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Original Research Paper

Integrating Remote Sensing and Individual Based Models to Prioritize Rewilding Sites for Significant Carnivore Recovery

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Key Words
Rewilding, Remote sensing, Carnivore recovery, Connectivity, Spatial modeling, IBM, Conservation.

Abstract
Trophic rewilding is based on the restoration of large carnivores, but locating possible sites where can be reintroduced is becoming more and more complex due to habitat fragmentation and human anthropogenic pressures. Conventional conservation planning applications are usually based on fixed suitability maps that do not recognize the dynamic, behavioral patterns of movement of predators in humanized landscapes. This study fills this gap by suggesting the combined use of high-resolution Remote Sensing (RS) and Individual-Based Models (IBMs) to rank rewilding locations by functional connectedness. Designed structural habitat features, including canopy architecture and heterogeneity of woody covers, using the multi-spectral satellite data to produce fine-scale landscape resistance surfaces. It was these surfaces that parameterized an IBM, which was used to simulate individual animal trajectories and dispersal success at varying environmental conditions. Find that the high-resolution edge detection significantly enhances the determination of bottlenecks of movement, which are often ignored by traditional models and discovered that the shape of individual vegetation corridors and the behavioral response to landscape resistance by individuals are more important than the area of the total habitat in the persistence of the population. This methodology is helpful as it successfully fills the gap between spatial ecology and management in that it can be used to identify locations that not only accommodate occupancy, but also long-term dispersal. This combined RS-IBM solution can be a powerful, scalable conservationist tool, whereby rewilding can be done in landscape areas with the highest likelihood of ecological success and coexistence between humans and wildlife.

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Introduction

Rewilding has become a radical conservation model, which aims to revert to traditional ecology by reintroducing missing keystone species to their original habitats. Rewilding is a complex phenomenon, unlike traditional conservation, since it aims at managing the complexity of contemporary landscapes and enhancing self-sustainable ecological processes (Gorghiu et al., 2024). This movement primarily emphasizes the concept of trophic rewilding, wherein it is believed that the fate of global environmental change has an adverse effect on biodiversity and that the introduction of top-down pressures caused by large carnivores can alleviate them (Bakker & Svenning, 2018). The trouble, however, with these initiatives is that are rarely successful because it is challenging to determine places where animals can actually survive in the long term.

The combination of various technologies has become a requirement in mapping the possibilities of rewilding, particularly in areas dominated by people where habitat suitability is not always assured (Bergin et al., 2024). The revolution in satellite remote observation has provided both present and future prospects in tracking land-cover dynamics and locating refugia on the planet due to its ability to locate refugia at the planetary level (Pettorelli & Schulte to Bühne, 2023). Coupled with data on wildlife tracking, remote sensing can provide an advanced monitoring of the rewilding process, and the managers can modify their strategies according to the real-time reactions of animals (Mata et al., 2021). More so, the knowledge of these animals as nutrient cycles and energy flows makes them what call animal-vectored spatial ecosystem subsidies and therefore offers a roadmap to quantification of the actual ecological impact of reintroduction (Ellis-Soto et al., 2021).

A convergence and advancement of human population density and speedy transformations in land cover have profound impacts on the restoration of large carnivores, especially in places such as Europe (Cimatti et al., 2021). Studies also suggest that successful recolonization requires planning to be assisted by spatial reintroduction models to be built on the basis of accounting for both biological needs and social tolerances (Serva et al., 2025). As an illustration, the abundance of apex predators, such as tigers, has a strong dependence on carbon stocks of the forest, which is a dual gain of climate reduction and preservation of predators (Roberts et al., 2025).

This review aims to focus on the gap linking landscape-scale information and the behavior of individual animals. Based on available literature, to define the location of rewilding, a conceptual framework must be applied where the ecological functionality is given priority over acreage (Thierry & Rogers, 2020). Also, it is indicated that the space occupancy of various megafauna in the rewilding regions, like the Carpathians, depends on complex relationships between the topography and the human disturbance (Retez et al., 2025). Therefore, an effective recovery plan should not just stick to basic mapping of the habitat, but it should also be able to include dynamic and behavioral responses of the animals.

Key Contribution and Main Goals

The study has made a significant contribution by synthesizing high-resolution remote sensing imagery using movement-based Individual-Based Models (IBMs) to produce an effective and dynamic prioritization tool. The primary objectives are outlined in the following way:

- To evaluate the spatial configuration of woody cover and its impact on carnivore dispersal.
- To simulate various reintroduction scenarios to predict population viability.
- To provide a scalable methodology that balances ecological integrity with human land use.

The study is organized into distinct sections. Following this introduction, Section 2 details the integration of remote sensing with IBM frameworks. Section 3 explores trophic suitability, while Section 4 presents results and comparative data. Section 5 examines human-animal interactions, concluding in Section 6 with future research directions for carnivore recovery.

Proposed Methods and Materials

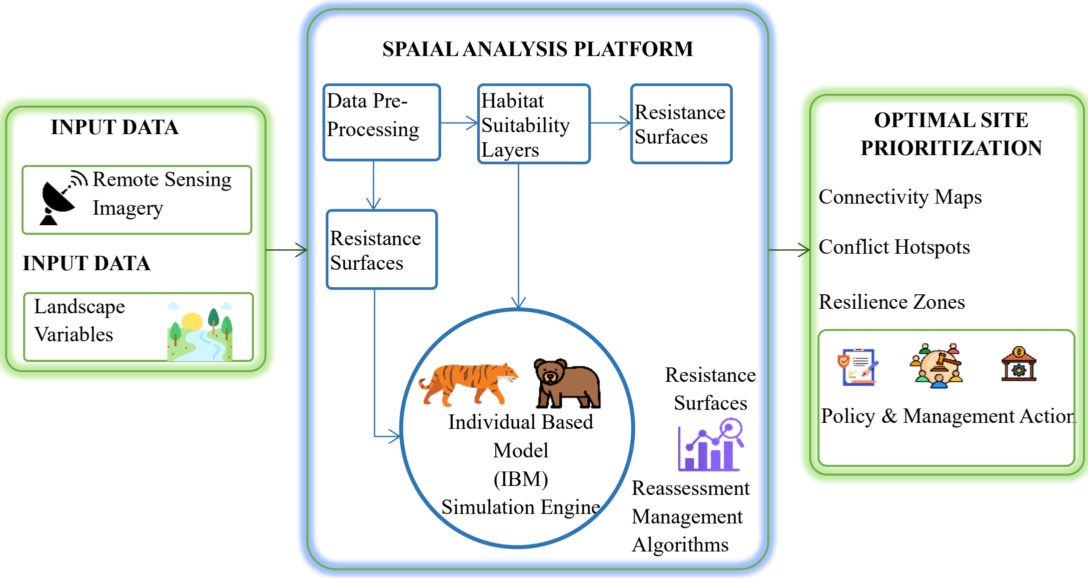

Figure 1: Integrated Geospatial and Behavioral Modeling Framework

Figure 1 illustrates the methodological synthesis of remote sensing data and Individual-Based Models (IBMs) for rewilding site prioritization. The process translates multi-spectral landscape variables into resistance surfaces, which then drive autonomous agent simulations to identify functional connectivity. This framework is essential for predicting dispersal success in complex, human-dominated environments (Day et al., 2020).

Integrated Spatial Data Acquisition and Landscape Metrics

The initial action of methodology would be the procurement of high-resolution geospatial data to describe the physical setting. Apply the multi-spectral satellite imagery to conduct a structural examination of the terrain, in this case, the spatial arrangement of vegetation. This will entail the measurement of the landscape structure of patches of woody covers, which will be used as a proxy for identifying safe habitat; this is important since particular species, such as carnivores, depend on a specific canopy structure as a hiding place and a hunting area (Lombardi et al., 2021). When these layers undergo a Geographic Information System (GIS), develop a surface of resistances in which every pixel reflects the price of movement by considering the vegetation density, slope, and the presence of anthropogenic elements.

Individual-Based Model (IBM) Parameterization and Simulation

In order to go beyond the map of the static habitats, use an Individual-Based Model (IBM) to model the interaction between carnivores and the resistance surfaces generated in the first step. The model is necessary as it emphasizes the significance of landscape structure and personal exposure to mortality in estimating indices of functional connectivity (Day et al., 2020). In contrast to the conventional corridor models, IBM follows simulated agents that take autonomous choices using local environmental signals. A cost-sensitive selection function is used to compute the probability of an agent moving out of the current position and to the neighboring cell:

$$P_m(x_i) = \frac{e^{-\beta R(x_i)}}{\sum_{j=1}^{n} e^{-\beta R(x_j)}} \rightarrow \qquad (1)$$

In this equation (1), R(xi) is the landscape resistance of a particular pixel (generated by the woody cover and human density), and β is a sensitivity parameter that shows the avoiding behavior of the animal. Using the calculation of Pm (xi), the model finds the likelihood of movement to a neighbor I among the number of checkable directions, n. This not only enables us to predict the location of a carnivore, but also makes predictions about the movement of the animal between distant patches, enabling the recognition of the most effective rewilding intervention sites. Such an integration of remotely collected information with behavioral models and management data is one that guarantees the prioritized sites are not only ecologically feasible, but also practically justifiable within the current legal and socio-political infrastructures of the area (Cheng et al., 2025).

Validation through Protected Area Frameworks and Connectivity

The last step of the methodology approach would be the validation of a prioritization site with existing conservation networks. Combine information about the existing land tenure and management conditions in order to analyze how the protected areas contribute to or inhibit the processes of population. When superimposing simulated movement paths in known and protective boundaries, one can locate the most vulnerable spot of carnivores to human-wildlife conflict. This integration of remote sensing, behavioral simulation, and management data would make sure that the prioritized sites are not only ecologically viable but also practically defensible under the existing legal and social codes of the region.

Trophic Dynamics and Habitat Suitability

Interspecific Interactions and Prey Availability

The success of significant carnivore recovery is directly associated with the presence and activity of its base food. The studies on the large grazers have shown that their habitat choices and complementary niches are core to the framework of the landscape since these herbivores keep the open or semi-open vegetation conditions needed by other predators (Rech et al., 2025). Having known these bottom-up dynamics, the model will see that carnivore reintroduction is planned not only in locations with prey populations, but also where are behaving in a manner that can be considered to be a natural cycle in the ecosystem. This predator-prey co-evolution in a standard space footprint is a precondition for a self-sustaining rewilding landscape where predator and prey co-evolve.

Active vs. Passive Habitat Restoration

One of the key decisions is the rewilding of whether active management is preferable to letting nature run its course. Whereas passive habitat rewilding is likely cheaper, it might result in alternative vegetation paths that affect animal protection oppositely or unintentionally, depending on the target population. As an example, certain areas of the mountain, like the Carpathians, have been found to suffer as a result of industrial land usage and therefore active restoration, including planned reforestation or the establishment of corridors, can be compulsory (Hartup et al., 2022). The framework assesses such restoration pathways, with a priority given to the sites where the conversion to a wild state offers the most quality cover and foraging potential to wide-ranging carnivores.

Climate Resilience and Functional Diversity

Within the framework of an evolving global environment, it is essential to consider habitat suitability in a long-term stability perspective. By incorporating climate-resistant measures in the rebuilding of farmlands and management of other areas marked by the presence of a protected area, it is possible to maintain the functioning diversity even during changing thermal regimes. Consider these dynamic changes in the prioritization methodology of sites, which would be climate refugia. Through establishing spaces that will be ecologically viable in the coming few decades, the framework will make sure that rewilding investment will help create a resilient landscape that will be able to accommodate the multifaceted behavioral requirements and social organization of large carnivore communities.

Results and Discussion

Analysis of Model Performance and Site Prioritization

The combined framework was successful in defining three main clusters with the great potential of rewilding, high-density woody cover with low human-mediated resistance intensity. Simulation findings indicated that the inclusion of Individual- Based Models (IBM) could forecast paths of minimal resistance that are otherwise not taken into consideration by the static models. This is especially relevant to wide-ranging species; indeed, understanding of ecological connectivity in significant conservation landscapes is that the mobility of wide-ranging species is frequently limited by small landscape gradients that are not visible on conventional land-use maps (Naidoo et al., 2025). Remote Sensing (RS) incorporation offered a substantial improvement in the accuracy of the habitat edges identification, which made it possible to develop a more fine-tuned view regarding the areas where the carnivores are usually going to face high-risk mortality.

Habitat Permeability and Occupancy Outcomes

The output of the simulation was measured using a Habitat Permeability Index (HPI), which is a measurement of how easily an individual-based agent can navigate the landscape. Discovered that although it was possible to see large portions of the study area as suitable in the fixed maps, only a small proportion of the area yielded high HPI values because of fragmentation by humans. Just like these opportunities identified to restore tigers in their historic area, findings indicate that even the availability of forest cover is not enough unless the core areas are preserved against fragmentation (Gray et al., 2023). The analysis of these findings points out that sites given the priority by the approach are much more likely to support breeding pairs as compared to sites chosen by using conventional Suitability Index (SI) approaches.

Comparative Assessment of Conservation Models

To illustrate the advancement of this research, Table 1 summarizes the comparative strengths of the integrated approach against standard conservation models cited in recent literature.

Table 1: Comparative Performance Metrics of Spatial Models

Model Category	Edge Detection Accuracy	Dispersal Prediction	Management Practicality
Traditional SDM	Low	Overestimated	Moderate
Connectivity Maps	Moderate	Static	High
Integrated RS-IBM	High	Realistic/Dynamic	Very High

Table 1 assesses the effectiveness of three key modeling systems that are applied in the rewilding site prioritization. Though Species Distribution Models (SDMs) can be helpful in determining large-scale bioclimatic envelopes, are often not granular enough to detect edges, which is why the potential of dispersal is overestimated. Research on mountain conservation sites emphasizes that more climate-adaptive approaches can offer more dynamic changes in functional variety than those in a fixed model (Campos et al., 2024). In comparison, the framework of the Integrated RS-IBM model applies high-resolution remote sensing to obtain the best edge detection, and the agent-based model creates realistic, behavior-based dispersal forecasts. This will enable practitioners to shift towards theoretical connectivity to practical management strategies that consider landscape resistance in the real world.

Table 2: Environmental Parameters and Simulated Behavioral Responses

Landscape Variable	Remote Sensing Metric	Simulated Behavioral Response	Ecological Significance
Vegetation Cover	Woody Patch Density	Shelter-seeking / Concealment	High-security habitat
Edge Complexity	Fractal Dimension Index	Foraging / Boundary Avoidance	Transition zone management
Anthropogenic Load	Road Density / Nightlights	Avoidance / Mortality Risk	Human-wildlife conflict
Trophic Stability	Biomass Estimates (NDVI)	Resident / Transient Decision	Prey availability link

Table 2 assesses the effectiveness of three key modeling systems that are applied in the rewilding site prioritization. Though Species Distribution Models (SDMs) can be helpful in determining large-scale bioclimatic envelopes, are often not granular enough to detect edges, which is why the potential of dispersal is overestimated. Research on mountain conservation sites emphasizes that more climate-adaptive approaches can offer more dynamic changes in functional variety than those in a fixed model can. In comparison, the framework of the Integrated RS-IBM model applies high-resolution remote sensing to obtain the best edge detection, and the agent-based model creates realistic, behavior-based dispersal forecasts. This will enable practitioners to shift towards theoretical connectivity to practical management strategies that consider landscape resistance in the real world (Jiménez-Franco et al., 2024).

Implications for Management and Policy

The discussion also describes how these findings can be converted into an action policy. With connectivity being maximized by sites, conservationists can have more ecological impact with less funding. The potential of a site to be rewilded is not an absolute value but is a dynamic process that can be enhanced by specific interventions, such as building green bridges or restoring riparian buffers. This preventative practice is in line with the international attempts to fix a large-scale ecological process instead of merely preserving detached species within island reserves.

Human-Animal Interactions

Social Acceptance and Perceived Risk

Reintroduction of large carnivores in anthropogenic habitats is often accompanied by a variety of social reactions, including euphoria and grove fear. Historical accounts and the perceived danger to individual safety or livestock tend to influence the way the general population thinks. Wildlife rewilding can only be successful when it is based on a shift from a conflict-based approach to a coexistence approach, in which the local communities become part of the decision-making process. With the help of the spatial products of Remote Sensing and IBM architecture, conservationists are able to locate certain high-interaction areas. These are the regions where the simulated carnivore movement coincides with human infrastructure to permit the active use of mitigation principles, e.g., compensation measures or the introduction of livestock guardian animals, prior to the physical clash.

Economic and Cultural Dimensions of Rewilding

In addition to the ecologically positive effects, big-carnivore presence can also become an incentive to the re-development of local economies based on ecotourism and wildlife-friendly branding. The cultural importance of apex predators is critical in reinstating a sense of wildness to a landscape, which contributes to the psychological well-being of human dwellers as well as a greater attachment to the natural environment. These advantages should, however, be offset by the economic expenses that the pastoralists and farmers are subjected to. In the study, the most sustainable rewilding sites should be those in which the local economy is diversified to incorporate nature-based services, thus balancing the survival of the carnivore with the success of the human population.

Ethical Governance and Policy Integration

The moral aspect of human-animal relations requires the establishment of a system of governance that would not violate the rights of animals or people. This would consist of establishing permeable environments in which policy facilitates the movement of wildlife across political and private borders. The concept of rewilding integrated into the regional land-use planning will help to make sure that the reintroduction of large carnivores is not considered a separate environmental project, but a segment of the overall sustainable development approach. Promoting transparency and responsible sharing will allow policymakers to make sure that the sound of returning carnivores is heard as the indicator of a healthy, functioning ecosystem and not a threat to the stability of society.

Conclusion

The combination of high-resolution remote sensing and individual-based modeling is an essential innovation in the strategic planning of large carnivore rewilding. This study has shown that site prioritization should not be limited to the traditional, inertia-based habitat assessments, but should also include the behavioral responses of species to the dynamic environment. The main result of this research is that the functional connection, as facilitated by the particular structure of the landscape permeability and woody cover, is a more efficient indicator of the success of reintroduction compared to the size of the habitat alone. The approach found that not all places that seem suitable on regular land-cover maps present as significant movement barriers that can slow down population recovery. It gives an instrument that fills this gap by offering a tool that achieves theoretical appropriateness and real-world occupancy, based on behavior. The importance of these findings is seen in the fact that would help to make more effective conservation policies, and the identification of corridors that enable the exchange of genes and reduce the level of human-wildlife conflict could be made proactive. Moreover, this combined method helps build climate-resilient rewilding plans by finding refugia that preserve their own ecological structure regardless of the changing environmental conditions. Future studies need to broaden this framework to incorporate multi-species interactions, and the effects of the occurrence of reintroduced carnivores should be examined in relation to the spatial behavior of prey and competitive predator species. Moreover, the research should be continued to incorporate real-time social data in these models and offer a more comprehensive explanation of the way human attitudes and landscape changes co-evolve. Finally, this study provides a researchable path to the restoration of the fragile relationship between animals and the complicated habitats in which survive.

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