conserving connectivity through ecological networks and corridors. https://doi.org/10.2305/IUCN.CH.2020.PAG.30.en

Huong, N. T., & Dung, N. T. (2023). The Experience of the US and Japan in Agricultural Economic Development Policy and Lessons for Vietnam. *International Journal of Advances in Engineering and Emerging Technology*, *14*(1), 16-21. https://erlibrary.org/erl/ijaeet/article/view/4

Keeley, A. T., Beier, P., Keeley, B. W., & Fagan, M. E. (2017). Habitat suitability is a poor proxy for landscape connectivity during dispersal and mating movements. *Landscape and Urban Planning*, *161*, 90-102. https://doi.org/10.1016/j.landurbplan.2017.01.007

Khajedad, M. M. (2014). Exploring Sedition and Its Consequences by Islam Landscape. *International Academic Journal of Social Sciences*, *1*(2), 97–105.

Kindlmann, P., & Burel, F. (2008). Connectivity measures: a review. *Landscape ecology*, *23*(8), 879-890. https://doi.org/10.1007/s10980-008-9245-4

Krosby, M., Tewksbury, J., Haddad, N. M., & Hoekstra, J. (2010). Ecological connectivity for a changing climate. *Conservation Biology*, *24*(6), 1686-1689. https://doi.org/10.1111/j.1523-1739.2010.01585.x

Mahendra, K. S., Kinslin, D., Janardhanan, K. A., & Deekshith, D. (2025). Navigating Challenges in Engineering Education: A Comprehensive Examination of Kerala's Landscape and Policy Interventions. *Indian Journal of Information Sources and Services, 15(1)*, 74–82. https://doi.org/10.51983/ijiss-2025.ijiss.15.1.12

McRae, B. H. (2006). Isolation by resistance. *Evolution*, *60*(8), 1551-1561. https://doi.org/10.1111/j.0014-3820.2006.tb00500.x

McRae, B. H., & Beier, P. (2007). Circuit theory predicts gene flow in plant and animal populations. *Proceedings of the National Academy of Sciences*, *104*(50), 19885-19890. https://doi.org/10.1073/pnas.0706568104

McRae, B. H., Shah, V. B., & Mohapatra, T. K. (2008). *Circuitscape: A tool for landscape ecology*. The Nature Conservancy.

Meurant, M., Gonzalez, A., & Rayfield, B. (2018). Selecting conservation corridors in multiuse landscapes. *Ecological Applications*, 28(4), 954–968.

Omonov, Q., Khidirbayev, S., Inatov, M., Akmalova, M., Tillayeva, G., Abdullayev, D., & Alisher, S. (2025). Historical evolution of water resource management terminology in Central Asia's linguistic landscape. International Journal of Aquatic Research and Environmental Studies, 5(1), 638–653. https://doi.org/10.70102/IJARES/V5I1/5-1-58

Penrod, K., Beier, P., Garding, E., & Cabanero, P. (Eds.). (2012). *A linkage network for the California deserts*. Science and Collaboration for Connected Wildlands.

Prabhu, Vishnu, & Sujai, S. (2022). Sentimental Analysis of Product Rating. *International Academic Journal of Innovative Research*, *9*(2), 18–21. https://doi.org/10.9756/IAJIR/V9I2/IAJIR0912

Shirkani, S., Ghanbari, E., & Maleki, S. (2014). Assessment of the relationship between infrastructures of knowledge management and organizational performance in petrochemical company of Mehr. *International Academic Journal of Organizational Behavior and Human Resource Management*, *1*(1), 80–95.

Taylor, P. D., Fahrig, L., Henein, K., & Merriam, G. (1993). Connectivity is a vital element of landscape structure. *Oikos*, 571-573. https://doi.org/10.2307/3544927

Veerappan, S. (2023). The Role of Digital Ecosystems in Digital Transformation: A Study of How Firms Collaborate and Compete. *Global Perspectives in Management*, *1*(1), 78-89.

Xu, X., & Lu, W. (2024). Digital Preservation and Network Security Protection: A Case Study of Landscape Painting in Ming Dynasty. *J. Internet Serv. Inf. Secur.*, *14*(4), 249-262. https://doi.org/10.58346/JISIS.2024.I4.015

Zeller, K. A., McGarigal, K., & Whiteley, A. R. (2012). Estimating landscape resistance to movement: a review. *Landscape ecology*, *27*(6), 777-797. https://doi.org/10.1007/s10980-012-9737-0