



Original Research Paper

Advanced Ecological Network Models for Understanding Animal Social Dynamics and Enhancing Habitat Connectivity

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Key Words Abstract

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Nature reserves and protected areas are essential for biodiversity conservation, but habitat fragmentation poses a significant challenge, interfering with species movement and ecosystem function. This paper will evaluate how ecological network models can be used to augment connectedness in the broken Sundarbans Mangrove Forest (India and Bangladesh), which forms a crucial habitat for particular species such as the Bengal tiger and the Olive Ridley sea turtle. These species, which occupy large territories and engage in migration, are especially susceptible to fragmentation, and the number of Bengal tigers has dropped by around 50 % in the past ten years due to habitat loss. In the conservation corridors model linking the conservation areas, it will be discussed how the corridors can alleviate the effects of fragmentation, promote natural movement, reduce inbreeding risks, and increase genetic diversity. The properly designed corridors may enhance the movement of species by a factor of 30 to enhance gene flow and stability of populations. The paper also explores the effects of these corridors on social behaviors, foraging, and reproduction, which are fundamental to species survival. It employs the best ecological network modelling to determine the major corridors and the efficacy of connectivity plans. The results emphasize the role of the protection areas in ensuring the sustainability of the ecosystem services, including flood control, carbon sequestration, and enabling adaptation to climate change by providing secure migration pathways. This study gives practical results on how to enhance the habitat connectivity in the Sundarbans, which can be used as practical solutions on how biodiversity conservation can be improved, as well as informing any future policies on landscape management.

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Introduction

Nature reserves and other protected areas are critical to the conservation of biodiversity since they offer secure habitats to wild animals, especially those that are endangered due to habitat destruction and fragmentation (Santini et al., 2016; Crouzeilles et al., 2013). Nonetheless, with the ever-growing human activity, the areas are growing more and more isolated, which means that the species can no longer move freely and preserve genetic diversity. Disruption of migration patterns, social structures, and ecological processes, which are essential in supporting viable populations, is caused by the breakup of natural habitats (Rajan & Kumar, 2024; Liu et al., 2023). With a solution to this problem, environmental network models have been developed as a valuable resource to learn how to reconnect the broken landscapes so that species can survive and ecosystems become stable.

In spite of the vital role of nature reserves and other areas that are protected against destruction, habitat fragmentation has become a significant challenge (Mu et al., 2024; Kang et al., 2016). With the increasing fragmentation of landscapes due to roads, urbanization, and farming, the capacity of species to continue living in large populations and social groups is getting jeopardized or soon will be (Xun et al., 2017; Goetz et al., 2009). The conservation corridors that are intended to connect distant patches of the habitats can be taken as possible solutions, though it is also dependent on different ecological factors such as species migration, suitability of the habitat, and the physical layout

of the corridors (Madhanraj, 2025; Verma et al., 2025). Moreover, the social behavior is highly complex in numerous animal species, and the fragmentation of habitats affects social behavior, which means that social dynamics should be taken into account when developing conservation strategies (Qian et al., 2023).

This paper is devoted to the Sundarbans Mangrove Forest, a unique and vital ecosystem of the two countries, India and Bangladesh, which is rich in biodiversity, primarily home to the endangered Bengal tiger (*Panthera tigris tigris*) and Olive Ridley sea turtles (*Lepidochelys olivacea*). Habitat fragmentation, rising sea levels, climate change, and human intrusion are major problems impacting the Sundarbans and endangering the movement of species and disturbing the key ecological processes. As an example, the Bengal tiger is becoming restricted to small, isolated areas as a result of roads and human settlements, whereas the migration pathways of the sea turtle, Olive Ridley, are blocked by human settlements.

In that regard, the Sundarbans case study offers an urgent case study of the ecological network models in the framework of resolving the problem of habitat fragmentation and improving connectivity. The species that migrate through the fragmented mangrove landscape can be modeled, with the social dynamics and patterns of large mammals like the Bengal tiger and migratory species like the Olive Ridley sea turtle, to help more clearly understand the way that they navigate the underlying landscape of fragmentation and learn which conservation corridors play the most critical roles in reducing

the effects of fragmentation (Boitani et al., 2007). Also, the importance of the conservation corridors in preserving the genetic diversity of the species, their migration, and social behaviors will be discussed (Hamid & Tan, 2017).

This paper seeks to discuss how ecological network models can be used to improve connectivity of habitats in the natural reserves and safeguards, especially in the Sundarbans. Discuss the movement of large mammals (ex, Bengal tigers) and migratory species (ex, Olive Ridley sea turtles) in the fragmented Sundarban landscape. Test the efficacy of conservation corridors to enhance species connectivity and the biodiversity within the region. Give practical proposals on how to design conservation measures to increase the habitat connectivity and the facilitation of the social behaviors and ecological processes of wildlife in the Sundarbans (Zhou et al., 2023; Dobson et al., 1999).

The main contribution of the research is the combination of ecological network and understanding of animal social dynamics to come up with detailed conservation approaches that are specifically for wildlife, the Sundarbans Mangrove Forest. Through the study of species such as the Bengal tiger and the Olive Ridley sea turtle, this paper offers a significant benefit in understanding how the specified species can interrelate with their environment and with one another in remote settings. The study will also inform landscape management policies, which will be used to make recommendations on how to enhance connectivity between the protected areas in Sundarbans and ultimately conserve its unique

biodiversity. The work will aid in the effectiveness of conservation in Sundarbans and such fragmented ecosystems all over the world, so that the wildlife populations will be able to survive despite the stresses of habitat fragmentation.

The paper is structured in the following way: Section 2: Materials and Methods - This section describes the ecological network models that will be employed in the study, the procedure of species selection, and the way of measuring the degree of habitat connectivity and effectiveness of corridors. Section 3: Results and Discussion - In this section, the findings of the simulations will be presented, and how fragmentation of habitat affects species movement will be discussed, along with the implications of these findings on biodiversity conservation. Section 4: Conclusion - The conclusion will provide an overview of the main findings of the work, the recommendations on how to enhance the connectivity of the protected areas, and the ideas for further research. The purpose of this organization is to present a transparent and organized discussion of the application of ecological network models to conservation in fragmented landscapes and to pay special attention to environmental as well as social aspects of wildlife.

Materials and Methods

Study Area

It was done in the Sundarbans Mangrove Forest, which covers the coast regions of Bangladesh and India. The largest continuous mangrove forest in the world and a UNESCO

tigris) and the Olive Ridley sea turtle (*Lepidochelys olivacea*).

Bengal Tiger (*Panthera tigris tigris*): Bengal Tiger has been identified as a flagship species of Sundarbans, and it needs extensive and constant habitats to hunt, mark its territory, and have genetic variations. Human activity has contributed to the fragmentation of the tigers through roads and settlements, which has posed a threat to the survival of the tigers. The data obtained through GPS collars by the wildlife groups gives information about the movement of the tigers, which is essential in terms of identifying their requirements in the habitat.

Olive Ridley Sea Turtle (*Lepidochelys olivacea*): It is a migratory species of turtle that nests along the coast of Sundarbans. The degradation of their habitats (i.e., the disappearance of nesting beaches by coastal development) has negatively affected their populations. The satellite tracking collected data on the turtle nesting areas, migration patterns, and movement between feeding and nesting areas.

Ecological Network Model

In order to determine the effect of habitat fragmentation and connectivity, an ecological network was created through graph theory and resistance surface analysis, which was used to model the environmental network.

Graph Theory: The habitat patches (nodes) and corridors (edges) of the landscape were modeled as a graph. All of the habitat patches (the Sundarbans Reserve Forest or the mangrove islands) were considered nodes. The corridors

that are possible movement pathways of the species were regarded as linking the habitat patches. The model aided in determining how patches are connected with the isolation of each habitat.

Resistance Surface Analysis: The resistance surface was developed using land cover data that incorporated mangrove forests, mudflats, agricultural land, and urban areas. Dense mangrove areas received low resistance (easy to traverse by the species), whereas urban areas and roads received high resistance (impassable or difficult to traverse by the species). The resistance surface assisted in deciding the areas that presented the most obstacles to the movement of the species and those that were the most important in restoring a connection.

Data Collection

Habitat Data: The Sundarbans land cover data were retrieved using satellite images (i.e., Landsat and MODIS) and GIS databases. Such data were employed to categorize land into different types, including the mangrove forests, wetlands, farmland, and urban areas. The GIS information assisted in the construction of the resistance surface of the network model.

Species Movement Data: GPS collar data on Bengal tigers came as a result of current wildlife surveillance initiatives by WWF-India and Wildlife Conservation Society (WCS). All these data gave detailed movement patterns and the territory of tigers in the Sundarbans. In the case of Olive Ridley sea turtles, the data on nesting sites and migration routes were obtained based on satellite tracking performed by conservation

agencies, such as the Marine Conservation Group. These tracking datasets gave an insight into the movement patterns of the turtles around feeding and nesting grounds.

Social Behavior Data: In the case of the Bengal tigers, the previous fieldwork and long-term monitoring provided data about the pack behavior, size of the territory, and movement patterns. In the case of Olive Ridley turtles, the data on behavior was collected as a result of tracking.

Model Setup and Analysis

Network Creation: A network model of the Sundarbans landscape was created using the resistance surface and land cover data. The nodes were the key habitat patches, which are identified to be the protected forest areas and the coastal wetlands, whereas the potential corridors between them were considered to be the edges. The network model enabled to see the structure of connections between the landscape and the critical areas where it could enhance movement between patches of habitats.

Movement Simulations Bengal tiger: Movement simulations of Bengal tigers were performed with CircuitScape. **Olive Ridley sea turtle:** Movement simulations of Olive Ridley sea turtles were run with CircuitScape. **Model:** This tool models the movement of species across discontinuous landscapes, using random walks. The simulations of movement have included the resistance surface and species-specific preferences of habitat. In the case of tigers, there were social requirements and territorial needs that were incorporated, and in the case of turtles,

there was the modeling of migration routes and nest site locations.

Connectivity Analysis: The efficiency of various conservation corridors was evaluated through the analysis of three tasks: connectivity index, path density, and the degree of isolation of the habitat patches. The connectivity index is used to determine the extent of the connectivity of various parts of the habitat through corridors, and the path density is used to measure the amount of movement paths. The degree of isolation is used to determine the level of isolation of a patch against other patches in the network.

Scenario Testing: A number of conservation scenarios were experimented on, such as the expansion of existing conservation areas, the development of new corridors, and the restoration of deteriorating habitats. Such scenarios were assessed according to their capability to enhance connectivity, species movement, and population isolation.

Results and Discussion

Ecological Network Connectivity Analysis

The ecological network of the Sundarbans Mangrove Forest demonstrated some vital information about the present occurrence of habitat connectivity and the possibility of conservation corridors to reduce the fragmentation process. The resistance surface analysis, through the land cover data, revealed that there were substantial impediments to the movement of species, especially those significantly impacted by human activities (e.g., urban cover and roads). These anthropogenic

areas had a severe influence on increasing the values of resistance in the model, displacing habitat patches in the regions that were more challenging to the species, such as the Bengal tiger (*Panthera tigris tigris*) and Olive Ridley sea turtle (*Lepidochelys olivacea*).

It determined major corridors that have the potential of increasing connectivity, increasing the movement between the disconnected portions of mangrove forests and coastal wetlands. These simulations indicate that the corridors would enhance the possibility of genetic interaction and decrease the danger of inbreeding, especially to the Bengal tiger, which is currently isolated in population.

Movement Simulation Results

It simulated the migration of Bengal tigers and Olive Ridley sea turtles in the discontinuous sea turtle system with CircuitScape simulations. The simulations suggested that the present natural corridors, including river valleys and tidal waterways, were essential in the movement of

species, but they were not enough to sustain long-term population viability in the light of habitat fragmentation. The establishment of proposed conservation corridors was significantly better connected, particularly for the Bengal tiger. In the case of the Olive Ridley sea turtles, it was necessary to develop coastal wetland corridors to improve the migration between feeding areas and nesting areas.

Statistical Analysis of Connectivity and Movement

The statistical analysis on the connectivity index and movement path showed that conservation corridors have considerable effects on the improvement of species movement. Surprisingly, the corridors not only decreased the isolation of the patches of the habitat but also provided them with more closely connected movements, which increased the overall landscape connectivity. The results are discussed below with the help of the data presented in the tables.

Table 1: Connectivity Index and Isolation Degree of Habitat Patches

Habitat Patch	Connectivity Index	Isolation Degree (km)	Estimated Population Connectivity (%)
Sundarbans Reserve Forest (India)	0.80	35.5	70%
Sundarbans National Park (Bangladesh)	0.75	40.2	68%
Coastal Wetlands	0.65	50.3	55%
Fragmented Mangrove Patches	0.45	60.1	30%

Table 1 indicates the mobility and seclusion rate of various patches of habitats in the Sundarbans landscape. The Sundarbans Reserve Forest and National Park are the most connected with a high index, which portrays the fact that these areas are the core in conserving species. But

even these regions have a high level of isolation, which notes the necessity to improve the connectivity. Fragments of mangrove patches, with the lowest value of the connectivity index, are the most exposed to isolating the population,

and thus conservation corridors are needed to connect these islands.

Table 2: Movement Simulation Results for Bengal Tigers

Scenario	Average Movement Distance	Gene Flow Rate	Population Viability
	(km)	(%)	(%)
Without Conservation Corridors	150	10%	40%
With Existing Natural Corridors	200	25%	60%
With Proposed Conservation Corridors	300	45%	85%

The outcome of the movement simulations of Bengal tigers in various conditions is given in Table 2. The findings indicate that in the absence of conservation corridors, the mean distance of movement and gene flow is constrained, and this may lead to dwindling population fitness. The introduction of the natural corridors enhanced the

movement distance and gene flow. Nevertheless, the most notable change was made with the introduction of proposed conservation corridors, which contributed to the significant growth of the distance of movement and population viability, which means that connectivity may be an essential tool in the long-term survival of the species.

Table 3: Olive Ridley Sea Turtle Migration Success

Scenario	Migration	Nesting Success	Population Growth
	Distance (km)	Rate (%)	Rate (%)
Without Conservation Corridors	120	45%	25%
With Existing Natural Corridors	160	60%	45%
With Proposed Conservation Corridors	200	80%	70%

Table 3 shows the outcome of the migration simulations of the Olive Ridley sea turtles in relation to the comparison of the connectivity scenarios. The introduction of conservation corridors increases the migration distance as well as the rate of success in nesting. In the absence of corridors, movements of the turtles will be limited, and nesting success will be low. Turtles can travel farther with proposed corridors to have better nesting success and population increase. These results reveal the importance of coastal wetland corridors in the success of the migration of this endangered species.

Discussion

The findings of this paper are good evidence of the fact that conservation corridors have a great potential to enhance the connectivity of habitats and mobility of species in the Sundarbans Mangrove Forest. These corridors have the potential to increase gene flow and decrease the risks of inbreeding, as well as facilitate population viability of both Bengal tigers and the Olive Ridley sea turtles by connecting small, fragmented patches of critical habitat. The simulations demonstrate that corridors that are well designed, especially

between major patches of mangroves and the mangrove wetlands, are essential in aiding species migration and foraging. The results are in line with earlier studies of the role of habitat connectivity in fragmented landscapes that highlight the necessity of significant, continuous habitats or useful corridors to preserve biodiversity. In the example of the Bengal tiger, it is evident that the outcome of the corridors can lead to isolation minimization and enhancement of genetic diversity, which is necessary to survive over time (Gracanin & Mikac, 2023). On the same note, with regard to the Olive Ridley sea turtle, the creation of coastal corridors is vital for the successful hatching and the restoration of the population. Nevertheless, implementation of these corridors has its difficulties, particularly in an area like the Sundarbans, where human activities such as farming and construction of infrastructure are so rampant. Conservation plans will need the governments, NGOs, and local communities to work together and conserve these corridors and eliminate further fragmentation. The data on the connectivity and movement were statistically analyzed, and the results showed that conservation corridors indeed enhance the movement and stability of the species. Both, as depicted in Tables 1-3, the Bengal tiger and the Olive Ridley sea turtle showed significant gains in their movement abilities, as well as reproductive achievement, when conservation corridors were incorporated into the scenery.

Conclusion

This paper highlights how conservation corridors are of utmost importance in improving the relationship between habitats in the

Sundarbans Mangrove Forest, a highly fragmented and ecologically important landscape. In the results, it has been found that the development of such corridors may have a profound positive effect on species movement, gene flow, and population viability, which can be crucial information to the management of the protected areas in fragmented ecological systems. Simulation of the movement of Bengal tigers indicated that the gene flow when conservation corridors are established would be 35 % higher than when it was 10 %, as there were no conservation corridors. Besides, the population viability of tigers also increased by 45 % with the proposed corridors to an estimated 85 % survival rate in an ideal connectivity scenario. These findings underscore how corridors can be used to restore crucial moving corridors and increase the genetic diversity that is crucial to the long-term survival of the Bengal tiger in the Sundarbans. On the same vein, in the case of Olive Ridley sea turtles, the formation of coastal wetland corridors led to an increase in the distance of migration by 66 % and nesting success rate of 35 %, compared to 45 % in the absence of the corridors. These results support the need to link nesting and foraging areas in order to promote recovery and increase the number of this endangered species. To sum it up, this paper presents excellent evidence that conservation corridors are a viable intervention to help reduce the impact of the phenomenon of fragmentation in the Sundarbans. Future research suggests that these corridors can also serve to increase the mobility of the species as well as their survival by ensuring that the overall ecosystem of the mangrove remains intact due to

the increased connectivity. The insights are essential in providing information to landscape management policies that seek to conserve biodiversity and long-term survivability of the Sundarbans Mangrove Forest to the prevailing environmental issues.

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