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Enhancing Habitat Connectivity through Cost-Effective Ecological Corridor Design Using Optimization

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ABSTRACT

The rapid exploitation of natural resources in Cabo Delgado, Mozambique, has expanded human settlements and fragmented ecosystems, threatening wide-ranging species like African elephants that depend on connected habitats. While viable elephant populations remain in Niassa Special Reserve and Quirimbas National Park, their movement through unprotected areas leads to human-elephant conflicts. Establishing cost-effective ecological corridors is essential for habitat connectivity. This study models the landscape as a grid of habitat patches, weighted by land-use resistance, and compares two corridor design strategies: graph-based shortest-path algorithms (A* and Dijkstra) and an integer linear programming model. Computational tests on grids ranging from 10×10 to 10×40 patches show that A* and Dijkstra generate high-quality corridors efficiently, while the linear programming model fails to converge for grids larger than 20×20 within 60 minutes. The results demonstrate the computational advantage of shortest-path algorithms for large-scale corridor planning in Mozambique.

KEYWORDS. Ecological corridor, Optimization, Biological conservation.

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1. Introduction

Rapid urbanization driven by the exploitation of natural resources in Cabo Delgado, Mozambique, fragments essential ecosystems and threatens local wildlife, particularly elephants, which require large, connected areas to survive. Despite the establishment of protected areas such as the Niassa Reserve and the Quirimbas National Park, elephants continue to migrate in search of resources, facing conflicts with human communities and risks of illegal poaching [Foloma, 2005]. To mitigate these impacts, the creation of ecological corridors has emerged as a critical strategy, allowing safe movement between isolated areas and promoting the environmental and genetic continuity of populations. However, effective planning and implementation of these corridors require sophisticated approaches that account for multiple factors, such as the cost of acquiring land fragments and budgetary restrictions, especially considering that many African states face structural financial limitations and rely largely on external resources to implement public policies in various sectors, including environmental protection [Francisco, 2019].



Figure 1: Destruction of agricultural crops by elephants
Source: [ZUMBO, 2024]

The application of mathematical optimization models in the design of nature reserves has proven to be a promising approach to the conservation of biodiversity.

Williams et al. [2004] documented the evolution of these techniques, from early methods using multiple criteria to the implementation of integer programming for optimal solutions. They emphasize the importance of complementarity in site selection, an approach that maximizes efficiency in species representation. Despite progress, computational challenges persist, particularly in large-scale problems. These models are fundamental as decision support tools that offer transparency and the ability to generate alternative solutions. The integration of dynamic models with spatial optimization frameworks is viewed as a crucial step in addressing the inherent complexity of conservation, underscoring the need for interdisciplinary collaboration for significant advances in the field.

Complementing this approach, Filho and Telles [2006] introduced the integration of population genetic structure into reserve network optimization models. They argue that incorporating genetic criteria is essential, particularly for widely distributed and abundant species, to ensure the

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representation of genetic diversity and the evolutionary persistence of species. The study proposes a heuristic and sequential algorithm that combines multiple networks of local populations, based on the spatial autocorrelation of genetic variability. This methodology ensures that significant genetic units are included in reserve modeling, contributing to more effective and comprehensive conservation strategies.

The study by St John et al. [2018] proposes an innovative approach that combines artificial intelligence-based path planning techniques with network optimization models to control geometric characteristics of corridors, such as width and length. Applying this methodology to both realistic and computer-generated landscapes, the results demonstrated efficiency in solving previously intractable problems. This approach not only improves habitat connectivity, but also has potential applications in areas such as route selection and barrier construction, exemplified by the creation of firebreaks for wildfire control. This innovation illustrates how integrating different disciplines can provide practical and robust solutions to complex challenges in biodiversity conservation.

Wang [2021] addresses the optimization of wildlife corridors and reserves through three conservation problems that integrate spatial, operational, ecological, and biological requirements. The first problem focuses on the design of the corridor to connect fragmented habitats using integer linear programming and acceleration techniques to solve large-scale instances. The second problem incorporates species dispersal, employing a Markov chain and dynamic programming algorithms to maximize corridor usage probability. The third problem balances connectivity and compactness in reserve design with a two-stage approach and specific algorithms.

These studies highlight the importance of integrating spatial and biological requirements in the optimization of conservation projects. This study proposes the development of ecological corridors using optimization techniques to minimize corridor cost while considering maximum length and connectivity.

2. Methodology

The methodology adopted in this study is based on computational experimentation, structured into two main stages: the generation and preparation of the data set and the execution of tests using a linear programming model formulation and the implementation of the A* and Dijkstra algorithms.

2.1. Data

The spatial data used in this study were obtained through the tracking of elephant movements using collars equipped with GPS technology. Figure 3 shows the distribution of geographic points corresponding to the locations traversed by the animals during the monitoring period.

Based on this information, the area of interest (located between two nature reserves) was discretized into regular polygons, arranged in the form of a square grid. Each cell in this grid represents a parcel of land measuring one square kilometer, eligible for selection as part of the ecological corridor. Figure 4 illustrates this discretization through a 10×10 grid, in which each cell contains information regarding acquisition cost and spatial position. The shaded parcels in the figure correspond to areas that are part of the reserves.

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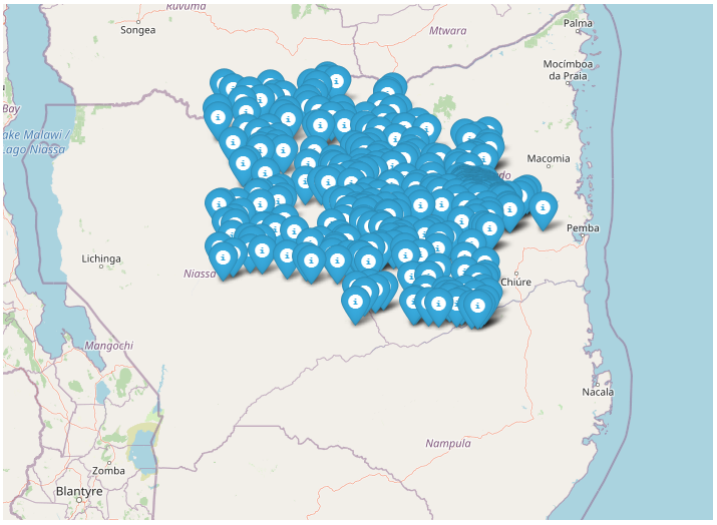


Figure 2: Location of tracked elephant movements
Source: Prepared by the author

(1,1) 88	(1,2) 78	(1,3) 64	(1,4) 92	(1,5) 57	(1,6) 70	(1,7) 88	(1,8) 68	(1,9) 72	(1,10) 60
(2,1) 60	(2,2) 73	(2,3) 85	(2,4) 89	(2,5) 73	(2,6) 52	(2,7) 71	(2,8) 51	(2,9) 73	(2,10) 93
(3,1) 79	(3,2) 87	(3,3) 51	(3,4) 70	(3,5) 82	(3,6) 61	(3,7) 71	(3,8) 93	(3,9) 74	(3,10) 98
(4,1) 76	(4,2) 91	(4,3) 77	(4,4) 65	(4,5) 64	(4,6) 96	(4,7) 93	(4,8) 52	(4,9) 86	(4,10) 56
(5,1) 70	(5,2) 58	(5,3) 88	(5,4) 67	(5,5) 53	(5,6) 74	(5,7) 63	(5,8) 99	(5,9) 58	(5,10) 75
(6,1) 51	(6,2) 69	(6,3) 77	(6,4) 96	(6,5) 56	(6,6) 93	(6,7) 57	(6,8) 96	(6,9) 84	(6,10) 63
(7,1) 66	(7,2) 85	(7,3) 99	(7,4) 89	(7,5) 53	(7,6) 51	(7,7) 55	(7,8) 91	(7,9) 53	(7,10) 78
(8,1) 67	(8,2) 75	(8,3) 93	(8,4) 83	(8,5) 59	(8,6) 85	(8,7) 63	(8,8) 80	(8,9) 97	(8,10) 64
(9,1) 57	(9,2) 63	(9,3) 72	(9,4) 89	(9,5) 70	(9,6) 65	(9,7) 94	(9,8) 67	(9,9) 96	(9,10) 73
(10,1) 75	(10,2) 74	(10,3) 94	(10,4) 90	(10,5) 78	(10,6) 64	(10,7) 94	(10,8) 50	(10,9) 74	(10,10) 56

Figure 3: Illustration of land parcels to be selected for the corridor
Source: Adapted from Wang et al. [2022]

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2.2. Mathematical Model

This minimum-cost ecological corridor construction problem can be treated as a network optimization problem and solved using a linear programming model, adapted from the model proposed by Wang [2021]. The model aims to design a corridor that minimizes the cost, while satisfying connectivity and maximum length constraints.

$$\text{Minimize} \quad \sum_{(i,j)\in A} c_{ij}x_{ij} \tag{1}$$

$$\text{subject to} \quad \sum_{(i,j)\in A} x_{ij} \geq 1, \qquad i = 1, ..., n, \;\; j = 1, ..., m \tag{2}$$

$$\sum_{(i,j)\in A} x_{i,j} \leq L, \qquad i = 1, ..., n, \;\; j = 1, ..., m \tag{3}$$

$$x_{i,j} \leq x_{i+1,j} + x_{i-1,j} + x_{i,j+1}, \qquad i = 1, ..., n, \;\; j = 1, ..., m \tag{4}$$

$$x_{i,j} \in \{0, 1\} \tag{5}$$

Where:

- A is the set of land parcels available for selection;
- c_{ij} is the cost of acquiring or restoring the parcel;
- x_{ij} is a binary variable that takes the value one if the parcel is selected to be part of the corridor, and zero otherwise.

The expressions:

(1) Minimize the total cost of the corridor;

(2) Ensure that at least one parcel is selected;

(3) The total number of selected parcels cannot exceed a maximum limit L

(4) Ensure corridor continuity, i.e., avoid isolated parcels;

(5) Define the parcel selection variable x_{ij} as binary.

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Although the exact model based on integer linear programming guarantees optimal solutions, its application to larger grids presents significant challenges in terms of processing time and memory usage. In this context, the adoption of algorithms such as A* and Dijkstra becomes a viable and efficient alternative, offering high-quality solutions with significantly superior computational performance.

2.3. Dijkstra's Algorithm

An approach to efficiently determine a minimum-cost solution Dijkstra's of Dijkstra's algorithm, proposed by Edsger W. Dijkstra in 1959. This algorithm is widely recognized for its efficiency in solving shortest path problems in weighted graphs with non-negative edge costs [Dijkstra, 1959]. In the implementation adopted in this study, each cell in the grid corresponds to a land unit with an associated acquisition cost, that is, the value required to incorporate that parcel into the final solution. Algorithm 1 presents the detailed fDijkstra's of Dijkstra's Algorithm.

Algorithm 1 Dijkstra's Algorithm

Initialization:
1.1. $dist[i][j] \leftarrow \infty$, for all (i, j)
1.2. $dist[i_0][j_0] \leftarrow$ initial cell cost
1.3. Priority queue: $heap \leftarrow \{(dist[i_0][j_0], i_0, j_0)\}$
1.4. Structure: $cameFrom = \{(i, j)$: predecessor node$\}$
Exploration:
2.1. While $heap$ is not empty:
  2.1.1. Remove from the queue the node with the lowest cost $(cost, i, j)$
  2.1.2. If $(i, j) = (i_t, j_t)$, terminate execution
  2.1.3. For each neighbor (ni, nj) in $\{(-1, 0), (1, 0), (0, -1), (0, 1)\}$:
    2.1.3.1. Check if $0 \leq ni < n$ and $0 \leq nj < m$
    2.1.3.2. Compute $newCost = dist[i][j] + cost_grid[ni][nj]$
    2.1.3.3. If $newCost < dist[ni][nj]$:
      Update $dist[ni][nj] \leftarrow newCost$
      Update $cameFrom[ni][nj] \leftarrow (i, j)$
      Insert $(newCost, ni, nj)$ into the queue
Path Reconstruction:
3.1. Start from the final node (i_t, j_t)
3.2. Backtrack using $cameFrom$ to the initial node (i_0, j_0)
3.3. Reverse the order of the cells to obtain the path

2.4. A* (A-star) Algorithm

Another efficient approach to determine the optimal path in a graph, combining actual cost information and heuristics to accelerate the search, is the A* algorithm, developed in 1968 by Peter Hart, Nils Nilsson, and Bertram Raphael at the Stanford Research Institute, which revolutionized fields such as navigation, robotics, and artificial intelligence [Hart et al., 1968].

In this study, A* was adapted to handle the variation in the costs associated with each land parcel in the grid, ensuring a balance between computational efficiency and solution quality. The detailed formulation of the algorithm is presented in Algorithm 2.

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Algorithm 2 A* Algorithm

Manhattan Distance:
1.1. $h(a, b) = |a_{x_1} - b_{x_1}| + |a_{x_2} - b_{x_2}|$
Priority Queue:
2.1. Structure: openSet $= \{(fScore, (x_1, x_2))\}$
2.2. Sorting: Prioritizes nodes with lower $fScore = gScore + h(n)$
2.3. Operations:
- push : $\mathcal{O}(\log n)$
- pop : $\mathcal{O}(\log n)$
Path Reconstruction:
3.1. Structure: cameFrom $= \{(x_1, x_2)$: predecessor node$\}$
3.2. Process:
3.2.1. Start from the final node
3.2.2. Backtrack via cameFrom to the start
3.2.3. Reverse the order to obtain the path
Neighbor Exploration:
4.1. Directions: $\{(-1, 0), (1, 0), (0, -1), (0, 1)\}$
4.2. Conditions:
4.2.1. $0 \leq x_1 < n$
4.2.2. $0 \leq x_2 < m$
4.3. Update:
4.3.1. If tentativeG $= gScore[current] + G[x_1][x_2] < gScore[neighbor]$
4.3.2. Update all data structures accordingly

3. Results

The implementation and execution of the linear programming model, as well as the A* and Dijkstra algorithms, were carried out in Python programming language, version 3.8.3, and executed on a computer with an AMD $A4 - 9125$ RADEON R3 processor, 4COMPUTER CORES 2C+2G (2CPUs), 2.3 GHz, and 4096MB of RAM. A dataset was generated with grid sizes of 10×10, 10×20, 10×30, 10×40, 20×20, 30×30, 40×40, 50×50, and 100×100 to solve the problem.

Table 1: Results of Computational Experiments

Instance	Grid Size	Exact Model		Dijkstra		A* Algorithm		No. of cells
		OF	Time (s)	OF	Time (s)	OF	Time (s)	
1	10×10	1288	9.5039	1288	0.000168	1288	0.0133	19
2	10×20	1900	34.4892	1900	0.000548	1900	0.0168	29
3	10×30	2545	59.9554	2545	0.000765	2545	0.0233	39
4	10×40	3263	127.1513	3263	0.000563	3263	0.0414	49
5	20×20	-	-	2539	0.000571	2539	0.0320	39
6	30×30	-	-	3684	0.001317	3684	0.1323	59
7	40×40	-	-	5118	0.001974	5118	0.1326	79
8	50×50	-	-	6213	0.003554	6213	0.3369	99
9	100×100	-	-	12549	0.014938	12549	1.4158	199

As shown in Table 1, the linear programming model and the A* and Dijkstra algorithms yielded the same results for instances 1 to 4, highlighting the efficiency of heuristic approaches in

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scenarios of lower complexity. However, for instances 5 to 9, the exact model did not converge to the optimal solution within the 60-minute computational time limit, revealing its practical limitations in the face of increased spatial complexity. In these cases, both the Dijkstra and A* algorithms were able to find high-quality solutions in significantly shorter times, ranging from milliseconds to a few seconds, even for grids composed of up to 10,000 cells.

The performance of the algorithms is particularly relevant given the spatial scale of the problem. The study area was discretized into regular parcels of 1 km^2, and the selection of the cells composing the ecological corridors followed connectivity criteria between protected fragments. To estimate the economic feasibility of the proposed solutions, the relative costs were converted into actual monetary values, using a reference value of USD 1,000 per cost unit. Based on this parameter, the total estimated investments for the corridors ranged from approximately USD 1.28 million to USD 12.5 million, with linear extensions of up to 199 km. These results demonstrate the scalability and applicability of heuristic algorithms in large-scale contexts, where exact methods prove computationally infeasible.

4. Final Considerations

This study proposed a methodological approach based on optimization techniques for the construction of a minimum-cost ecological corridor, with the goal of promoting connectivity between protected areas and mitigating the effects of habitat fragmentation. The problem was modeled through an integer linear programming formulation, complemented by the implementation of efficient algorithms such as A* and Dijkstra, aiming to overcome the computational challenges posed by large-scale instances.

The computational results demonstrate that, although the exact formulation yields optimal solutions for small instances, its scalability is limited due to high computational costs. On the other hand, the A* and Dijkstra algorithms exhibited superior performance in terms of execution time, while maintaining solution quality in larger instances, highlighting their practical applicability in real-world territorial planning contexts.

The adopted model considered a spatial discretization of the study area into regular 1 km^2 parcels, where the optimal selection of parcels respected connectivity criteria. The conversion of relative costs into actual monetary values, using USD 1,000 as a reference for each cost unit, allowed for estimating the total investment required for corridor implementation, ranging from approximately USD 1.28 million to USD 12.5 million, with linear extensions of up to 199 km.

It is concluded that the combined application of linear programming techniques and heuristic algorithms, such as A* and Dijkstra, proved effective for constructing a minimum-cost ecological corridor. While the exact model was helpful in validating solution quality in minor instances, the algorithms demonstrated high scalability, offering good-quality solutions with reduced computational time.

As future work, it is proposed to expand the current model to cover multiple protected areas simultaneously, enabling the design of an integrated network of ecological corridors that connects various reserves on a regional scale.

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