Complex Network Analysis and its Application to Wildlife Corridors using Machine Intelligence

A thesis submitted to the

UPES

For the Award of

Doctor of Philosophy

In

Computer Science & Engineering

By

SAURABH SHANU

December 2023

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DECLARATION

I declare that the thesis entitled "Complex Network analysis & implementation to Wildlife Corridors using Machine Intelligence" has been researched by me under the guidance of Dr. Alok Aggarwal, Professor, School of Computer Science, UPES, Dehradun and Dr. Yadvendradev Jhala, Dean (Retd.), Wildlife Institute of India, Dehradun. No part of this work has formed the basis for the award of any degree or fellowship previously.

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CERTIFICATE

We certify that Mr. Saurabh Shanu has prepared his thesis entitled "Complex Network analysis & implementation to Wildlife Corridors using Machine Intelligence" for the award of a Ph.D. degree from the University of Petroleum and Energy Studies, under our guidance. He has carried out the work at the School of Computer Science, UPES, Dehradun with key support from Wildlife Institute of India, Dehradun.

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ABSTRACT

Complex networks are intricate systems with numerous nodes and intricate patterns of connections, characterized by various disciplines such as social sciences, biology, transportation, and computer science. Complex network analysis is a multidisciplinary field that delves into intricate network structures found in diverse domains like social networks, biological networks, the World Wide Web, and transportation networks.

Incorporating complex network analysis into ecology and wildlife conservation provides a powerful framework for understanding complex relationships within ecosystems, identifying critical areas for protection, and designing more effective strategies for biodiversity preservation and sustainable natural resource management. This work aimed to use machine intelligence and complex network analysis for designing wildlife corridors, focusing on tigers as the focal species. The major goal had been to create computational models for identifying wildlife habitats and landscape's essential points for maintaining contiguity within a landscape.

Wildlife habitat patches are vital zones in the landscape that provide food, water, and ecological conditions for wildlife species to thrive. Habitat fragmentation and loss have led to discontinuity in focal species' habitats, forcing them to use managed ecosystems. Studies have supported habitat conservation through the development of wildlife corridors between fragmented habitat patches, encouraging the movement of organisms between regions of intact habitats.

This study computes a viable tiger corridor network architecture in the focal landscape using the Clique Percolation Method (CPM), recommending understanding the interactions between

multiple vertices, as tigers can migrate to several habitat patches depending on migration reasons. The Habitat Suitability Index (HSI) is used to determine these interactions in real-world scenarios for a particular species, and Remote Sensing and Geographic Information System (GIS) datasets are used to calculate HSI for a species over a landscape.

The study also analyzes dispersal patterns of tiger in a hypothetical environment with all essential components of any landscape. Tensor-based computational models are used to address data resolution and impact of seasonal variation on the vegetation which further affects the dispersal of tigers within a landscape. A cumulative model is developed to illustrate a decision-support system for planning wildlife corridors with tigers as the focal species.

The outputs of the recommended models were compared to the most current tiger report from the Government of India (at the time of publication), and a significant degree of accuracy was observed discovered. The greatest highest accuracy was 98%, and the lowest was 83%, depending on the area and type of datasets used. To compare them, the output maps created by the developed models and the output maps provided in the reports were utilized. Individual pixel assessments at the same scale were utilized to construct this assessment technique.

This work would be very useful for the wildlife stakeholders for conservation plannings and thus lead to a balanced environment. Properly designed wildlife corridors facilitate seed dispersal, maintain ecosystem balance and resilience. Additionally, optimized corridors can help mitigate conflicts between wildlife and human activities, promote responsible eco-tourism, enhance landscape connectivity, and enhance water quality.

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Chapter 1

INTRODUCTION

Complex networks are intricate systems defined by their non-trivial topological characteristics, typically featuring a multitude of nodes and intricate patterns of connections. These networks manifest across a diverse array of disciplines, encompassing social sciences, biology, transportation, and computer science (Boccaletti et al., 2006). Notable attributes of complex networks comprise the small-world phenomenon, where nodes are remarkably interconnected, permitting relatively short paths between most nodes, giving rise to the notion of a "small world" as epitomized by the "six degrees of separation" concept. Additionally, complex networks often exhibit a scale-free property, characterized by a few highly connected hub nodes amidst a majority with low degrees (Bullmore & Sporns, 2009). They also frequently display a community structure, with nodes forming modular clusters marked by dense intra-cluster connections and sparse inter-cluster links, facilitating the identification of functional or thematic groups. Furthermore, the resilience and vulnerability of these networks are paramount considerations, as they can withstand random node failures but are susceptible to targeted attacks on hubs. Complex networks encompass not only small-world and scale-free varieties but also various other models that capture distinct facets of real-world systems, including random graphs, hierarchical networks, and spatial networks (Boutaba et al., 2018). Consequently, extensive research utilizing graph theory, network science, and computational tools has been devoted to understanding complex networks. Their applications extend to the analysis and modeling of a wide spectrum of real-world systems, spanning social networks, biological networks like protein-protein interaction networks, the World Wide Web, and transportation networks, offering valuable insights into system organization, information dissemination, and the development of robust and efficient systems (Szklarczyk et al., 2014). As a result, complex network analysis offers several perspectives on the research subject.

Complex network analysis is a multidisciplinary field that delves into intricate network structures found in diverse domains like social sciences, biology, technology, and transportation. These networks are marked by complex topological features (Rubinov & Sporns, 2010). The analysis encompasses various essential components. It deals with topology assessment that entails scrutinizing network structural characteristics like degree distribution, clustering coefficient, and average path length, which reveal crucial properties like small-world tendencies, scale-free patterns, and community structures within networks. Further centrality evaluation is employed to identify influential nodes in networks, crucial for understanding information flow and influence in various contexts, including degree centrality, betweenness centrality, and eigenvector centrality (Sun et al., 2017). Also, community detection, detect groups or clusters of nodes with denser connections, unveiling the modular nature of networks (Newman, 2006). Robustness and Vulnerability analysis helps understand how networks respond to node failures or attacks to provide insights into network resilience and susceptibility. Complex network analysis extends to processes like information diffusion and disease spread, employing models such as the SIR model and percolation theory (Pei et al., 2018). Further, visualization tools are pivotal for understanding complex network structures, aiding effective representation and exploration. This analysis is applied in various fields. It aids in social network analysis, uncovers protein-protein interaction networks in biology, and supports route optimization and traffic analysis in transportation (Amaral & Ottino, 2004). A core area of research focuses on understanding how complex networks change over time, including the emergence of new connections and alterations in network properties.

Complex network analysis (CNA) is a valuable tool in ecology and wildlife conservation. It can be used to model and analyze food webs, species interaction networks, landscape connectivity, biodiversity conservation, disease spread analysis, ecosystem resilience, invasive species management, species distribution and cooperation and collaboration between different stakeholders (Elith & Leathwick, 2009). Food web analysis helps in understanding the stability of ecosystems, the impact of species removal, and the flow of energy and materials through the food web. Species interaction networks, including predator-prey interactions, mutualistic relationships, and competition, help predict the consequences of species introductions, extinctions, or other perturbations (Cardinale et al., 2012). Landscape connectivity is essential for wildlife conservation, as it helps assess how wildlife can move and disperse across fragmented landscapes (Bennett, 2003; Bunn et al., 2000; Rosenberg et al., 1997). Biodiversity conservation can be prioritized by identifying key areas as hubs in ecological networks, ensuring the preservation of biodiversity. Disease spread analysis helps in developing strategies to mitigate disease outbreaks and protect endangered species. Ecosystem resilience can be assessed by understanding how ecological networks respond to disruptions, which informs conservation strategies. Invasive species management can be developed by analyzing the spread of these species through ecological networks (Elith & Leathwick, 2009). Cooperation and collaboration between different stakeholders in wildlife conservation efforts can be modelled, leading to more effective conservation initiatives. Incorporating complex network analysis into ecology and wildlife conservation provides a powerful framework for understanding complex relationships within ecosystems, identifying critical areas for protection, and designing more effective strategies for biodiversity preservation and sustainable natural resource management (Angeler & Allen, 2016). The models proposed through this work focus on complex network analysis for wildlife corridor design and thus landscape connectivity.

Landscape connectivity for wildlife refers to the ability of natural landscapes to support the movement, dispersal, and migration of diverse species, a vital concept in ecology and conservation biology with far-reaching implications for species habitat access, resource availability, genetic diversity, and adaptation to environmental changes (Bennett, 2003). Human-induced habitat fragmentation, stemming from activities like urbanization, agriculture, and infrastructure development, poses a significant challenge. To counter this, conservationists establish wildlife corridors, which can be naturally occurring or deliberately constructed pathways, to facilitate species movement and gene flow (Shanu et al., 2019; Dutta et al., 2015). Seasonal migrations, especially for large mammals and birds, depend on these corridors to access breeding and feeding areas, and landscape connectivity plays a pivotal role in enabling species to respond to climate change by moving to more suitable regions (Bellard et al., 2012). Moreover, it ensures access to essential resources like food, water, and nesting sites, guiding the design of protected areas and reserves that prioritize connectivity with adjacent landscapes. Efforts to mitigate barriers such as roads and buildings through wildlife crossings further underscore the importance of landscape connectivity, which can operate both locally and globally, impacting long-distance species dispersals. Ecologists and conservationists employ diverse techniques to comprehensively study and monitor the implications of landscape connectivity for wildlife. Because they permit species dispersal and the upkeep of healthy ecosystems in geographically dispersed areas, landscape connectivity using wildlife corridors are essential for maintaining biodiversity (RodríGuez et al., 1996; Wade et al., 2015).

Wildlife corridors, sometimes known as ecological or habitat corridors, are essential pathways that link fragmented habitats, facilitating the movement, dispersal, and migration of wildlife. These vital ecological features are paramount for preserving biodiversity by promoting gene flow, ensuring access to critical resources, and enhancing species survival through the mitigation of human-made development barriers. Beyond safeguarding individual species, wildlife corridors contribute to the overall health and resilience of ecosystems, enabling animals to find suitable habitats, connect with potential mates, and adapt to changing environmental conditions. Consequently, conservation initiatives often prioritize the establishment, preservation, or restoration of these corridors to bolster wildlife populations and ensure their long-term survival (Jhala et al., 2021; Biswas et al., 2020; Shanu et al., 2021).

Wildlife corridors are a cornerstone of species conservation, underpinning the fundamental processes of enhancing gene flow, facilitating migration and dispersal, enabling rescue effects, ensuring habitat access, and supporting climate change adaptation. By permitting individuals from isolated populations to traverse and intermingle with others, these corridors bolster genetic diversity, diminishing susceptibility to diseases, environmental changes, and diminished fitness. In tandem, they offer safe passageways for seasonal migrations and dispersal, especially critical for large mammals and birds, enabling the completion of life cycles and access to vital areas. In instances of population decline or local extinction, corridors act as a lifeline, permitting the recolonization of areas and averting the total loss of species in specific regions (Yumnam et al., 2014, Jhala, et al., 2023; Schoen et al., 2022).

Moreover, they provide essential access to diverse habitats for various life stages, sustaining healthy populations and accommodating an array of species' needs. These corridors become invaluable amid climate change, offering a continuous avenue for species to adapt to shifting environments. Beyond species-focused advantages, they contribute to the enduring viability of ecosystems by allowing the free movement of predators, prey, pollinators, and other keystone species (Schoen et al., 2022). As platforms for education and advocacy, wildlife corridors raise public awareness about the significance of habitat conservation and wildlife connectivity. Strategically incorporated into conservation initiatives, these corridors expand the effective reach and size of protected areas by linking them, strengthening species' prospects. Finally, collaboration across multiple stakeholders, including government agencies, non-governmental organizations, researchers, and local communities, becomes essential in the implementation and management of these corridors, fostering more effective and coordinated conservation endeavors. In summation, wildlife corridors stand as a linchpin in species conservation, nurturing genetic diversity, facilitating movement and adaptation, upholding vital life processes, and fortifying the resilience and vigor of ecosystems (Jhala et al., 2021; Armstrong et al., 2021; Mondal et al., 2019).

Depending on the objectives of conservation and the unique biological setting, wildlife corridors may be created to support a single species or to support several. Multi-species corridors are made to benefit a range of animals, whereas species-specific corridors are made to meet the special habitat and mobility needs of a single species (Rautela et al., 2022). Using tigers *(Panthera Tigris Tigris*) as the focal species, species-specific corridor planning strategies have been developed in this work using complex network analysis and various logics of computation.

The tiger has been chosen as the focal species as its conservation holds immense significance for a multitude of reasons. Tigers, as apex predators, wield substantial influence in maintaining the ecological equilibrium of their habitats, averting overgrazing, and habitat degradation. They serve as indicators of ecosystem health and function as keystone species, shaping the composition and structure of their environments (Thinley et al., 2018). Ensuring the preservation of genetic diversity within tiger populations bolsters their resilience to diseases and environmental fluctuations. Beyond their ecological role, tigers provide economic benefits by attracting tourists to national parks and wildlife reserves, bolstering local and national economies through ecotourism. Furthermore, they hold profound cultural and spiritual significance in various countries and cultures, symbolizing strength, power, and beauty (Sinha et al., 2012).

The presence of tiger safeguards forests and other ecosystems from degradation and deforestation, conferring benefits not only upon tigers themselves but also upon a myriad of other species. Tiger-inhabited forests act as vital carbon sinks, aiding in the mitigation of climate change, and their conservation is a tangible contribution to global climate efforts. Tiger conservation frequently necessitates the protection of extensive, unspoiled habitats, thereby benefiting numerous other species and reinforcing the preservation of many endangered or threatened animals (Nunes et al., 2020). This overarching effort raises awareness about the critical importance of wildlife and environmental preservation and nurtures a sense of responsibility and stewardship toward nature. Additionally, international cooperation plays a pivotal role in the collective mission to conserve these majestic creatures (Haron et al., 2020). In summation, tiger conservation transcends the safeguarding of a single species, encompassing the broader health and sustainability of ecosystems, biodiversity, and the welfare of local communities.

Wildlife corridors are vital for tiger conservation due to their role in maintaining genetic diversity, population viability, habitat access, range expansion, and climate change adaptation. These corridors connect isolated tiger populations, facilitating gene flow and interbreeding, which helps maintain genetic diversity and ensure the long-term survival of the species. They also provide tigers with the opportunity to find mates from different populations, minimizing the risks of inbreeding and increasing susceptibility to health issues and fitness (N. Bennett et al., 2017).

Tigers require diverse habitats for various life stages, and corridors enable these movements, allowing them to fulfill their ecological needs (Puri et al., 2022). They also provide continuous paths for tigers to move and adapt to new environmental conditions. Without corridors, tiger populations can become isolated in fragmented habitats, making them vulnerable to local extinctions and hampering their ability to recolonize areas where they have been extirpated (I. Mondal et al., 2016).

Healthy tiger populations indicate the overall health of their habitats, and preserving tiger populations through corridors benefits entire ecosystems by regulating prey species and maintaining ecological balance. Conservation awareness is raised among local communities and the public, and international collaboration is often required for tiger conservation efforts (Gray et al., 2023).

Thus, wildlife corridors are essential for tiger conservation, promoting genetic diversity, supporting population viability, ensuring habitat access, and enabling range expansion and adaptation to change conditions (Jhala et al., 2008). The models presented in this work focus on leveraging machine intelligence and complex network analysis to build wildlife corridors. Finding relatively higher deterministic solutions to issues in wildlife may be greatly aided by the application of computing in sustainability and management.

Machine intelligence (MI), sometimes referred to as artificial intelligence (AI), is the ability of computers or other machines to carry out operations that normally call for human intellect (Wang, 2022). This includes a broad variety of tools and applications designed to make it possible for machines to mimic cognitive processes like those of humans, including language comprehension, learning, reasoning, problem-solving, perception, and decision-making (Mehlstäubl et al., 2023). The creation of algorithms, software, and hardware that enable computers to handle and evaluate data, provide predictions, and adjust to changing circumstances is the basis for machine intelligence (Saxena et al., 2023). Natural language processing, computer vision, robotics, machine learning, and data analysis are just a few of the domains in which it finds use. It is also becoming more and more incorporated into common place technologies and systems to help with complex problem solving and automate operations. This work utilizes the capabilities of MI and CNA for enhancing the strengths of decision-making strategies to design wildlife corridor networks for tigers in different landscapes.

The study presented in this thesis aims to use machine intelligence to the construction of wildlife corridors through the performance of complex network analysis. With tigers as the focal species, the work's initial goal is to create computational models for identifying wildlife habitats. Next, it aims to identify the landscape's essential points for maintaining contiguity within a landscape.

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Wildlife habitat patches are critical zones in the landscape that supply wildlife species with food, water, and ecological conditions to flourish and reproduce. These ecosystems are supported by a variety of forest successional processes, which are controlled by weather and terrain. When planning for wildlife protection, each component of wildlife appropriateness, such as food, shelter, and reproduction, must be considered. (Glass and Pienaar, 2020; Brawn, 2017; O'Connell, 2009; Johnsingh and Joshua, 1994).

Habitat fragmentation and loss have resulted in discontinuity in the habitats of focus species at the landscape level, requiring them to rely on managed ecosystems to meet their needs (Chetkiewicz et al., 2006; Dale et al., 2001). Several studies have found that creating wildlife corridors between fragmented habitat areas can help to conserve habitat. These corridors promote creature mobility between intact habitat zones, hence creating landscape connectivity patches. (Conard et al., 2010;

Hanski and Gilpin, 1991; Hanski and Ovaskainen, 2000; Harris and Gallagher, 1989; Shanu et al., 2019).

The main goal of this study is to use the Clique Percolation Method (CPM) to calculate a suitable tiger corridor network design in the focused landscape. The study intends to propose the study of relationships between many vertices since tigers might travel to different habitat patches depending on their needs. It also implies that interactions between habitat patches should be used to construct a wildlife corridor network. (Doreian and Conti, 2012).

The interaction between habitat patches is designed and studied using graph theory, with each acceptable habitat considered as an element of the vertex set V and the interaction between these vertices as the set of edges E. One of the major models in assessing these interactions in the actual world for a certain species is the Habitat Suitability Index (HSI). To compute HSI for a species over a landscape, remote sensing, and Geographic Information System (GIS) information are employed. (Dale et al., 2001; Erős and Lowe, 2019; Matisziw and Murray, 2008).

A suitability-clustering challenge is characterized as finding prospective habitat and supporting linkages for tiger dispersal (Dutta et al., 2015). Clusters of data points derived from HSI modelling incorporate tiger movement preferences via cumulative landscape factors. These clusters serve in determining the most significant landscape matrix elements capable of supporting a sustainable tiger population and relative migration.

Based on the applicability of each feature, the tiger corridor network is created and designated as crucial cliques that might serve as various interlinking of habitat patches. The CPM is then applied to the landscape matrix to get overlapping communities to validate and preserve the landscape complex's contiguity. (Bordenave et al., 2018; Pattabiraman et al., 2015; Palla et al., 2005).

Once a model for identifying significant habitats and landscape connectivity had been created, it had been critical to determine the influence of the tiger's dispersal cause on the species dispersal pattern (Rautela et al., 2022). The next study in this thesis employed computing logic to identify these dispersal patterns and the landscape criticals that either favour or impede tiger propagation.

The following section of the study sought to comprehend and analyze the distribution patterns of tiger species in a fictitious ecosystem that included all fundamental components of any terrain. Understanding why an individual disperses outside their natal area is critical for maintaining ecological equilibrium, and the tiger is the focal species. (Fourcade, 2016; Montero-Pau and Serra, 2011). Landscape complexes feature a variety of biotic and abiotic characteristics that interact with dispersing species, providing them with support on a positive or negative scale. Each component interacts differently with various species, resulting in species-specific distribution patterns within a landscape.

To accomplish this goal, the landscape is split into equal-sized grids, each of which serves as an element of the landscape matrix (Cho, 2014). Each grid's interactions are simulated to provide a cost surface that indicates whether it favors or discourages tiger passage over it. The major purpose is to give a basic computational framework for better understanding and forecasting tiger distribution patterns in any environment.

Understanding tiger dispersal patterns in a landscape is addressed as a cost allocation issue, with the reasons why tigers leave their original habitat factored into the task via dispersal weights. The dispersal weights are determined by a cognitive evaluation of tiger needs based on dispersal causes (Kacprzak, 2019), which offer the dispersal coefficient for each landscape parameter, illustrating how much each property effects the grid's cost distribution.

The interaction of each attribute using a two-player prisoner's dilemma game is also modelled (Shanu et al., 2019), with the payoffs merged with the dispersal coefficients to provide a starting cost to each grid providing a flavor of using quantum game theory with the dispersal coefficients providing the q-bits for scores of two-player prisoner's dilemma game (Bush et al., 2023; Banu & Rao, 2023; Bostanci & Watrous, 2022). The presence or absence of co-predators in the grids is one of the most critical and changeable characteristics of the environment that impacts tiger dispersal (Reddy et al., 2012).

The next set of problems involves working on computational models to check the impact of data resolution and seasonal variation on the dispersal of tigers within a landscape. This is done by gaining insight into the reason for migration and developing a computational model to take it into consideration for designing tiger corridors (Shanu & Agarwal, 2023). Tensor-based computational models are employed in the thesis's subsequent section to address these problems.

Wildlife corridors are landscape elements that allow animal dispersal for various ecological purposes, making them highly species-specific. The preservation and creation of these corridors are essential for species conservation, as they are highly species-specific (Trakhtenbrot et al., 2005). This study focused on tigers and aimed to develop a computational model for building wildlife corridors that considers temporal data and its impact on overall network modeling.

A key consideration before developing a conservation strategy is the visualization of data, which would be helpful in developing policies for landscape level conservation (Yumnam et al., 2014). The method described in this work constructs tiger corridor networks using a temporal representation of the data. Computational approaches are necessary to simulate Tiger corridors between source and sink habitat regions due to the numerous aspects that must be deterministically studied and presented (DeMatteo et al., 2017).

The model uses set theory to eliminate duplicate data and analyzes the amount to which certain qualities help or impede tiger mobility in the terrain. A tensor representation method is used to show how temporal variations in landscape level data affect parameters and the dispersal of species in the landscape (Goyal & Aggarwal, 2012).

An important study had been presented that indicates how the season influences conservation planning strategies in the target area. Results are created by applying three different seasonal settings to the central scene, showing how different seasons impact the curvature and geodesic distance of tiger dispersal.

The study concluded that creating wildlife corridors using GIS and remote sensing is successful, but field research is necessary to create a better corridor model. Additionally, the tensor approach is used, among other things, to show how data resolution affects parameters, species dispersal in the landscape, and data (Shanu et al., 2023).

A cumulative model was developed to illustrate the decision-support system for planning wildlife corridors with tigers as the focal species after the various computational models had been defined.

The degree to which an ecosystem facilitates transit among resource habitat patches is referred to as landscape connectedness, with corridors being crucial components of biological landscapes. These corridors connect two or more habitat areas, improving or preserving essential animal populations' passage (Beier & Noss, 1998). Wildlife corridors are intended to enable the movement of both biotic and abiotic processes, as well as to ensure gene flow across geographically separated populations of species that have been fragmented owing to landscape change (Shanu et al., 2019).

Within a particular environment, the existence of species-specific wildlife corridors can improve gene flow and population levels of the species. Accurate wildlife corridor modelling must be a species-specific endeavor, with appropriate habitat selection for the applicable target species. This paper describes a computational technique for building a tiger corridor in India, considering the relative physical placement of national reserves (Rautela et al., 2022). The selection of critical tiger habitats (CTH) in such a decision-support model must consider how their spatial structure maintains a high degree of interconnection across predominantly human-dominated landscapes throughout time (Shanu et al., 2023).

Designing the connectivity among current or possible CTH using a network model would be one way to accomplish the goal. Each tiger habitat in such a network would be considered a vertex, and the tiger corridors connecting these vertices would be the edges. The main goal is to present a fundamental computational architecture for comprehending a workable corridor network design inside the focal landscape complex for tigers. The basic notion of connectedness, which requires recognition and total decision-making by landscape characteristics and structure, is the center of all arguments and observations in this study (Shanu & Agarwal, 2023).

The design of tiger corridors within the landscape is stated as a connectivity subgraph issue, with the conflict between the travelling tiger and Eco-geographical features, which is mostly caused by human activity, incorporated via an assurance game. The study presents an optimized path and employs these optimized paths to generate a Deterministic Finite Automata to provide the language for generating corridors, which can be claimed as a rule foundation for corridor construction after considering potential costs (Shanu & Agarwal, 2022).

When the models in this work were applied to several Indian settings with a healthy tiger population, highly positive outcomes were seen. When the results of applying the suggested models were compared to the most recent tiger report (at the time of publishing) from the Government of India, a notable degree of accuracy was found (Jhala et al., 2018). Depending on the region and kind of datasets utilized, the maximum accuracy was 98%, and the lowest was 83%. The output maps generated by the designed models and the output maps included in the reports were used to compare them. To derive this assessment approach, evaluations of individual pixels conducted at the same scale were used (Mei et al., 2022).

This research, which focuses on the presence or absence of elements in different grids within a landscape complex, might serve as a model for conservationists and wildlife managers to consider when making judgements about tiger distribution patterns and corridor design plans.

The next sections of this thesis discuss in detail how to develop computational models for tiger corridor design. The next chapter focuses on the research work statement, which addresses the problem description, background for the task, and research motivation. In continuation, the following chapter examines the key objectives of the study and the strategy to achieving the intended objectives. A full literature study has been presented following the implementation approach to support the work. Following the literature evaluation, the paper discusses the research approach used for the project. Finally, the work's scientific contributions have been examined, along with the conclusion and future scope.

Chapter 2

STATEMENT OF THE RESEARCH WORK

Problem Statement

Wildlife corridors are stretches of landscape that connect isolated or fragmented habitats, allowing species to disperse freely between them. These pathways are crucial for preserving genetic variation, biodiversity, and sustaining thriving populations of different plant and animal species. They facilitate migration across communities, reducing inbreeding and preserving genetic variety. Seasonal dispersals, such as breeding, feeding, and other purposes, require secure routes to meet the needs of species.

Corridors also provide resources like food, water, and shelter for species, enabling them to relocate to new habitats when climate changes. Young individuals of certain species often need to leave their birth range to avoid competing with more experienced ones. Natural calamities like wildfires, hurricanes, and disease outbreaks can alter ecosystems, making corridors essential for building larger, more viable habitats for endangered or vulnerable species.

This work aims to use computational modelling techniques to create a network of wildlife corridors using the tiger as the focal species. Popular methods for creating wildlife corridors include circuit theory and Minimum Spanning Tree principles, which support and encourage wild animals to move freely in specific terrains. However, these methods do not account for all possible species dispersal routes and do not account for the behavioral patterns of species in and around the corridors.

This research proposes a strategy using machine intelligence to address the above limitations and produce a cognition-oriented solution. The model developed will focus on complex network analysis and machine intelligence application in wildlife corridors, deducing inferences based on the science of interaction between tigers and landscape variables.

Background

Landscape connectivity refers to the degree to which the environment hinders or promotes mobility among resource patches. A corridor is a habitat that connects two or more larger patches of habitat, providing linkage between them. These corridors are essential components of biological landscapes, enabling species and processes to disperse between regions of intact habitat. They are areas covered in natural vegetation that connect dispersed, unconnected, and non-contiguous animal habitat patches. Wildlife corridors demonstrate the interaction of natural and human elements with other landforms and promote landscape connections. Landscape connections describe how terrain restricts or facilitates species dispersal between territorial regions. They are important for conservation, preserving or improving species populations in territorial areas, and maintaining source-sink dynamics.

Landscapes are dynamic, with structural (pattern) and functional (process) characteristics in common. Corridors are important parts of landscapes, with structural corridors provided by the physical existence of the landscape between two habitat patches, and functional corridors by species and terrain. A viable wildlife corridor is a species and landscape-specific concept, resulting from the combination of the landscape's pattern and process qualities.

Understanding the dispersal pattern of large ranging animals like tigers involves various assumptions and hence a good design is essential while predicting these linkages. In addition, the proper integration of patterns and processes within the landscape matrix is crucial in designing wildlife corridors. Wildlife corridors must encourage the tenacity of species movement and thus compulsorily maintain the integration between ecological patterns and processes within a landscape. Formally, the ecological pattern has been identified as a three tuple $(P, \partial, \prod)$ such that $P = \{P_1,\ P_2,\ P_3, \ldots,\ P_n\}, n \in \mathbb{N}$, is a set of habitat patches supporting tiger populations within a landscape, ∂ is the relationship function indicating the ecological processes $\partial \colon [P]^n \rightarrow\ \prod; n\ \geq 2, n \in \mathbb{N}$ where $\prod$ is a set of associated payoff with cardinality 2^n. The associated payoff could be decided by the stakeholders based on various spatial-temporal states, the interacting patches, features of the landscape and focal species of concern between the interacting habitats. At a discrete-time interval and an identified region of the landscape, if k habitat patches interact then the relationship function ∂ provides a payoff to various ecological processes within the focal landscape matrix as $\partial[P^k] =$

$\prod_{P^k} : 2 \leq k \leq n$. Hence, an n-ary interaction of varied habitat patches where $n \geq 2$ provides a balance between different spatial-temporal conditions required for wildlife corridor designs.

Motivation/need for the research

Wildlife corridor conservation is driven by a mix of ecological, environmental, and ethical concerns.

Wildlife Conservation

Human caused extinction are like a mass extinction event and preserving all life forms from extinction is the need of the hour, and hence best possible efforts must be done to maintain nature's equilibrium. Through love, respect, and compassion, the environment, and all living species things within it can be protected for maintaining the equilibrium.

Nature God has bestowed onto this planet a wonderful gift in the form shape of animals. In addition to wild animals, the term "wildlife" refers to all undomesticated lifeforms such as birds, insects, plants, fungi, and even small critters. Animals, plants, and marine species are just as important as humans in maintaining a healthy ecological balance on earth. Every organism on our planet plays a unique part in the food chain, each of which contributes to the ecosystem in its own unique way.

Many animals and birds are currently becoming endangered. Humans are destroying animals and plants natural habitats for land development and farming. Other prominent causes of wildlife extinction include animal poaching and hunting for fur, jewelry, meat, and leather. Possible efforts should be taken so that if no quick effort is made to save animals, they will soon be added to the list of extinct species. A very over-lauded sentence

The 5% of Indian landscape that is legally protected includes most ecoregions and protected areas. India has robust conservation legislation, government investment in 54 Tiger Reserves, and government compensation mechanisms that promote local support, all of which bode well for the future. Many protected areas, however, are too small to support a complete complement of species, making connectivity and species usage of buffer zones critical issues. Therefore, wildlife corridors have become an essential conservation management strategy. A wildlife corridor, also known as a habitat corridor or a green corridor, is a section of habitat that connects animal populations that are divided by human activities or constructions. This permits individuals to disperse between habitats, perhaps reducing the detrimental consequences of inbreeding and genetic diversity loss (due to genetic drift) that may occur in isolated populations.

The presence of species in the corridors provides a suitable platform for illicit operations by hunters, poachers, and others. Second, corridors reduce the danger of numerous biological occurrences such as competition, which aids in the long-term objective of animal conservation. As a result, modelling and constructing wildlife corridors as complex networks can aid in the knowledge of many phenomena and promote wild species conservation both inside and beyond the Protected Areas (PAs).

Absence of deterministic model

Creating wildlife corridors is a difficult endeavor. There is no one-size-fits-all approach to design parameters, and the best method is determined by a variety of elements such as species needs, geographical context, land availability, and human intervention, among others. While there appears to be widespread agreement on helpful concepts for building wildlife corridors, however there are no generally universally applicable guidelines that can be applied to a variety of corridor settings without modification. The literature in this field is sparse, with best-practice suggestions that are panoptic at best.

To achieve the optimum answer, the suggested problem can be solved using a deterministic solution for the whole network analysis. However, due to process uncertainties, this approach is challenging to accomplish in practice (i.e., variability in parameters, evolving characteristics, etc.). The suggested framework is meant to be used to iteratively solve complex network analysis problems to deal with process uncertainty. Furthermore, the answers obtained from a deterministic solution would demonstrate the model's usefulness in forecasting the accuracy of biotic and abiotic uncertainty, which would be very handy for designing wildlife corridor networks.

Complex system analysis and progressive work

The Earth's temperature, human brain, infrastructure, transportation, communication networks, social and economic institutions, ecosystems, living cells, and the entire universe are examples of complex systems. Because of dependencies, competitions, and linkages, these systems display difficult-to-describe behaviors. Nonlinearity, emergence, spontaneous order, adaptability, and feedback loops are all features of these systems. Their parallels have resulted in their own field of research due to their ubiquitous presence. It can be useful in some circumstances to describe complicated systems as networks, with nodes representing components and connections indicating their interactions.

Designing wildlife corridor networks is a complex task, and the modelling that would be created for the purpose would be related with comprehending the entire complex system and then developing a decision support system. According to the task's literature research, it was determined that the challenge is a complex system problem aimed at bringing a solution to the ecological world. One of the primary objectives for the research had been to examine the complex system of biotic and abiotic factors in any focal landscape and offer a computational model for the construction of wildlife corridor networks.

To understand and work for the above motivations, the following steps have been planned and carried out. Further the objectives are decided based on the below mentioned steps:

1. **Data Collection and Parameter Correlation:** The primary goal of the effort is to identify and work with the parameters that influence the dispersal of tigers through the landscape. The identification of factors is beneficial in understanding tiger's favored movement. Further, there it is needed to understand the link between the parameters, as these correlations aid in identifying the influence of one parameter over another and, therefore, the dispersal of tigers. As a result, the first goal aids in the development of the first fundamental computational framework for the aim of applying Machine intelligence to the construction of tiger corridors.
2. **Spatial-temporal study of tiger movements:** The second goal of the work is to identify landscape characteristics such as woodland, grassland, agricultural areas, and so on through which the tigers often disperse. Identification of these characteristics' aids in understanding tiger movement patterns and would serve as an input layer for the proposed computational model. Further, to get a better understanding of the temporal dynamics of tiger dispersals by pursuing this goal. It is beneficial to build up the next layer of the computational architecture, which would offer an input to the other levels, because species dispersal is influenced by temporal factors such as daytime, season, and so on.
3. **Creating a complex system analysis model for wildlife corridor planning using tigers as the focus species:** The suggested study's main and final goal had been to comprehend and operate with the complex system generated through the aims to develop a machine intelligence model. The model was built on equational and algorithmic constraints

established with reference to the study of the complex system, and it integrated it to offer the most suitable pathways to be depicted as tiger's corridors.

Objective

The focal research problem of this work is:

To design a model which would provide a computational template by parametrizing the criticals in any Landscape complex for designing of tiger corridors.

Sub-Objectives

1. To identify the critical parameters and ecological indicators which affect the dispersal of tigers in any focal landscape.
2. To develop an algorithm and thus a function which would work on the interactions of all parameters to find the best paths to be designated as corridors.
3. To develop a machine intelligence approach that would help in identification of the changes in LULC (Land Use Land Cover), deduce the correct corridor designing measures and compare with traditional techniques.

Chapter 3

LITERATURE REVIEW

The integration of computational methods into ecology has revolutionized the study of interactions among organisms and their environment. This shift has been a gradual transition from traditional observational studies to data-driven computational approaches, with early research primarily relying on field observations, experiments, and statistical analyses. The literature review highlights ecological aspects of corridor design, computational concepts, and the foundational works in computational ecology, such as the development of mathematical models for population dynamics, spatial ecology, and community interactions.

Ecological informatics and data analytics have reshaped ecological research, with advancements in sensor technologies, satellite imagery, and automated data collection generating massive datasets. Researchers use computational tools to process, analyze, and interpret these data, providing insights into global ecological patterns, climate change impacts, and biodiversity trends.

Ecological modeling and simulation have seen significant strides, with various modeling approaches available, including individual-based models (IBMs), agent-based models (ABMs), and ecosystem-scale models. These models enable researchers to simulate ecological processes, predict outcomes under different scenarios, and test hypotheses that would be challenging to address through traditional methods.

Network ecology and complexity science have been applied to ecological research, using computational tools to analyze food webs, study connectivity patterns, and understand emergent properties of ecological networks. Artificial intelligence and machine learning techniques have also been increasingly used in ecological research, enabling species identification, habitat mapping, and predicting ecological trends.

However, challenges and limitations remain, such as data quality, model validation, and ethical implications of using advanced technologies in ecological research. Future directions include citizen science, real-time data streams integration, and interdisciplinary collaborations.

The literature review has been categorized into three major sections to illustrate the details and the problems addressed in this work. The first segment examines the literature on ecological issues of species survival and corridor design. The second portion focuses on the literature linked with computational principles, and the third section goes into depth about the computational work done in the field of ecology and corridor design. Furthermore, after the investigation of all three literatures, a section dealing with the research gaps and solutions provided in this thesis for the research gaps has been examined and discussed.

Literature Associated to Ecological Concepts

Ecosystems are crucial for the survival of iconic species like tigers, who require a deep understanding of their habitats. The design of tiger corridors is crucial to preserve these predators, as fragmented habitats threaten their genetic diversity and long-term viability. This literature review examines the scientific discourse surrounding tiger corridor design, focusing on ecological considerations such as habitat connectivity, landscape permeability, and impacts on local biodiversity. The review aims to contribute valuable insights to the past and ongoing discourse on optimizing ecological aspects of tiger corridor design for the benefit of both the species and their ecosystems.

Table 3-1: Literature Associated to Ecological Concepts

Literatures reviewed	Key concepts drawn from the Literature
(Baum et al., 2004)	Plantation forestry's impact on biodiversity is a contentious issue, with some highlighting its benefits and others arguing for its detrimental effects. Management methods and environmental matrix influence biodiversity, with native woods restricted to small areas.

(Briers, 2002)	Iterative reserve selection methods consider connectivity and pond macroinvertebrates data set, reducing fragmentation and enabling species dispersal for long-term survival. Spatial criteria alone do not perform as well as basic greedy algorithms for connectivity.
(Conrad et al., 2010)	Wildlife corridors aim to connect biologically valuable regions, reducing habitat fragmentation. What is the significance of this line? This work presents a model for maximizing habitat quantity in a budget-restricted parcel network. 1-2 more lines are need giving the technical details of this work.
(Dutta et al., 2013)	A study in central India assessed gene flow and population numbers of leopards, finding no genetic bottleneck, and maintaining migration-drift equilibrium.
(Gopal et al., 2010)	Large carnivore conservation faces challenges due to their high food chain concentration and habitat dependence. Human conflict, habitat destruction, hunting, and traditional medicine have led to extinctions and fragmentation of populations, affecting biodiversity conservation efforts.
(Hanski, 1998)	Metapopulations biology focuses on migration and regional persistence of species in unstable local populations. Habitat patch area and isolation impacts migration, colonization, and population extinction. Models can forecast individual migration, species dynamics, and multispecies community distribution in fragmented environments.
(Hanski & Gilpin, 1991)	The work explores metapopulations theory's early stages, culminating in Levins' 1969 model. It provides a glossary of terminology and discusses studies on single-species and multispecies metapopulations. Metapopulations concepts are

	increasingly significant in landscape ecology and conservation biology.
(Harvey et al., 2008)	Corridors for moving creatures between refuges are mixed with other purposes, making it difficult to measure cost efficiency. They aim to reduce extinction rates, demographic stochasticity, prevent inbreeding depression, and meet mobility demands.
(Henein & Merriam, 1990)	Small animals spread via corridors, with different survivability ratings depending on size and cover. This deterministic model identifies two types of corridors based on their likelihood of survival during dispersal events.
(Jhala et al. 2008)	This study assesses tigers, co-predators, and their prey in India, focusing on occupancy, population limitations, habitat quality, and connectivity for conservation strategies and survival, moving away from protected areas.
(Jhala et al. 20011)	Tigers inhabit six landscape complexes in India, sharing a similar gene pool due to continuous habitats. These complexes consist of contiguous habitats and one to many breeding populations, with the possibility of controlling some within each unit.
(Johnsingh et al., 1990) (Locke & Dearden, 2005) (Johnsingh & Negi, 2003)	The Rajaji-Corbett Tiger Conservation Unit (RCTCU) in northern India is one of 11 Level-I TCUs for long-term tiger conservation. It spans over 7500 km2 and includes parts of the Outer Himalaya and Shivalik highlands. Only a third of the TCU is protected, with the rest divided into reserve forest divisions.

(Johnsingh et al., 2004)	
(Johnsingh et al., 2005)	
(Jordán et al., 2006)	Local species extinction or significant changes in abundance significantly impact other species in the community. Direct and indirect contact spread across society. Network views on ecology help map these impacts, such as indirect trophic interactions in food webs. However, there is a conceptual maximum range in topological space beyond which interactions have no impact, which is not adequately quantified by local features or global web characteristics.
(Folke, 2006)	Landscape ecologists use normative landscape scenarios, which enable science to be included in policy development and investigate problems in realistic simulated environments. This approach offers criteria and strategies for constructing normative scenarios.
(Lindenmayer et al., 2007)	Landscape management for biological conservation and ecologically sustainable natural resource utilization is a global challenge. Despite extensive research, there is no consensus on basic principles or broad considerations for landscape conservation. This work addresses six key issues and highlights 13 critical factors for effective strategies.
(Özgür et al., 2008)	Biological sciences aim to understand genetics' role in illnesses, with the Human Genome Project resulting in increased publications. However, manual databases and time-consuming studies make it crucial to anticipate good candidate genes.

(Pulliam, 1988)	Animal and plant populations often occupy local regions with varying birth and death rates. Reproductive surpluses from source habitats can help maintain populations in sink environments where local success falls short of mortality. An ecologically and evolutionarily stable equilibrium with both habitats is possible for species with active habitat selection.
(Sharma et al., 2013)	Understanding gene flow patterns in endangered species' metapopulations is crucial for successful conservation planning. Tigers, critically endangered, were examined to determine if corridors in central India's Satpura-Maikal terrain functioned, using multi-locus genotypic data from 273 individual tigers.
(Taylor et al., 1993)	Nature provides essential resources for life and human wellbeing, including air, water, soil, medicine, industry, relaxation, and carbon sequestration. Maintaining ecological connectivity is crucial for the long-term protection of our ecosystem.
(Taylor & Fahrig, 2006)	Oceanic islands have high biodiversity and dynamic ecosystem integration, but habitat fragmentation and poor spatial connectivity between protected areas and human settlements are causing significant pressure on their ecosystems. The research aims to develop a new framework using urban ecological networks to address connectivity issues.
(Urban & Keitt, 2001)	Landscape connectedness examines the impact of species mobility capacities and landscape structure on survival, gene flow, and ecological processes in fragmented landscapes. It involves assessing functional connectedness, considering habitat quantity, matrix quality, species perceptions, and population density.

(Yumnam et al., 2014)	Tiger conservation faces threats from poaching, habitat degradation, and isolation. Approximately 3,000 wild tigers survive in scattered groups, and long-term conservation requires establishing connections to sustain gene flow.

Literature Associated with Computational Work

This section of the literature review explores the relationship between mathematics and tiger corridor design in wildlife conservation. It highlights the complexity of landscape connectivity for large predators and the importance of mathematical models, spatial analyses, and optimization algorithms in strategic planning. The review synthesizes existing literature to understand the mathematical frameworks used in various ecological aspects, examining their effectiveness in facilitating species movement, maintaining genetic diversity, and mitigating human-wildlife conflicts. It aims to contribute valuable insights to the ongoing discourse on conservation biology and applied mathematics, highlighting the importance of effective corridor design in wildlife conservation.

Table 3-2: Literature Associated to Computational Work

Literatures reviewed	Key concepts drawn from the Literature
(Bondy & Murty, 2008)	Graph theory is a rapidly growing field with numerous theorems and applications in computer science, combinatorial optimization, and operations research, influencing modern applied mathematics.
(Kúkelová et al., 2008)	This work discusses the history and proposes a solution of the Minimum Spanning Tree issue, a foundational problem in combinatorial optimization.
(Brandes & Erlebach, 2010)	Network analysis studies various structures like the Internet, interlocking directorates, transportation networks, disease transmission, metabolic pathways, and web graphs.

(Estrada & Rodríguez-Velázquez, 2005)	New centrality metric identifies node participation in network subgraphs, enhancing network motifs by prioritizing smaller subgraphs.
(Estrada & Bodin, 2008)	The study investigates identifying key patches in landscapes and their impact on organism mobility and dispersal using graph-theoretical landscape modelling. Centrality depends on the model's construction, with basic network representations ignoring flux intensity and directionality.
(Estrada, 2010)	This work introduces a technique for zooming in and out of a node's topological surroundings in complex networks, generalizing subgraph centrality. The zooming in method uses well-known matrix functions for local focus, while the zooming out technique provides a global view, allowing for varying scales of node's surroundings impacting centrality.
(Gastner & Newman, 2006)	The work reveals distinct topography and usage patterns in transportation networks and the Internet, affecting costs and benefits. It provides a Monte Carlo optimization model to accurately reproduce the qualitative characteristics of these networks.
(Girvan & Newman, 2002)	Recent research on networked systems, including social networks and the World Wide Web, focuses on small-world characteristics, power-law degree distributions, and network transitivity. The article examines community structure, where nodes are grouped in tightly knit groups with loose connections. A technique is presented for recognizing these communities using centrality indices.
(Higham, 2008)	Matrix functions have been studied since the beginning of matrix algebra, with Cayley's work on the square root and Sylvester's definitions. They have evolved into applied mathematics, with applications in science and engineering.

	Research involves various theories and methods, including matrix theory, numerical analysis, approximation theory, and algorithm creation.
(Hofbauer & Sigmund, 1998)	Game theory posits a population with diverse strategies, resulting in monomorphic or polymorphic populations with multiple phenotypes.

Literature Associated with Computational Work in Ecology

The integration of computational approaches in ecology has revolutionized the way researchers analyze and model complex ecological systems. Advanced technologies, algorithms, and simulations have enhanced our understanding of ecological dynamics, enabling ecologists to unravel intricate patterns, predict trends, and address environmental challenges. This section of literature review explores the diverse applications of computation in ecological research, highlighting how it redefines ecological inquiry boundaries and opens new frontiers for innovative conservation strategies and sustainable environmental management.

Table 3-3: Literature Review Associated to Computational Work in Ecology

Literatures reviewed	Key concepts drawn from the Literature
(Axelrod & Hamilton, 1981)	Evolutionary theory has struggled with species cooperation since Darwin. The Prisoner's Dilemma game model suggests evolutionarily stable strategies, illustrating reciprocity-based cooperation in an asocial world. It can prosper with various strategies and resist invasion, using territoriality, mating, and illness.
(Sachs et al., 2004)	The rational choice theory suggests people rationally seek goals that advance their interests. Work defines it as hyper-rational decision-making, considering both the profit or loss of others and one's own. This study helps model human behavior considering environmental factors, behavioral contact, valuing systems, and societal beliefs. Avoid wring help word, what max can be written is proposes

(Borgatti et al., 2009)	This study proposes a uniform approach for calculating centrality in social network analysis, considering nodal involvement, walk type, walk feature, and summary measure, based on four important parameters. This is the way it should be written, not like others which I have changed to red color. It would be better if one more line can be written for this reference.
(Bunn et al., 2000)	Focal-species analysis in North Carolina's Coastal Plain demonstrates graph-theoretic landscape connectivity, showcasing the ecological value of mathematical networks in habitat connectedness.
(Cantwell & Forman, 1993)	This work aimed to create a graph theory-based modeling technique for comparing land mosaics and identifying common spatial patterns in various landscapes. The models used spatial layouts, ecosystems, and connections to represent landscape elements and common boundaries.
(Chetkiewicz & Boyce, 2006)	Corridors connect wildlife habitats, but habitat selection and migration are often overlooked. New technology and analytical tools can integrate landscape patterns with behavioral processes.
(Dunne et al., 2002)	The study analyzed 16 food webs and observed found that food webs are more resilient to random species removal than selective removal of species with the greatest trophic connections, as found in other networks.
(Fall et al., 2007)	To ensure conservation and restoration goals in land management, well-founded methodologies for assessing habitat connectivity are essential. Graph-based methods estimate routes and dispersal movement lengths, while traditional graphs lack geographic reference, reducing the transmission capacity and value of geospatial data.

(González et al., 2010)	High centrality ratings are crucial for network structure and stability in complex networks. Centrality measurements can detect keystone species and distinguish them in ecological networks. This study investigates the connection between species generalization level and closeness and betweeness centrality in pollination communities.
(Hanski & Ovaskainen, 2000)	Metapopulations capacity is the leading eigenvalue in a landscape matrix, indicating a species' persistence if its capacity exceeds a threshold. This approach evaluates landscapes' ability to host viable metapopulations and reveals how habitat fragmentation affects it.
(Jiang & Zhang, 2015)	Keystone species research in food webs is crucial for conservation, biodiversity, habitat management, and ecosystem stability. Network approaches using topological structure offer advantages over biological tests. Findings show significant variations in ranking species based on centrality metrics.
(Minor & Urban, 2007)	Using spatially explicit population models (SEPMs) is crucial for forecasting and controlling species distributions in diverse settings. However, SEPMs are computationally demanding and require extensive animal biology knowledge. Graph theory offers an efficient alternative with minimal data requirements, making it ideal for ecological applications involving connection or mobility.
(Minor & Urban, 2008)	Habitat patch connectivity aids genes, individual, population, and species movement across temporal and geographical scales. In North Carolina Piedmont, graph theory defines landscape connectedness, comparing it to simulated networks. Graph metrics like compartmentalization and clustering can identify resistant regions for conservation or human growth.

(Heller & Zavaleta, 2009)	Sustainable biodiversity planning in urbanizing environments involves considering habitat quality, quantity, layout, and landscape permeability. A system of interconnected indexes, using metapopulation ecology, calculates cohesiveness index and outlines building species persistence indicators in such networks.
(Opdam et al., 2006)	This study proposes an ecological network idea for integrating biodiversity protection into long-term landscape development, requiring a cohesive spatial organization of ecosystems in multifunctional, human-dominated environments for ecological viability.
(Paladugu et al., 2008)	Protein functional characteristics, like essentiality and dispensability, are correlated with local connectivity and global location in protein interaction networks. This study investigates the prediction potential of protein interaction networks for synthetic genetic interaction in Saccharomyces cerevisiae, an organism with high-confidence networks and synthetic sick/lethal gene pairs.
(Rayfield et al., 2011)	Over 60 network metrics are available to ecologists, highlighting the ecological significance of these metrics. A methodology categorizes measures based on connectivity attributes and the habitat network's structural level.
(Urban et al., 2009)	Graph theory studies network connectivity, flow, and routing, influencing landscape ecology and conservation biology. Graph models, based on metapopulations theory, represent habitat patches and links show functional relationships between populations.

(Wikramanayake et al., 1998)	Habitat degradation, fragmentation, lack of prey, and persecution have led to the decline of large carnivores like tigers and dholes. In Thailand's Dong Phayayen Forest Complex, researchers assessed tiger population, dhole occupancy, and prey availability using camera traps and Bayesian geographic capture-recapture methods.
(Wikramanayake et al., 2004)	Wildlife populations in isolated reserves face threats from genetic and demographic factors. Biologists recommend metapopulation management, using breeding subpopulations as source pools for long-term persistence. A cost-distance model using GIS creates a conservation landscape for Asia's largest predator, the tiger, in the Himalayan foothills.

Research Gaps:

This section explores the integration of ecological aspects and computational work in ecology, revealing significant progress but also highlighting critical gaps in knowledge. The review aims to identify areas where the integration of ecological aspects and computational work is underexplored or insufficiently addressed. The goal is to provide a roadmap for this thesis's investigations, fostering a more comprehensive and refined approach to ecological research that harnesses the full potential of computational tools.

Table 3-4: Literature Review with Research Gaps associated with the work

Essential Literatures reviewed	**Themes drawn from the Literatures**	**Research Gaps (if any)**	**Remark**
(Baum et al., 2004)	The impact of plantation forestry on biodiversity is a contentious topic in the literature. While some writers	Only plantation not the feature for corridor development	The environmental matrix is a second key component. Native woods are restricted to tiny areas surrounded by a

	emphasize the beneficial benefits of plantations, others believe they have a primarily detrimental impact		plantation-dominated landscape. The management is rather intense, and it is not intended to preserve biodiversity.
(Briers, 2002b)	The geographical placement of sites is often overlooked when choosing sites for inclusion in reserve networks, resulting in extremely fragmented networks.	Sites not chosen whereas satisfy the preferential conditions	In terms of reserve connectivity, methods that solely used spatial criteria when there were ties between sites performed no better than a basic greedy algorithm.
(Cantwell & Forman, 1993)	Given the dizzying range of landscapes and conceivable patterns within them, the goal of this work was to explore if a viable modelling technique for directly comparing land mosaics based on graph theory could be created, and if basic spatial patterns that	Cross dependency of landscape features not identified.	Landscape elements were represented by nodes, while common boundaries between elements were represented by connections. The models successfully included corridors, corridor junctions, and the matrix.

	are common to various landscapes could be found		
(Chetkiewicz & Boyce, 2006)	Corridors are often utilized to connect pieces of wildlife habitat, however the process of habitat selection and migration for target organisms is often overlooked when conservation corridors are identified	Corridors may not be just binary connectivity of vegetative indices.	Landscape patterns may now be better integrated with behavioral processes thanks to new technology and analytical tools
(Dunne et al., 2002b)	The impacts of biodiversity loss, such as secondary and 'cascading' extinctions, are mediated through food web structure.	No dimension of animal movement justified.	Presented a good model towards complex systems.
(Dutta et al., 2013)	Gene flow is a vital biological mechanism that must be preserved to offset the negative effects	Gene flow has been recognized but how to maintain through	The work used noninvasive sampling to assess historical and current gene flow and

	of genetic drift in fragmented populations, with conservation advantages ranging from encouraging the persistence of tiny populations to disseminating adaptive characteristics in changing settings.	the corridors not justified.	effective population numbers of leopards in a terrain in central India
(Estrada & Bodin, 2008)	The work studies how to identify key patches in the landscape and how these central patches impact (1) organism mobility inside the local neighborhood and (2) organism dispersal outside the local neighborhood using a graph-theoretical landscape modelling technique	Work concentrated only on the binary features of connectivity.	It was discovered that centrality is dependent on how the graph-theoretical model of habitat patches is built, albeit even the most basic network representation, which ignores the intensity and directionality of prospective organisms fluxes, gives a coarse-grained evaluation of centrality.

(Estrada, 2010)	A technique is devised for zooming in and out of a node's topological surroundings in a complex network	Work divided the problem well but lacks in considering n-ary interactions.	These indices allow for a change in the scales at which a node's surroundings impacts its centrality.
(Gopal et al., 2010)	Large carnivore conservation is a problem for biodiversity conservation since they are at the top of the food chain and are found in low concentrations.	Designed corridors using circuit theory with an assumption of zero rheostat resistance.	Several factors, including habitat destruction and excessive hunting by humans in the absence of a real or perceived threat to people and their livestock, as well as the use of body parts for traditional medicine, have resulted in the extinction of many populations while shrinking, fragmenting, and isolating the majority of others to varying degrees.

(Hanski, 1998)	The dynamic implications of migration among local populations, as well as the circumstances of regional persistence of species with unstable local populations, are the focus of metapopulations biology.	-	Explains the use of parameters for complex system analysis.
(Hanski & Gilpin, 1991)	The work examine the early stages of metapopulations theory, which culminated in Levins' well-known model in 1969.	Old models with no computations.	In landscape ecology and conservation biology, metapopulations concepts are becoming increasingly significant.
(Hanski & Ovaskainen, 2000)	Technically, the leading eigenvalue of an adequate 'landscape' matrix is metapopulations capacity	Single parameter concentrative model.	The work also determines how the metapopulations capacity is affected by deleting or adding habitat pieces to certain geographical

			areas using this approach
(Harvey et al., 2008)	Corridors for moving creatures between refuges are mixed up with corridors for other purposes, making it difficult to measure cost efficiency.	Interaction theory ignored for the cost evaluation. Available information are enough.	There is a scarcity of information on how corridors are used and if this use reduces extinction by resolving these issues.
(Henein & Merriam, 1990)	Small animals have been observed to spread via corridors linking habitat patches in diverse settings. Depending on their size and the amount of cover they provide, corridors may have various survivability ratings	Corridors are species specific so checking them on same scale is not equitable.	Based on the likelihood of surviving during a dispersal event, two types of corridors are identified.
(Taylor et al., 1993)	Nature, via its ecological and evolutionary processes, supplies resources essential to life and human	-	These functions rely on a well-connected ecological “web” of high-quality land as well as biological diversity. In the short

	wellbeing, such as air, fresh water, and soils for food production, sources for medicine and industry, and places to relax, as well as carbon sequestration and climate change mitigation		and long term, maintaining a healthy ecological connectivity safeguards the whole system on which model humans rely.
(Urban & Keitt, 2001)	Landscape connectedness is a multi-scale concept that allows researchers to look at how the combination of species mobility capacities and landscape structure impacts species survival, gene flow, and other important ecological processes in fragmented landscapes	Only structural connectivity checked not the functional connectivity.	The consequences and restrictions imposed by rising rates of landscape and environmental change must also be considered when quantifying functional connectedness.

(Wikramanayake et al., 2004)	The viability of wildlife populations in tiny, isolated reserves is threatened by genetic and demographic factors	Good identification of problem but demand for computational model presented without providing any model.	Landscape elements were represented by nodes, while common boundaries between elements were represented by connections. The models successfully included corridors, corridor junctions, and the matrix.
(Yumnam et al., 2014)	Despite widespread support for tiger (Panthera tigris) conservation, poaching, habitat degradation, and isolation pose serious threats to their existence.	Threats have been identified but why the threats arise have not been given importance.	Due to a lack of objective information on their value, habitat corridors that connect regional tiger populations are frequently destroyed to development projects.

Chapter 4

RESEARCH METHODOLOGY

Theoretical framework

Complex systems may be formally and thoroughly described using networks. Often used to simulate experimental data when *n-ary* interaction plays a significant role and changes throughout a certain region. The link between the landscape's features that either facilitate or hinder tiger dispersal is significant to the work and might change over time and space (Lomas, 2023). Therefore, a perspective based on the theory of complex networks would be used to represent such complex systems.

A network N is a four tuple $(V_\lambda, E_\lambda, \psi_\lambda, \Lambda)$ with an algorithm β such that for $\Lambda \neq \phi, k \in \Lambda, V_\lambda$ is a set of vertices V_k, E_λ is a set of edges E_k, ψ_λ is an incidence function $\psi_k : E \to [V]^2$ where $[V]^2$ is the set of not necessarily distinct unordered pairs of vertices such that (V_k, E_k, ψ_k) is a graph given by the algorithm $\beta(k)$. The incidence function ψ provides structure to a graph by associating to each edge an unordered pair of vertices in the graph as $\psi(x) = \{v_k, v_q\}: v_k, v_q \in V, \forall\, x \in E \subseteq [V]^2$. Here k is the temporal component by virtue of which a network can evolve as per the given algorithm β (Upadhyay et al., 2019).

An unlabeled graph is an isomorphism class of an otherwise labelled graph since a graph is an algebraic object. A network is considered a static network if the temporal component Λ consist of a single element k, otherwise the network is a dynamic network (Kurapov & Davidovsky, 2022). In the proposed study, an ecological network is defined as a network N in which V_λ is the set of habitat patches for the tigers, and E_λ is the set of paths between two distinct habitat patches. As a result, a network is made up of nodes connected by links, while a graph is made up of vertices connected by edges. The connections and nodes in a network are determined by the incidence function and the conclusion of the spatial-temporal evolutions. The terms "graph" and "networks" are used interchangeably throughout the proposed work (Shanu et al., 2019).

Centrality measures are essential to structural research; they were first created as a fundamental foundation for utilizing network and graph theory to study social systems. Structural measurements such as centrality measures have been more important in ecological network research and design in recent years (Riquelme & Vera, 2022). Centrality measure's inherent notion is to rank a graph *G's* edges (*E*) or vertices (*V*) by allocating real values according to the vertex's significance. Consequently, we may find a graph's core components with the use of centrality measurements. A vertex in *G* that has the smallest feasible maximum degree is said to be its center. Nonetheless, the graph's topology affects the centrality measurements (Choi et al., 2017). The following definition of a structural index states the underlying application:

Structural index. Let $\Gamma_1(V(\Gamma_1), E(\Gamma_1), \Psi_{\Gamma_1})$ and $\Gamma_2(V(\Gamma_2), E(\Gamma_2), \Psi_{\Gamma_2})$be two graphs and let X represent the set of vertices or edges of Γ_1, G and H represent two sub graphs of Γ_1. Then, $s: X \rightarrow \mathbb{R}$ is called a structural index if and only if the following condition is satisfied: $\forall x \in X: G \tilde{=} H \Longrightarrow s_{\Gamma_1}(x) = s_{\Gamma_2}(\phi(x))$, where $\phi: V(\Gamma_1) \rightarrow V(\Gamma_2)$ is an isomorphism, and $s_{\Gamma_1}(x)$ denotes the value of $s(x)$ in Γ_1 and $s(\phi(x))$ denotes the value of $s(x)$ in Γ_2 (Shanu et al., 2019).

Nominally, a centrality measure c induces at least a semi-order on the set of vertices or edges of the graph in consideration as is required to be a structural index. Thereby, model say $x \in X$ is at least as central as $y \in X$ if $c(x) \geq c(y)$.

For corresponding modelling and real-world situations, different centralities are employed. The centralities that are suggested to be employed for the work are explained in the paragraphs that follow.

Degree centrality ($\boldsymbol{DC}$). The degree centrality of a vertex is the number of edges incident to it. In formal notation, degree centrality of a vertex v,

$$DC(v) = \deg(v) \text{ ---(1)}$$

Degree centrality is a principle that suggests vertices with more edges represent more alternative ways and resources to achieve goals (Pavel et al., 2023). It has been successfully applied in protein-protein interaction and species interaction networks to identify significant vertices. In a habitat patch, a high degree of a vertex indicates a higher number of species pathways, implying a higher rate of species traffic. Conservation of vertices with high degree centrality is crucial, as any compromise directly affects many species relying on these pathways (Barish & Shibuya, 2023).

Eigenvector centrality (EC). If the adjacency matrix of the graph is given by $A = (a_{ij})$, the eigenvector centrality of a vertex v is given by

$$EC(v) = \frac{1}{\lambda} \sum_{\mathrm{i} \in \mathrm{V}(\Gamma)} a_{vi} EC(i) \text{ ---(2)}$$

where $\lambda \in \mathbb{R}$.

In vector notation, this can be rewritten as the eigenvector equation:

$$Ax = \lambda x \text{ ---(3)}$$

for which a unique eigenvector solution with all positive entries exists. The v^{th} component of the related eigenvector then gives the centrality score of the vertex v in the graph (Liu & Zhao, 2023).

Eigenvector centrality is a method of analyzing a network by decomposing it into linearly independent subnetworks, each with varying amounts of each vertex. The entire network is the sum of these subnetworks weighted by the eigenvalues, with the largest eigenvalue containing the most information about the entire network. The eigenvector centrality uses an iterative estimation approach, weighing each vertex's centrality by the centrality of its neighbors (Was & Skibski, 2018). It functions as a generalized version of degree centrality, where the ranking of a vertex depends on the degree of adjacent vertices. Since its inception, eigenvector centrality has been used extensively to identify synthetic genetic interactions and gene-disease associations. In the tiger corridor network, computing eigenvector centrality helps identify habitat patches with fewer species pathways due to their proximity. Damage to these patches adversely affects many species, who rely on these pathways for their travel (Astudillo et al., 2020).

Betweenness centrality (BC). Betweenness centrality quantifies the number of times a vertex acts as a bridge along the shortest path between two other vertices. Formally, the betweeness centrality of a vertex v is given by:

$$BC(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \text{ ---(4)}$$

where σ_{st} denotes the number of shortest paths from vertex s to vertex t, and $\sigma_{st}(v)$ denotes the number of such paths passing through v (Dolev et al., 2010).

Betweeness centrality is a measure of a vertex's connection to other vertices, indicating its importance based on the probability of it occurring on a randomly chosen shortest path. Betweenness centrality indicates important vertices that lie on a high proportion of paths between other vertices in a network (Bockholt & Zweig, 2018). In the tiger corridor network, vertices with high betweeness centrality indicate habitat patches that often act as bridges between other patches, disrupting species' travel between habitats. Damage to these vertices disrupts species' ability to travel between habitats.

Closeness centrality (CC). Closeness centrality of a vertex v is defined as the reciprocal of the sum of geodesic distances (i.e., the shortest path) between v and all other vertices. In formal notation,

$$CC(v) = \frac{1}{\sum_{t \in V(\Gamma) \setminus \{v\}} d_{\Gamma}(v,t)} \text{ ---(5)}$$

where $d_{\Gamma}(v,t)$ denotes the geodesic distance between vertex v and t (i.e. the number of edges in the shortest path between v and t) (Zhu et al., 2021).

Closeness centrality is a measure of how close a vertex is relative to other vertices in terms of the shortest path between them, used to identify keystone species in pollination networks. It indicates important vertices that can communicate quickly with other network vertices, based on geodesic distance (Regunta et al., 2021). In the tiger corridor network, vertices with high closeness centrality represent habitat patches nearest to most other patches. These patches are chosen by most species as they allow efficient travel distance. Knowledge of these patches can prevent epidemic spreading among species by quarantining them and serve as a reference for constructing safe human settlements within the network (Ahn & Kim, 2021).

Subgraph centrality (SC). The subgraph centrality of a vertex v is defined as the "sum" of closed walks of different lengths in the networks starting and ending at vertex v. Formally,

$$SC(v) = \sum_{k=0}^{\infty} \frac{(A^k)_{vv}}{k!} = (e^A)_{vv} \text{ ---(6)}$$

Subgraph centrality is a rule that states that the contribution of closed walks decreases as the length of walks increases, based on the observation that motifs in real-world networks are small subgraphs (Li et al., 2013). It is used in protein-protein interaction networks to determine the ranking of vertices based on scale-free characteristics. In the tiger corridor network, vertices with high subgraph centrality indicate habitat patches with a high proportion of closed subnetworks (Horton et al., 2019).

From an ecological perspective, a patch with large subgraph centrality allows a species to move between multiple patches using predominantly closed walks of small lengths, making them central for round travel and energy management.

Detecting community structure. A network has community structure if its nodes can be easily grouped into densely connected sets (Fang et al., 2009). These communities can represent real social groupings, metabolic network nights, or web pages on related topics. Identifying these communities can help us understand and exploit these networks more effectively. For example, in the tiger corridor network, communities represent groups of habitat patches related by similar features. Studying these communities could deepen our understanding of species' behavior and travel patterns, making them crucial in understanding complex networks (Zarei & Meybodi, 2020; Guo et al., 2018).

For detecting communities in the proposed network, the model uses the Newman – Girvan algorithm, which is based on edge-betweeness centrality.

Edge-betweeness centrality. The edge-betweeness centrality is the analogue of the standard betweeness centrality, applied to edges (Hurajová et al., 2022). Edge-betweeness centrality quantifies the number of times an edge acts as a bridge along the shortest path between two vertices. Formally, the betweeness centrality of an edge e is given by,

$$BC(e) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(e)}{\sigma_{st}} \text{ ---(7)}$$

where σ_{st} denotes the number of shortest paths from vertex s to vertex t, and $\sigma_{st}(v)$ denotes the number of such paths passing through e (Jamour et al., 2018).

Edge-betweeness centrality is a measure of an edge's importance based on its relationship with unconnected vertices. It indicates important edges that occur on a high proportion of paths between vertices in a network. In the tiger corridor network, edges with high edge-betweeness centrality indicate pathways that often act as bridges between patches, which may not be adjacent otherwise (Alves et al., 2022).

Newman – Girvan algorithm. The Newman – Girvan algorithm is an algorithm used for detecting communities in networks. It works based on the principle of edge-betweeness centrality. The idea behind the algorithm is that if a network contains communities or groups that are only loosely connected by a few intergroup edges, then all shortest paths between different communities must go along one of those few edges, and such edges will have high edge-betweeness (Khatoon & Banu, 2021). By removing these edges, the groups are separated from one another to reveal the underlying community structure of the network (Devi & Rajalakshmi, 2023).

The algorithm is simply stated as follows:

1. Calculate the edge-betweeness for all edges in the graph.
2. Remove the edge with the highest betweeness.
3. Recalculate the edge-betweeness centrality for all edges affected by the removal.
4. Repeat from step 2 until no edges remain.

Simplicial Complex. It is a quotient space of a collection of disjoint simplices obtained by identifying certain of their faces via the canonical linear homeomorphisms, which preserve the ordering of vertices (Wu et al., 2023). A simplicial complex S may be defined as a set of simplices such that if a simplex P is an element of the set S then all faces of P are also elements of S. To capture the essence of simplicial complexes in Complex networks, a defined dimensional space happens to be of key importance. Thus, a k-simplex is a mathematical object with $(k + 1)$ vertices, which exists in a k-dimensional space (Farber et al., 2021). A set of simplices constitutes the Simplicial Complex For example if $A = \{a_0, a_1, a_2, \dots, a_k\}$ creates a simplex then all its faces $F = \{a_0, \dots, a_{i-1}, a_{i+1} \dots, a_k\}$ also create a simplex. Further all the faces of F, $F` = \{a_0, \dots, a_{i-1}, a_{i+1}, \dots, a_{j-1}, a_{j+1}, \dots a_k\}$ also create simplex until 0-simplices formed just by the nodes is reached (Palafox-Castillo & Berrones-Santos, 2022).

Clique Complex. A clique complex can be obtained from a network. The set of the network becomes the set of the clique complex (Abdullah & Hossain, 2022). Let Z be a clique of n vertices in the network. Then, Z is a *(n − 1)*-simplex in the clique complex. As an example, Figure 4-1 describes a simplicial complex which has one 3-simplex $\{a_0, a_1, a_2, a_3\}$, and six 2-simplices $\{a_0, a_1, a_2\}$, $\{a_0, a_1, a_3\}$, $\{a_0, a_2, a_3\}$, $\{a_1, a_2, a_3\}$, $\{a_2, a_3, a_4\}$, and $\{a_3, a_4, a_5\}$. It also has eleven 1-simplices represented by the edges and seven 0-simplices, the vertices (Nasirian et al., 2020).

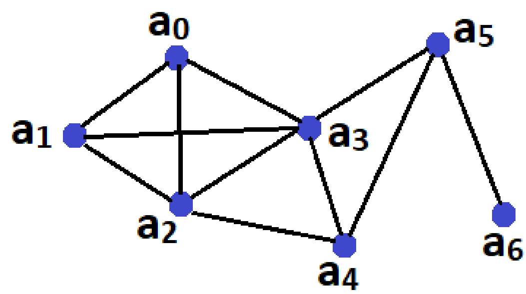


Figure 4-1: A simplicial complex with labeled vertices

Adjacency in simplicial complexes is challenging to define, with two n-simplices p and q having two ways of defining it: lower and upper adjacency (Zhang et al., 2023).

Definition 1. Let p and q be two n-simplices. Lower adjacency exists between the two n-simplices if they share a common face (Milanič & Uno, 2023). Which implies, for two distinct n-simplices $p = \{p_0, p_1, \dots, p_k\}$ and $q = \{q_0, q_1, \dots, q_k\}$, p and q are lower adjacent if and only if there is a $(n - 1)$-simplex $\beta = \{r_0, r_1, \dots, r_{k-1}\}$ such that $\beta \subset p$ and $\beta \subset q$. Lower adjacency is denoted by $p \smile q$ (Lee et al., 2023). In the simplicial complex in Figure 1, the 2-simplices $\{a_0, a_1, a_3\}$ and $\{a_1, a_2, a_3\}$ are lower adjacent because they share a common 1-simplex $\{a_1, a_3\}$ which is a common face for both. So, it can be written as $\{a_0, a_1, a_3\} \smile \{a_1, a_2, a_3\}$.

Definition 2. Let p and q be two n-simplices. Then the two n-simplices are upper adjacent if they both are faces of the same common $(n + 1)$-simplex (Liwat & Eballe, 2023). That is, for $p = \{p_0, p_1, \dots, p_k\}$ and $q = \{q_0, q_1, \dots, q_k\}$, p and q are upper adjacent if and only if there is a *(n +1)*-simplex $\lambda = \{r_0, r_1, \dots, r_{k+1}\}$ such that $p \subset \lambda$ and $q \subset \lambda$. The upper adjacency is denoted by $p \frown q$ (Madriaga & Eballe, 2023). In the simplicial complex in Figure 1, the 1-simplices $\{a_2, a_4\}$ and $\{a_3, a_4\}$ are upper adjacent because they are both faces of the 2-simplex $\{a_2, a_3, a_4\}$ which is a common face for both. So, it can be written as $\{a_2, a_3\} \frown \{a_3, a_4\}$.

Sources of data – Primary or secondary data:

The work's main goal had been to provide a computational model that can help with the construction of complicated networks utilizing machine intelligence. Primary and secondary data had been gathered for creating the model using the following methods:

1. Literature Survey: The focus of the literature review would be on understanding important components of the problem and identifying significant indicators.
2. Interviewing the experts: The study is in the field of computational sustainability, with a particular focus on developing a computational architecture for constructing wildlife corridor networks. Expertise in two disciplines of study, namely computer science and wildlife sciences, was required for the work. The team had the competence to work on computer science tasks, and comprehensive interviews with wildlife specialists in the target domain of tiger conservation was beneficial in gaining important insights on the ecological components.
3. Field Survey: Planned field surveys with the assistance of professional organizations were beneficial in gaining a better understanding of both the intuitive and empathic aspects of work in relation to the locals and environmental variables.
4. Wildlife Science Journal Articles: Published peer reviewed scientific paper can be utilized for verification and validation activities since they address many case studies of animal migrations.
5. Ministry reports
6. Survey of India maps

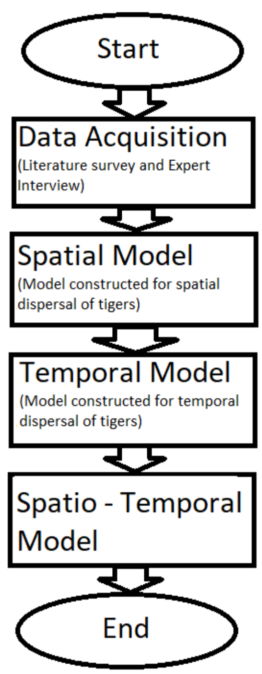


Figure 4-2: Workflow Diagram (Clarity on developing system/Method/Model/Platform/Apparatus)

Schematic flow Diagram of conducted work:

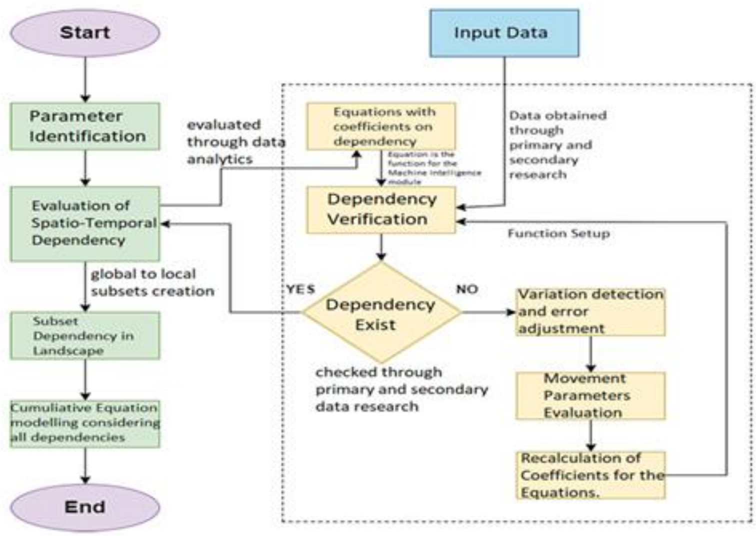


Figure 4-3: Schematic Flow Diagram

Chapter 5

RESEARCH FINDINGS & CONTRIBUTIONS

The primary contributions of this research endeavor are included in this portion of the report. The section with the relevant articles presented with each sub section has discussions of each aim and their corresponding techniques.

Objective 1:

To identify the critical parameters and ecological indicators which affect the dispersal of tigers in any focal landscape:

Wildlife habitat patches are crucial for the survival and reproduction of wildlife species, providing essential food, water, and ecological conditions. They are vital segments of ecological systems that provide shelter, food, and reproduction for focal species. However, human activities have reshaped these habitats, leading to habitat fragmentation and loss (Kelt et al., 1999; Glass and Pienaar, 2020). This study aimed to compute a viable tiger corridor network architecture in the focal landscape using the Clique Percolation Method (CPM) (Doreian and Conti, 2012). The objective is to understand the interactions between habitat patches supporting tiger populations as vertices and the interaction between these vertices as edges.

Graph theory is used to design and study the interactions among habitat patches, with each suitable habitat treated as an element of the vertex set V and the interaction between these vertices as the set of edges E. The Habitat Suitability Index (HSI) is one of the key models in determining these interactions for a particular species. Remote Sensing (RS) and Geographic Information System (GIS) datasets are used to calculate HSI for a species over a landscape (Dale et al., 2001; Erős and Lowe, 2019; Matisziw and Murray, 2008).

The suitability-clustering problem is defined as identifying potential habitat and supportive links for tiger movement. By creating clusters of data points obtained through HSI modelling, the model integrates tiger movement preferential features through cumulative landscape aspects. These clusters aid in identifying the most important landscape matrix elements that could sustain a viable tiger population and relative movement (Dutta et al., 2015).

The work defines a tiger corridor network and identifies essential cliques that could serve as diverse interlinking of habitat patches based on the suitability of each feature. CPM is then used to obtain overlapping communities in the landscape matrix to verify and preserve the landscape complex's contiguity (Palla et al., 2005; Bordenave et al., 2018).

Terai Arc Landscape

The Terai Arc Landscape, which spans 810 km from west to east in the Himalayan foothills between the rivers Yamuna and Bhagmati, includes the Shivalik slopes, the connecting bhabhar zones, and the Terai floodplains. These features are primarily found across three Indian states: Uttarakhand, Uttar Pradesh, and Bihar (Bhatt et al., 2023).

The research region is in Terai Arc Landscape, which is defined by the Yamuna River (30˚30 to 77˚30'), which indicates its western boundary, and the Sharda River (27˚20' to 81° 22'), which marks its eastern boundary. As seen in Figure 1, the study region also includes a portion of Nepal, Himachal Pradesh, Uttar Pradesh, and Haryana. The lowest temperature is below 5ºC, while the highest is 40ºC. Over this region, there is an annual precipitation range of 1000 mm to 2500 mm. Sal is the predominant species in the region's natural vegetation, which is mostly composed of dry and damp deciduous woodland.

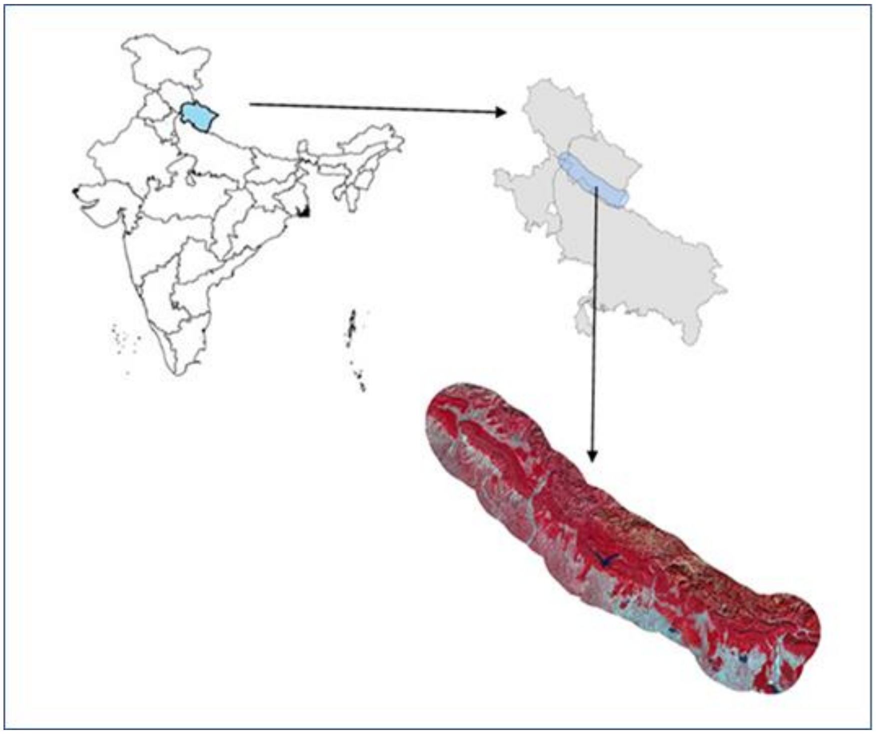


Figure 5-1: Location of the study area – Terrai Arc Landscape

Materials and Methods

Database Creation. The study used a hybrid categorization approach to create a map of the study area's land use and cover using satellite data from Landsat-8. The data was divided into 13 classes using the Normalized Difference Vegetation Index (NDVI). Forest cover density was categorized into low, medium, and high-density groups. The ASTER digital elevation model was used to construct aspect, slope, height, and altitude maps. Highway shape files were obtained using open street maps. (Sonawane and Bhagat, 2017).

Habitat Suitability Index (HSI). By employing RS-derived data and the Analytic Hierarchy Process (AHP) to model HSI in a GIS setting, possible habitats for the various species in the target landscape may be spatially identified using a clustering technique. The percentage of a habitat that is suitable for a particular species based on an assessment of the environment's attributes is known as the habitat suitability index. HSI are records in the sense that they often combine many variables (such as height, soil type, and land spread) into a single composite value. Habitat quality and species distributions are frequently predicted using HSI models (Zajac et al., 2015). The greatest quality of habitat in the landscape for the focus species is represented by the value 1 of the HSI, which has a value between 0 and 1.

The AHP is a powerful instrument for managing complicated decision-making dynamics; it was utilized in this study to test the consistency of the manager's assessments for HSI evaluations, decreasing the tendency in the dynamic decision-making method. (Saaty, 1990; Assad, 2017; Wojcik and Kurdziel, 2018).

Next, the HSI for tigers is used in the landscape to propose a computational model of the tiger corridor network in the focus landscape. To ensure that the section is self-contained, several basic ideas that are needed for the modelling that was previously mentioned—such as networks, graphs, cliques, centrality, communities, overlapping communities, and the CPM—are repeated from widely used mathematical sources and addressed. Examining relationships between habitat patches as vertices within the landscape that might assist to explain tiger mobility between them has been one of the paper's main points of contention. Because they take into account the interaction of vertices, networks may be highly helpful in researching and creating such models (Upadhyay et al., 2017). Because tigers were included in this study both inside and outside of PAs, the region between the vertices facilitating tiger migration is critical. The fact that tigers use the entire area as a territorial border outside of PAs if the HSI is above the "Suitable" class demonstrates the importance of regions rather than points or lines in the landscape matrix. After modelling the tiger corridor network, we use clique to understand the relationships inside it. Because different cliques may be close to one another, Participatory centrality (PC) was used to determine the vertices of diverse cliques that support the adjacency of two cliques. (Ghalmane et al., 2019).

In this work, the adjacency of cliques depicted as a clique graph shows that vertices that support the tiger population and mobility are located at the junction of two distinct areas. Finding the community that emerges from the cliques had been a useful way to construct the corridor networks because it indicated the structural and functional connection in the fractured landscape that gives the focus species more mobility options. Using clique graphs, the overlapping communities in the tiger corridor network are also identified. The communities described in this study consist of a collection of vertices, linkages connected to these vertices, and the region bounded by them. These communities have structural and functional traits that facilitate the migration and population of tigers. Determining the collection of vertices that can be understood as generating multilevel pairwise interactions between them is made easier using this. When two distinct communities have one or more identical vertices in common, they overlap. Because they help to maintain continuity between the communities and provide a gradient of structural and functional features that allow tigers to move from one to the next, these common vertices are important (Palla et al., 2005; Bordenave et al., 2018; Fortunato, 2010; Tóth et al., 2012).

Network and Graph. Networks provide a complete and formal description of complex systems. usually employed to replicate experimental data in which interactions play a significant role and change over time within a certain area. Because the interactions between habitat patches may change across time and space, they are significant to the work being done here. Thus, in order to describe such complex systems, one must take a viewpoint and use the theory of complex networks.

A network N is a four tuple $(V_\lambda, E_\lambda, \psi_\lambda, \Lambda)$ with an algorithm β such that for $\Lambda \neq \phi, k \epsilon \Lambda, V_\lambda$ is a set of vertices V_k, E_λ is a set of edges E_k, ψ_λ is incidence function $\psi_k : E \to [V]^2$ where $[V]^2$ is the set of not necessarily distinct unordered pairs of vertices such that (V_k, E_k, ψ_k) is a graph given by the algorithm $\beta(k)$. The incidence function ψ provides structure to a graph by associating to each edge an unordered pair of vertices in the graph as $\psi(x) = \{v_k, v_q\}: v_k, v_q \epsilon V, \forall x \epsilon E \subseteq [V]^2$. Here k is the temporal component by virtue of which a network can evolve as per the given algorithm β (Upadhyay et al., 2017).

An unlabelled graph represents an isomorphism class of otherwise labelled graphs in an algebraic object known as a graph. As a result, a graph is used to represent a network. For our work in this work, model define an ecological network as a network N in which V_λ is the set of habitat patches for the tigers, and E_λ is the set of relations encoded as edges representing the movement of tiger between two distinct habitat patches (Upadhyay et al., 2017; Shanu et al., 2019). Having argued as above in this work, model shall use the terms graph and networks interchangeably.

Clique

Definition: A set of vertices C is a clique of the graph G, if and only if $C \subseteq V(G)$; $x, y \in C \text{ and } x \neq y \Rightarrow \{x, y\} \epsilon E(G)$, where $V(G)$ represents the Vertex set of G, $E(G)$ represents the set of edges of G and $\{x, y\}$ represent a edge between vertex x and vertex y (Bondy and Murty, 2008).

A clique is a complete subgraph in which every vertex is connected to every other vertex. A k-clique denotes a clique of size k, where each vertex has a certain degree $\geq (k-1)$, and vertices with a certain degree $< (k-1)$ will not be included in the clique. The model uses a greedy method to find a clique in the sub-network after recursively applying a pruning technique to sample a sub-network from the specified network (Estrada and Ross, 2018; Hatcher, 2002). Figure 5-2 shows 3-cliques obtained over a hypothetical network.

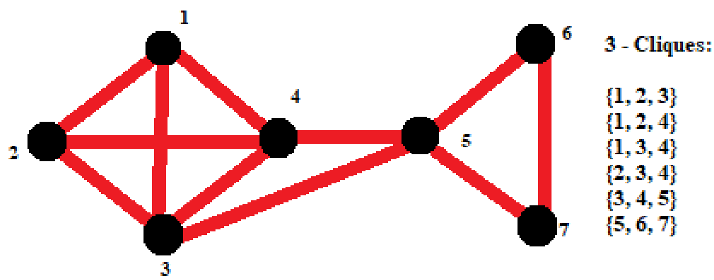


Figure 5-2: 3-cliques obtained over a hypothetical network.

Communities. Communities on the web may represent related web pages; communities in the landscape may reflect regions with structural and functional similarities to some focal species; communities in a metabolic network may represent cycles and other functional groupings; and communities in a social network may represent related real social groupings, possibly based on interest or background (Girvan and Newman, 2002; Doreian and Conti, 2012; Kuikka, 2021). It may be better equipped to comprehend and utilize these networks if these groups could be recognized. Communities in the tiger corridor network are collections of habitat patches, the linkages that connect them, and the area that these links contain. These aspects bind the communities together (Shanu et al., 2019). Finding and researching these communities may be crucial to expanding our knowledge of the behaviour and migration patterns of many species. In addition, community detection helps pinpoint the crucial points in the tiger corridor network that are required to preserve landscape continuity.

Overlapping Communities. The network is said to have communities if its vertices can be easily separated into groups of vertices that are each highly linked internally and may even overlap in the case of overlapping communities (Palla et al., 2005). When several communities form in a network and are all tied to one another because they share some or all of the vertices, the communities overlap (Bordenave et al., 2018). Even though the mathematical definition of a community is not established, but rather mainly agreed upon in the literature, the model must specify below the motion of overlapping communities for use in this study.
Definition: Let *G* be a graph with n-communities $\{C_1,\ C_2,\ C_3, \dots,\ C_n\}$, if $C_i\ \cap\ C_j\ \neq \{\}\ \forall\ i,\ j\ \in \{1, 2, 3, \dots, n\}$, then all the communities are said to be overlapping communities in the graph.

In order to identify critical vertices or habitat patches that are essential for preserving landscape continuity for tiger movements and interaction in the tiger corridor, the detection of overlapping communities is necessary for the study in this research (Shanu et al., 2019).

The tiger corridor network is analyzed by the model using a PC. The model will identify overlapping communities in the network using a PC-based CPM.
Initially, centrality measurements were presented as a fundamental idea in social network analysis (Bayleas, 1948; Bayleas, 1950). Since then, they have become much more widely used, and their extensive application to ecological networks has shown to be highly productive (Cantwell and Forman, 1993; Chetkiewicz et al., 2006). The result of a centrality measure, as indicated in the description of a structural index that follows, is influenced by the structure of the network:

The model specifies the PC of vertex, a basic combinatorial measure, as follows to identify the major vertices that are responsible for community identification.

Participatory centrality (PC). The number of cliques to which a vertex *v* can belong is defined as the Participatory centrality of the vertex *v*. for a graph *G* where $n\ number\ of\ k - cliques$ are formed, the Participatory centrality of a vertex v is given by,

$$PC(v) = \sum \alpha_{cb}(v) \text{ ---(8)}$$

where $\alpha_{cb}(v)$ is the number of cliques that have *v* as a vertex.

According to PC's guiding theory, vertices that are part of numerous cliques may indicate that they have a variety of resources and alternate routes to achieving their objectives, making them relatively advantaged and so more significant (Gupta et al., 2016; Ghalmane et al., 2019).

A vertex's (habitat patch) high involvement in the present network suggests that there are more landscape features next to it, which suggests that there is a higher rate of species traffic across the vertex. As a result, in our situation, maintaining vertices with a high PC is crucial since many species depend on the greater number of paths that surround them for mobility, therefore any compromise on these vertices has a direct impact on them.

Clique percolation method (CPM)

Definition: (Tóth et al., 2012) define the k-clique community as the union of all linked k-cliques. The model uses the CPM to find overlapping communities in our network, which is based on internal community relationships that are likely to create cliques as well as intercommunity links that are unlikely to form cliques.

In the simplicial complex, the CPM discovers overlapping communities (Fortunato, 2010; Wang et al., 2015). Overlapping communities are feasible if each vertex in the simplicial complex belongs to more than one community. In the CPM, the model takes a parameter k and a specific network as inputs. All cliques of size k are discovered in the provided network, and a clique graph is created. The clique graph is constructed by joining cliques that share $(k-1)$ vertices and placing all cliques as vertices. A community is formed by the union of each connected clique in the clique graph. Figure 5-3 depicts the communities obtained for the hypothetical network of Figure 5-2.

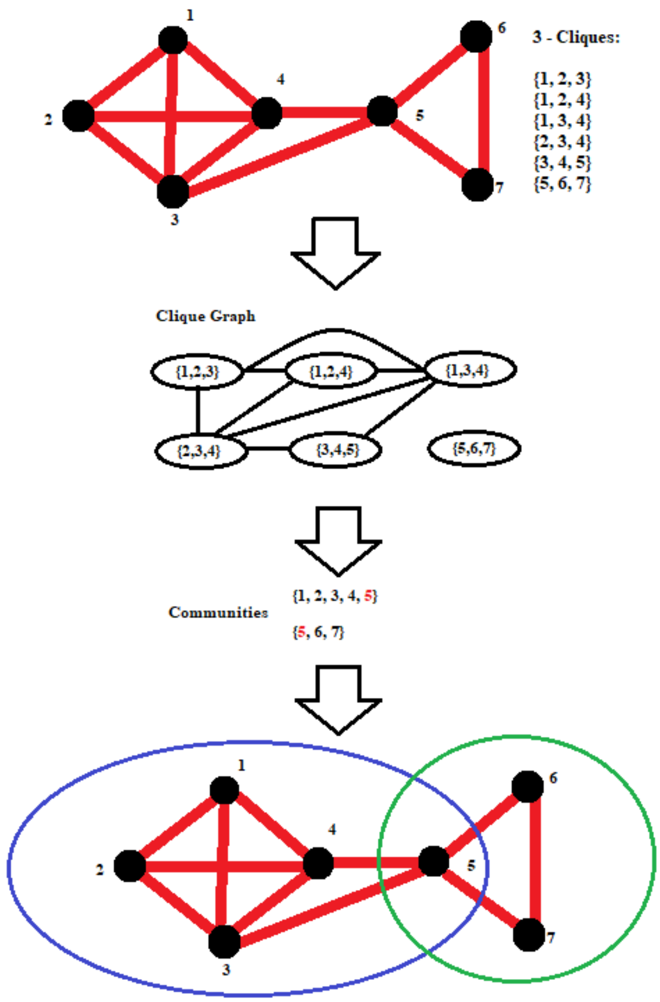


Figure 5-3: Community Detection using the CPM on the hypothetical landscape by obtaining the 3-cliques.

Methodology and Modelling

To begin, the HSI was used to model the focal landscape in order to identify the most significant areas that might serve as prospective homes for tigers in Protected Areas (PAs) as well as territorial tigers in the corridors. Second, the model was built on methodology and ideas to generate an overlapping community in the tiger corridor network.

Habitat Suitability Index (HSI)

The HSI evaluates species-specific factors as well as the appropriateness of important habitats (Tirpak et al., 2009). Factors linked to tiger distribution and abundance of its prey species were evaluated in the Terai-arc landscape complex utilizing data from various field surveys, expert studies, and literatures as input data for HSI modelling. The HSI model determines the HSI for the Tiger and its prey species, which include Sambar deer *(Cervus unicolar)*, spotted deer *(Axis axis)*, barking deer *(Muntiacus muntjak)*, wild boar *(Sus scrofa)*, and blue bull *(Boselaphus tragocamelus)*.

Information on possible variables impacting species habitat and topographical dispersal is critical for building HSI and giving major planning returns (Duflot et al., 2018). Vegetation type, forest density, slope, aspect, distance from water, and distance from anthropogenic disturbances were identified as significant factors for tiger habitat appropriateness and prey compatibility based on earlier habitat studies. The priority values for these eight environmental variables were calculated by the model based on their biological relevance for the species inside each stratum for each class.

The modelling system integrates several geographical datasets from remote sensing and auxiliary sources, as well as field data, and uses a multi-criteria approach to assess tiger habitat appropriateness. The weights of various elements were calculated using the aforementioned analysis and linear additive equation.

Habitat suitability map of Tiger

Tiger's habitat suitability map contains a layer for their prey's compatibility. An output map with four degrees of compatibility was constructed for each variable: very highly suited, extremely suitable, moderately suitable, and least suitable. Each variable was weighted based on the relevance of the prey (Appendix A). All the output layers were layered to form the habitat suitability diagram. The weights were obtained via a pairwise comparison, and the linear additive equation was as follows:

$$HSI = (Sambar * 0.43) + (0.30 * Chital) + (0.17 * Barking\ Deer) + (0.07 * Wild\ boar) + (0.03 * blue\ bull) \text{ ---(9)}$$

Corridor Network Modelling and Community Detection

In continuation with the last discussion, create a model that finds communities in the HSI-built corridor network. After the Habitat Suitability Index has been calculated, the procedure comprises recognizing potential habitat patches. The vertices *(P)* of the tiger corridor network are protected areas (PAs) and prospective habitat patches. The interaction of various habitats serves as the linkages *(E)*, and the availability of Habitat Suitability conditions in the landscape serves as the algorithm *(A)* for determining vertex interaction in the network. The model expected to do so because tigers are specialist animals, and landscape contiguity at a regional level, which is represented as a polygon on the landscape matrix, allows them to migrate from one habitat patch to the next (Walsh at al., 2011).

When corridors are only specified in terms of linking vertices via pathways, which are represented as lines on the landscape matrix, tiger movement is limited to simulations that may or may not be correct. In addition to the preceding discussion, a region-based interaction between vertices will assist decide communities generated by the vertices, so that the species individuals inside the community can interact with each other more frequently than those outside the community (Minor and Urban, 2007; Minor and Urban, 2008; Flowers et al., 2020; Wang et al., 2014).

To do this, the model first examines the adjacency matrices produced from the vertices (that is, protected areas and possible habitat patches) of the tiger corridor network and the relationships between them. The cliques were discovered when discussing the environment and habitat patches in the terrain since they contribute to the network's overall connectivity (Eros and Lowe, 2019). Tiger mobility in the landscape is unfettered in the absence of anthropogenic disturbances but restricted in the presence of a high level of anthropogenic disturbances and a variable amount of biotic assistance. Cliques, as full subgraphs, assist in identifying crucial adjacencies in the corridor network that can manage these limitations, as well as connections to remote habitat patches. This work's complete algorithm for recognizing network cliques is defined and provided as follows:

Algorithm 1: *Clique_from_Network*
//input: Network N
//output: Cliques in the network
DECLARATION SECTION
x, y, e, t, a, p, n, k as integer
V, L, R as set of nodes
PROCEDURE SECTION
    for k = 2 to n

```
            Empty R
9           n = no. of nodes in the Network
10          for x = 1 to n
11                insert x in V                // Each node for which model begin to see all the cliques it belongs to are inserted in V
12                for y = 1 to n
13                      e = adj (x, y)         // adj(x, y) can be check from the Adjacency Matrix obtained for the network
14                      if e = 1 then
15                         V = V U {y}
16                         if |V| = k then     // To check for the cliques using all links of x
17                               Goto Line 21
18                         end if
19                      end if
20                end for
21                Check_Clique (x, V-{x}, k)   // to restart the process with a different node
22                Empty V
23          end for
24          if |R|! = k, Stop                  // to check the maximum clique that can be obtained in the network and then stop.
25    end for
26 RESULT SECTION
27    k - Cliques obtained

28 Function Check_Clique (a, L, p)
29    n = |L|
30    Insert a in R
```

```
        for t = 0 to n-1
                if adj (L(t), L(t+1)) = 1 then
                        R = R U {L(t), L(t+1) }
                        if |R| = p then
                                Goto 39
                        end if
                        L = L - L(t)
        End if
        Record R
        Update R id                                  //id updated to store new set of sets.
        Check_Clique (a, L, p)
Output: Set R that is a set of all p-cliques in the network.
```

The model uses the CPM over the results of the designed algorithm to detect overlapping communities. Overlapping communities are one of the most important aspects of this work since the key issue of the work focuses on is maintaining landscape contiguity. The model classifies overlapping communities to identify related habitat patches and the gradient of landscape features as a tiger moves from one community area to the next. This is useful for preparing and strategizing conservation plans because it can help distinguish movement trends in different spatiotemporal domains. The algorithm to classify overlapping communities uses clique graphs. A detailed algorithm for recognizing overlapping communities in a simplicial complex is defined and presented as:

Algorithm 2: *Clique_Percolation*

//input: output obtained from the Algorithm 1 i.e. set R.

//output: Overlapping Communities in the network

```
DECLARATION SECTION
k, n, m, I, q, j as integer
R, A, V', E', Comm as sets
PROCEDURE SECTION
    for k = 2 to n
        m = |R[k]|
        for i= 1 to m-1
            A[k] = R[k] (i-1) ∩ R[k] (i)
            if |A(k)| = k-1 then
                V' = V' ∪ {R[k] (i-1), R[k] (i)}     // each set of node becomes a set of vertex
                E' = E (R[k] (i-1), R[k] (i))        // each edge obtained between set of vertices
            end if
        end for
    end for
    Construct Clique Graph G = (V', E')              // update graph ID from New clique
    B = Adjacency matrix of Clique Graph
    q = |V'|
    for i= 1 to q
        for j= 1 to q
```

```
            if adj(i, j)= 1 then
                Comm = Comm ∪ {i, j}
            end if
        end for
    end for
    Publish Comm                                   // updation for new cliques
    clear V', E', Comm.
RESULT SECTION
    Set of Overlapping Communities.
```

Result

This effort took a few phases to create a functional tiger corridor network, and this section mentions the results obtained via these methods. The links between favorable habitat areas for tiger populations were established and then simulated. The modelling created a network H with 18 vertices in the landscape and 27 links between these vertices that characterized the interaction between the vertices, as shown in Table 5-3. When tigers move from one habitat patch to another, several regions can be employed to identify their existence, according to the findings of these cliques. Different cliques are also interconnected, thereby broadening the extent of tiger movement. As indicated in Table 5-5, the Participatory Centrality (PC) application is utilized to obtain the connections of various cliques as well as the necessary vertices required for these connections. The interconnection of several cliques, as well as the transit of tigers via several cliques, reveal the presence of communities of habitat patches in the landscape matrix. Some structural and functional properties are shared among habitat patches in the same community, but they are unique from those in other communities. The network's communities were created using a clique graph with all three cliques as vertices and the presence of an edge if at least two vertices are shared by two cliques, as shown in Table 5-6. After analyzing the data in Table 5-6, it was established that every community in the network had at least one common vertex with every other community, resulting in overlapping communities. The CPM outlined in method 2 was applied to the tiger corridor network, and overlapping communities were observed. All judgements were made using the tiger's HSI, including the appropriateness of two habitat patches to allow interaction between these habitat patches. The findings of the different processes are discussed in the order in which they were received in this section.

The most significant parameters affecting Tiger habitat appropriateness were forest cover, prey availability, distance to the water source, and disturbances. To construct the habitat suitability maps in the research region, the essential input parameters were merged. Figure 5-4 shows how the satellite data was turned into a land use/land cover map using unsupervised classification. Table 5-1 depicts the area covered by various plant types as well as a map of Land use Land cover (LULC). Figure 5-5 depicts a forest canopy density map of the research region that was obtained using NDVI and divided into four categories of tree crown cover, namely Very high density (>60%), High density (40-60%), Medium density (20-40%), and Low density (10-20%).

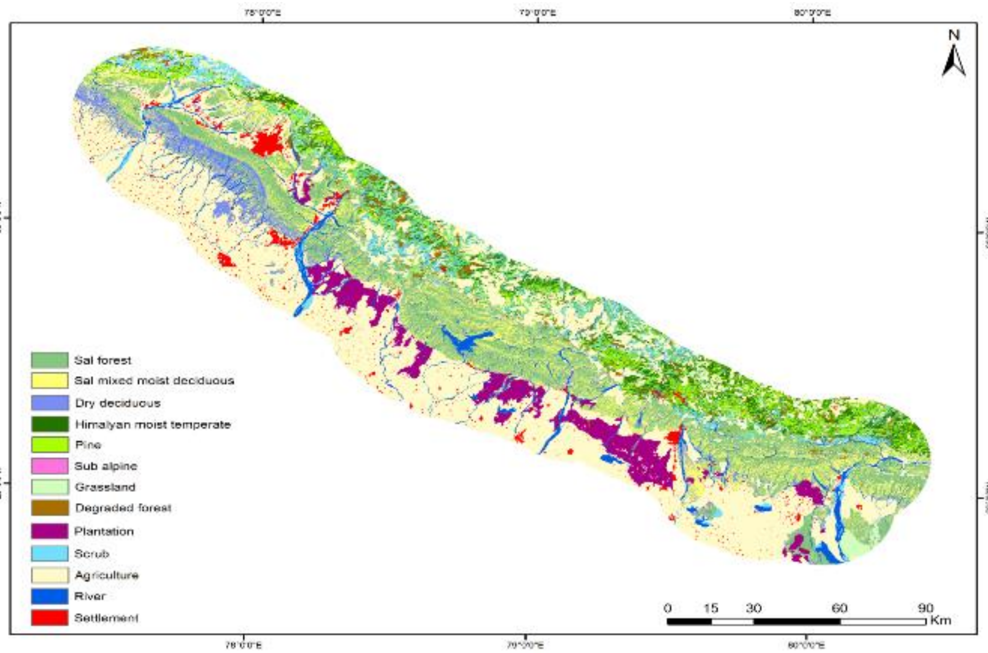


Figure 5-4: Land use Land cover Map

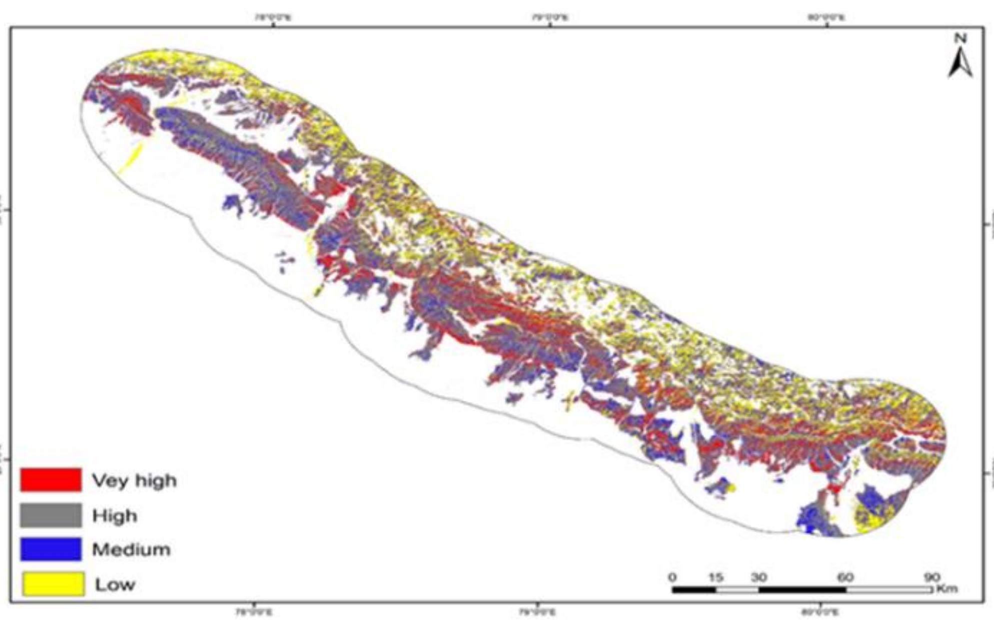


Figure 5-5: Forest density map

Table 5-1: Percentage of different forest cover and LULC types

SI. NO.	Cover types	Percentage
1	Agriculture	39.8

2	Sal Forest	14.5
3	Sal Mixed Moist Deciduous	10.5
4	Scrub	6.04
5	Pine	5.87
6	Plantation	5.29
7	Himalayan Moist Temperate	5.01
8	River	4.60
9	Dry Deciduous Forest	4.20
10	Settlement	2.05
11	Degrade Forest	1.67
12	Grassland	0.50
13	Sub Alpine Forest	0.01
Total		**100.0**

As previously stated, the presence of tigers is mostly influenced by the availability of appropriate prey (Jordan et al., 2006). Consequently, habitat suitability models for each prey species were constructed, and a composite tiger model based on prey species was established. The HSI for the primary prey species in the study region was calculated using the linear additive model, and Habitat Suitability maps are displayed in Figure 5-6. The ecological information on the distribution of prey species and their abundance regions is collected by pairwise comparison for weightage, and the habitat suitability maps in Figure 5-6 are derived using AHP. Table 5-2 summarizes the area in the landscape that is appropriate for the various prey species.

Table 5-2: Habitat suitability status of Prey species (Area in sq. km)

SI.NO.	Suitability classes	Spotted Deer	Sambar	Barking Deer	Wild Boar	Blue Bull
1	Very Highly suitable	2715.96	1974.3	2162.30	2191.59	1229.40
2	Highly Suitable	4559.56	3862.75	3571.41	4489.76	3681.47
3	Moderately suitable	3542.39	3728.85	3325.21	3187.88	4409.039
4	Least Suitable	11122.69	12374.71	12881.69	12071.38	12620.7
Total area		**21940.61**	**21940.61**	**21940.61**	**21940.61**	**21940.61**

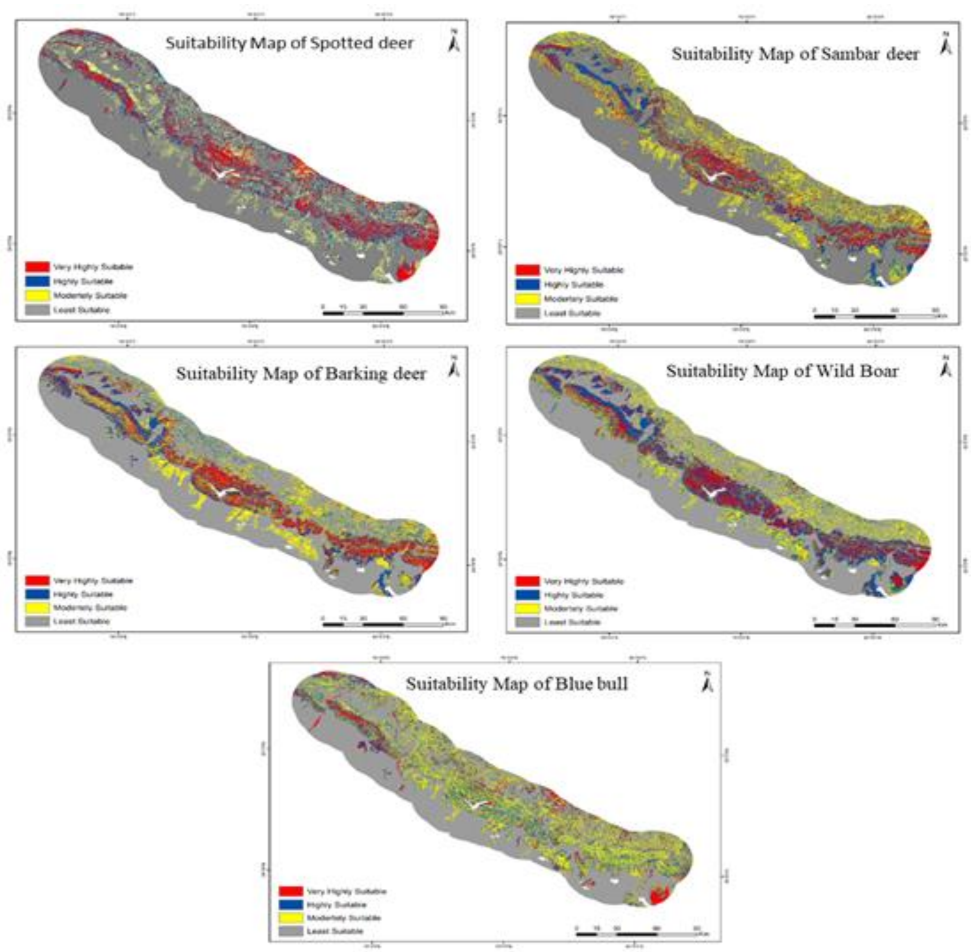


Figure 5-6: Habitat Suitability Map of Prey Species in the order – Spotted deer, Sambar deer, barking deer, wild boar, blue bull. The red colour in the map denotes "very highly suitable", blue colour represents "Highly Suitable", yellow colour represents "Moderately Suitable" and the grey colour represents "Least Suitable".

The tiger habitat suitability map was constructed using prey base distribution (Figure 5-7). In the research region, 3198 km^2 was judged to be extremely appropriate for Tigers. The overall amount of extremely appropriate land was calculated to be 4698 km^2. The area of generally acceptable habitats was around 3593 km^2, whereas the area of least suitable habitats, which were in towns and agricultural fields, was approximately 10450 km^2.

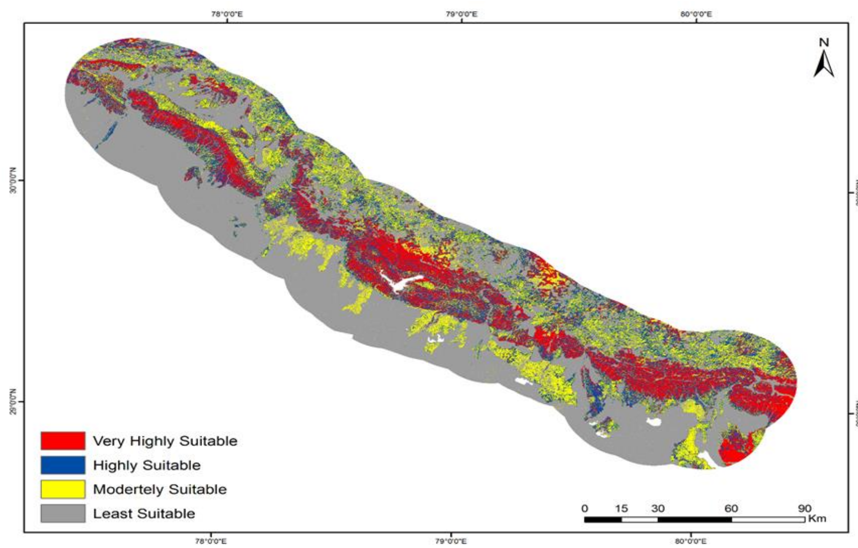


Figure 5-7: Habitat Suitability Map of Tiger

As a main goal of this research, the model is predicted to find communities between the locations specified by the tiger's Habitat Suitability map (Han, 2011). The result in (Figure 5-7) is examined using data mining techniques to derive the link between acceptable habitats and Habitat Patches, and a set of 18 nodes is created, as shown in Figure 5-8. These newly found nodes have the potential to aid in the survival of viable tiger habitats as well as function as connections between different habitat patches, allowing tigers to easily move between them.

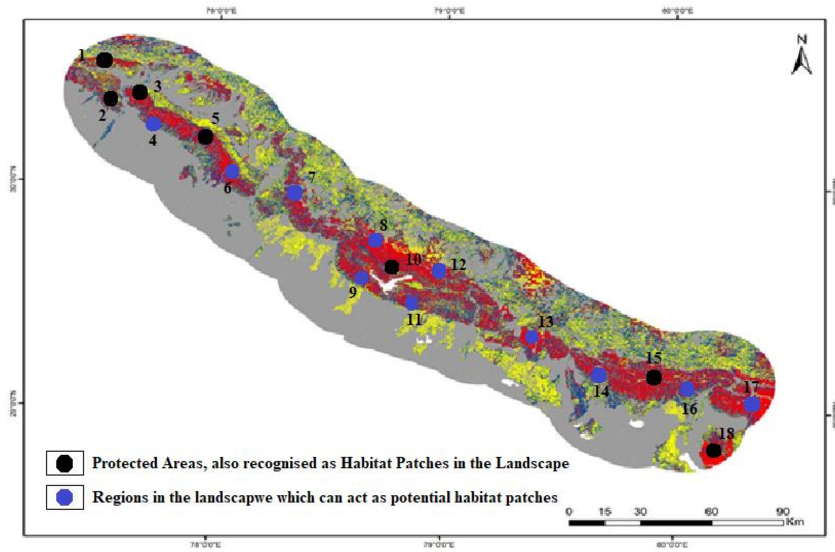


Figure 5-8: Tiger Habitat Suitability Map showing the landscape habitat patches that could support a viable tiger population.

The prospective habitat patches found in the landscape by the HSI calculations comprise both protected areas and other vegetated areas that may serve as potential habitat patches. There must be continuity in the terrain for tigers to travel in the region (Shanu et al., 2019; Taylor et al., 1993). The HSI model's many biotic and abiotic factors help to the protection and management of this contiguity. According to the literature, a tiger's ability to move through the landscape matrix of movement is dependent on the best survival conditions. As a result, to promote tiger mobility, a region inside the landscape matrix must be demarcated, signifying high-sensitivity conservation zones. In order to get the polygons or overlapping communities inside the landscape matrix, the model operates on the network depicted in Figure 5-9, which is obtained by the suitability index of various landscape matrix components.

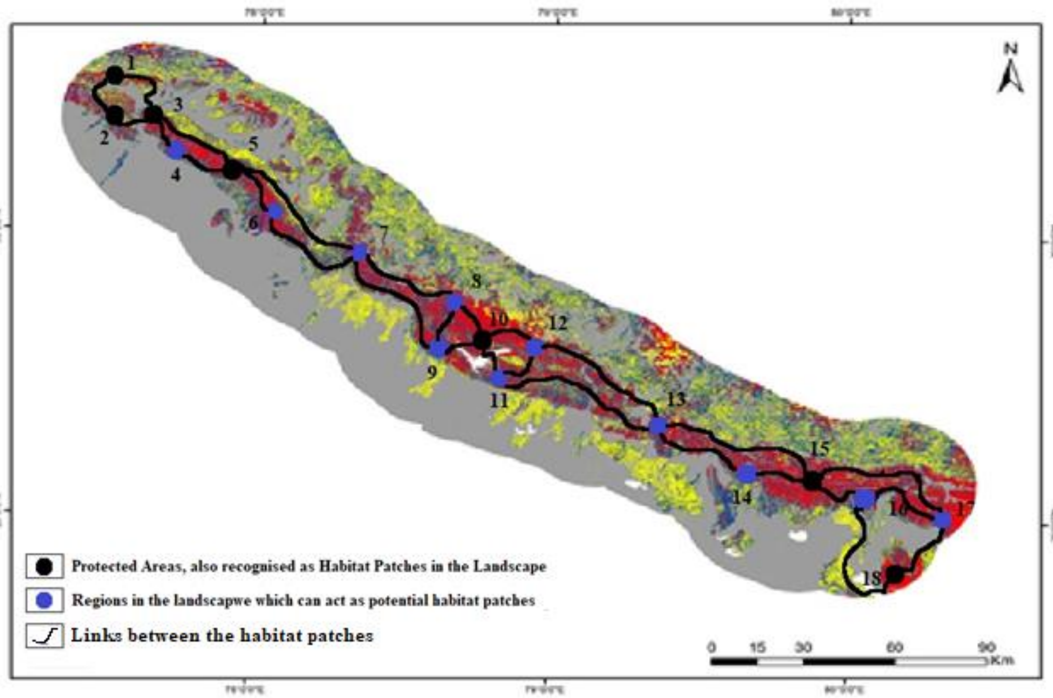


Figure 5-9: Network yielded in the focal landscape, working with the nodes found in Figure 5.8 and using the same HSI model to detect connections between these identified habitat patches.

The HSI-computed suitability values are utilized to identify the adjacencies between the vertices in the tiger corridor network. These values illustrate where smooth interaction, i.e., movement of tigers, exists by exhibiting the appropriateness of terrain between the two vertices. The Adjacency matrix in the landscape generated between the nodes from the resulting network depicted in Figure 5-9 is presented in Table 5-3.

Table 5-3: Adjacency Matrix with respect to the identified habitat patches in the tiger corridor network in Terrai Arc Landscape

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		1	1															
2			1															
3				1	1													
4					1													
5						1	1											
6							1											

7								1	1									
8									1	1								
9										1								
10											1	1						
11												1	1					
12													1					
13														1	1			
14															1			
15																1	1	
16																	1	1
17																		1
18																		

To locate the cliques in the network, the model employs the Algorithm 1 given in the section on Modelling Approach. Table 5-4 displays the established cliques' outcomes as well as the remarks. The cliques in the tiger corridor network represent perfect mutuality. The complete mutuality is crucial since it supplied the background for defining the PC of the vertices and, as a result, the importance of preserving landscape contiguity.

Table 5-4: The Cliques obtained from the Tiger Corridor Network using Algorithm 1

N	**Clique of size n**	**Remarks**
2	{1,2}, {1,3}, {2,3}, {3,4}, {3,5}, {4,5}, {5,6}, {5,7}, {6,7}, {7,8}, {7,9}, {8,9}, {8,10}, {9,10}, {10,11}, {10,12}, {11,12}, {11,13}, {12,13}, {13,14}, {13,15}, {14,15}, {15,16}, {15,17}, {16,17}, {16,18}, {17,18}	The 2-Cliques denote the connection between the nodes, which can be a landscape field.

3	{1,2,3}, {3,4,5}, {5,6,7}, {7,8,9}, {8,9,10}, {10,11,12},{11,12,13}, {13,14,15}, {15,16,17}, {16,17,18}	The 3-Cliques represent the interaction of three nodes within a defined area.
4	{}	Since there are no 4 Cliques, the algorithm comes to a halt here.

To classify potentially critical patches, PC is done on the network using 10 3-cliques. Table 5-5 displays the vertices (habitat patches) ordered by PC ranking (highest to lowest), emphasizing the importance of habitat patches in conjunction with the vertices required for community formation.

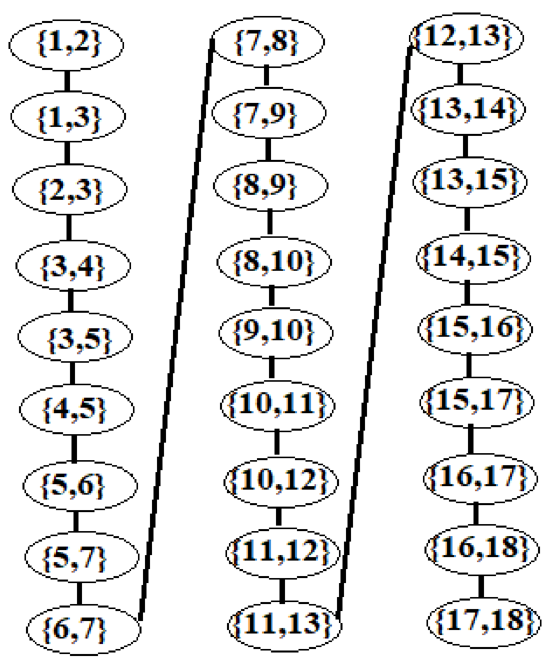
Table 5-5: Ranking of tiger habitats by PC over the 3-cliques

Vertex	PC	Rank
1	1	2
2	1	2
3	2	1
4	1	2
5	2	1
6	1	2
7	2	1
8	2	1
9	2	1
10	2	1
11	2	1
12	2	1
13	2	1

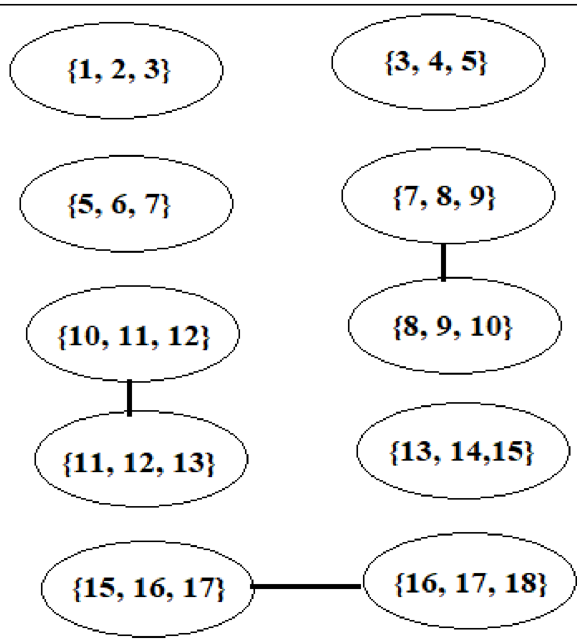
14	1	2
15	2	1
16	2	1
17	2	1
18	1	2

To locate the clique graphs and overlapping communities in the network, utilize the Algorithm 2 given in the section on Modelling Approach. Table 5 displays the findings of the clique graphs and overlapping communities, as well as comments.

Table 5-6: The clique graph and overlapping communities obtained using Algorithm 2

<table>
<tr><th>n</th><th>Clique Graph</th><th>Communities</th><th>Remark</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>

Clique graph of all the 2-cliques in network</td><td>{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14,15, 16, 17, 18}</td><td>This demonstrates that the entire landscape is a single community, and that tigers are free to travel from one habitat patch to the next. The existence of 2-cliques and the community created by 2-</td></tr>
</table>

			cliques also implies that the entire landscape must be contiguous.
3	 **Clique graph of all the 3-cliques in network**	{1, 2, **3**} {**3**, 4, **5**} {**5**, 6, **7**} {**7**, 8, 9, **10**} {**10**, 11, 12, **13**} {**13**, 14, **15**} {**15**, 16, 17, 18}	When model increase our precision over the number of cliques, model see that there are seven main communities, which also reveals the landscape's mesoscale features. This also indicates the critical nodes needed to preserve landscape contiguity for Tiger movement.

The colored (other than black) elements in the "Communities" column of Table 5, shows the essential vertices responsible for community overlap. It is essential to note that in two different communities C_1 & C_2 if $C_1 \cap C_2 \neq \{\}$, then the element of intersection between C_1 & C_2 is shown with same color. For example, within 2 different communities $\{1, 2, 3\}$ and $\{3, 4, 5\}$, the common element *"3"* is shown with red color.

When the landscape level matrix is examined, the findings in Table 5 are depicted in Figure 10, indicating the existence of seven significant communities. The model findings also indicate that there are a few essential habitat patches that are located at the confluence of two separate communities and play a vital role in sustaining landscape continuity as well as overlapping community traits.

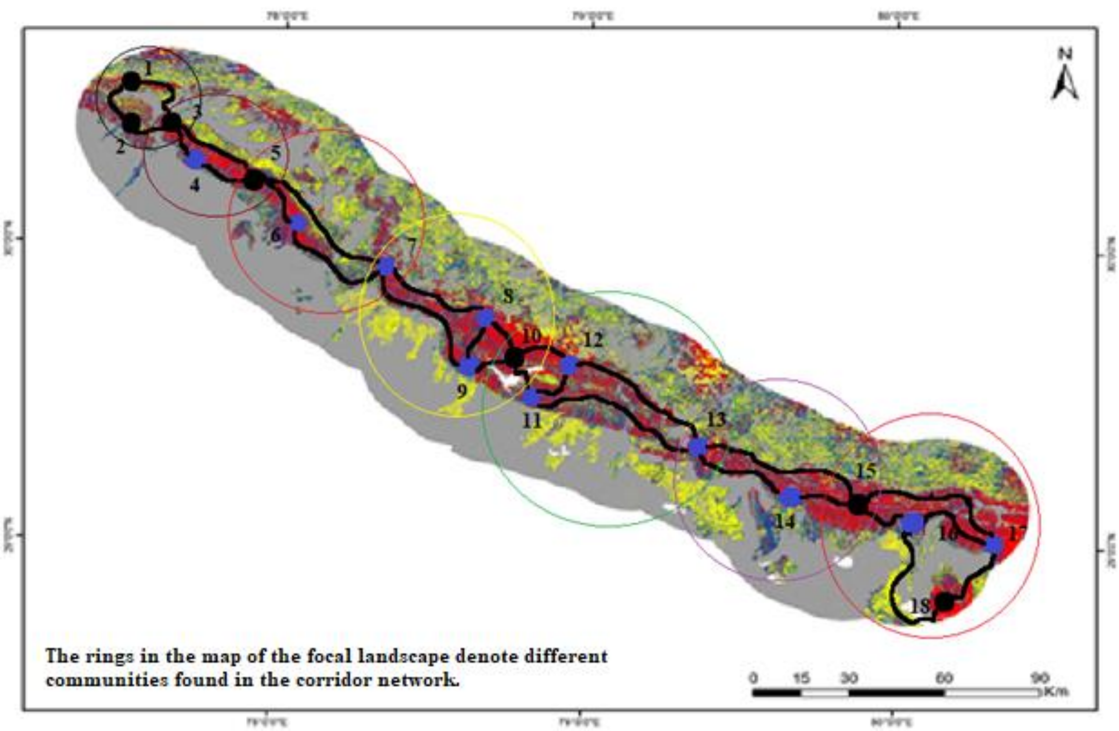


Figure 5-10: Landscape level communities detected in the Tiger Corridor Network

Discussion

Tiger corridors are natural terrain features that allow tigers to move from one habitat patch to another. The wildlife corridor must be ideal in both structural and functional connectivity, according to multiple previous models built using various techniques. Based on the cliques, the findings of this study show that corridors connect habitat patches in a landscape complex, considering all structural and functional elements of habitat appropriateness for tiger mobility. The findings of algorithm 1 also reveal that there can be loops between landscape vertices that diverge from the tiger corridor criterion (Shanu et al., 2019).

The landscape contiguity is one of the most essential aspects in promoting tiger migration in a landscape. Tigers, being specialized animals, require a continuous line of travel that serves all of their survival and mitigation needs (Jhala et al., 2018). Thus, in order to create and build tiger corridor networks, landscape contiguity must first be identified. The notion of overlapping communities was used to discover landscape contiguity. The methodology suggested in this study employs algorithm 2 to identify essential overlapping communities in the CPM-generated tiger corridor network. The overlapping communities in the network are derived from habitat patches both inside and outside of the PAs. The overlapping communities show the importance of a few vertices in maintaining the continuity of the landscape.

Even though tiger conservation is emphasized in protected areas throughout their range nations, the species is known to frequent forests and neighboring landscapes with varied levels of protection (Nitin et al., 2018). The once-forested Terai tract is now predominantly agricultural, with animals restricted to residual forest patches (Baral et al., 2022). The analysis of habitats for animal sustenance is becoming increasingly important for protected area development and administration. The effects of habitat loss and fragmentation, which are anthropogenically changed and impacted by landscape design, have a direct impact on the size, shape, and format of habitat fragments (Frankham, 2003). With rising habitat fragmentation and shrinking habitat size, it is vital to establish spatial databases on habitat quality, which is critical for habitat protection. Without thorough ground-based knowledge on their physiology and behaviour, geospatial modelling can considerably aid in spatial modelling of habitat suitability for faunal species. Ecological methods are extraordinarily complicated and difficult to anticipate if they impact species abundance or distribution (Altieri & Letourneau, 1982).

The identification of LULC and plant types, as shown in Table 5-1, Figure 5-4, and Figure 5-5, was useful since it highlighted the geographical zones that must be taken into account when evaluating tiger dispersals. As a result, a network based on habitat patches, linkages between habitat patches, and the contained area by the links gives an accurate estimate of the landscape's tiger corridors. Furthermore, the HSI model and data clustering indicated a few habitat patches that are not protected areas but can act as beneficial landscape components for tiger populations to grow. With the PAs, these ecological patches have also been considered vertices in the landscape.

The high rank vertices designated by PC are the critical vertices responsible for maintaining vertices interaction and consequently community formation in the network. The rankings between the vertices shown in Table 5-5 serve in determining the vertices that are crucial for sustaining landscape contiguity with overlapping communities. With the use of HSI assessed for tigers in the focus landscape, the model can locate the most essential habitats as the vertices of the tiger corridor network.

Figure 5-10 displays the mentioned settlements' schematic location on the terrain. The fact that all of the communities overlap on one or both dimensions is an important discovery in Figure 10. The overlapping of communities is caused by the communities sharing just one vertex, since the largest clique contained in the work is a 3-clique. These mutual vertices are known as key vertices or Critical habitat Patches, and they help to maintain landscape continuity in order to support tiger mobility. As a result, the preservation of these vertices is crucial, both environmentally and in terms of landscape design. Table 5-7 shows the critical vertices for the derived tiger corridor network and landscape.

Table 5-7: Essential Vertices of Overlapping Communities and Related Information

Vertex Number	**Vertex Name**	**Protected Area**	**Potential Habitat**
3	Kalesar National Park	Yes	Yes

5	Rajaji Tiger Reserve	Yes	Yes
7	Kortdwar Forest Division	No	Yes
10	Corbett Tiger Reserve	Yes	Yes
13	Haldwani Forest Division	No	Yes
15	Nandhaur Wildlife Sanctuary	Yes	Yes

This study used the Tiger Report 2018 to confirm the accuracy of a spatially explicit tiger density model. The report included a map of the Terai Arc landscape within India's political boundaries, which was extracted and digitized with respect to the latitude and longitude of the focal region. The map was then superimposed to place grids on the extracted map and the corridor network map, which was obtained using the proposed model. A matrix was created corresponding to each image, indicating the presence/absence of tiger population within each grid. The occupancy map of the report and the results of the proposed model are shown in Tables 8 and 9, respectively. The accuracy of the model was confirmed using the extracted map and grids.

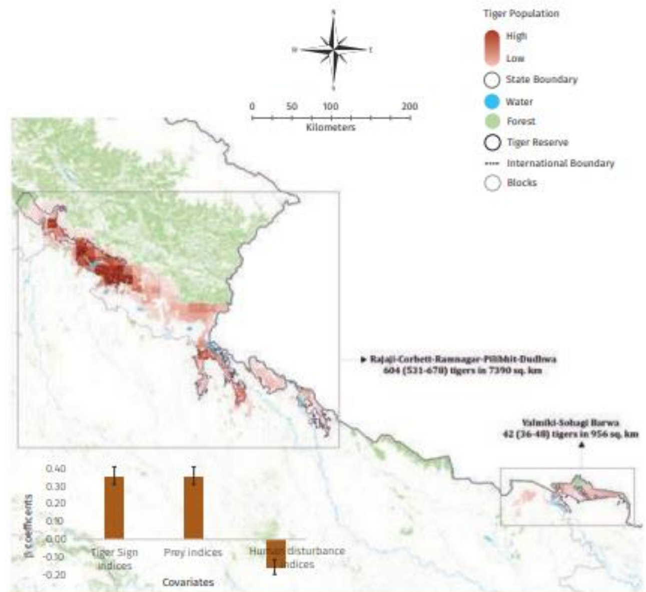


Figure 5-11: Map obtained from the Tiger Report 2018, highlighting the presence/absence of tigers in the focal region (Jhala et al., 2020).

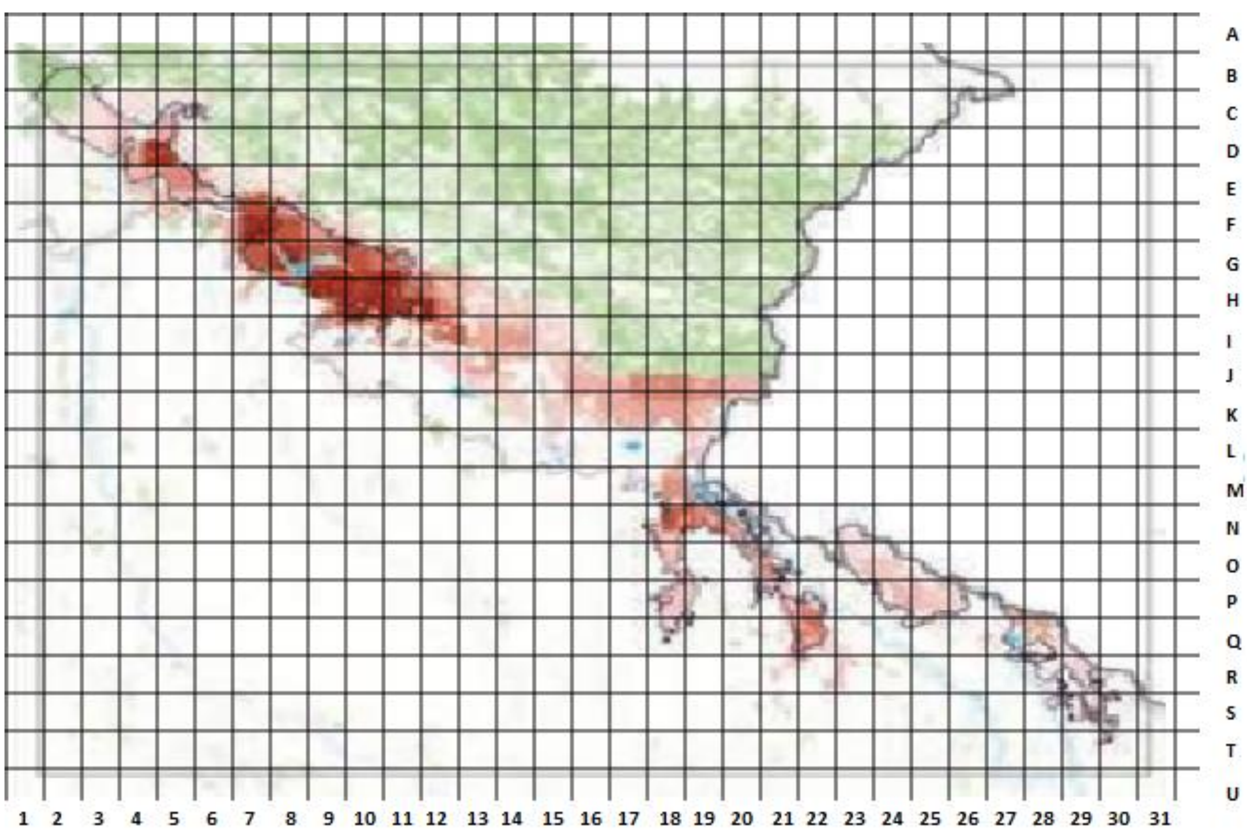


Figure 5-12: Set of grids overlaid on the focal region after digitizing from Figure 5-11.

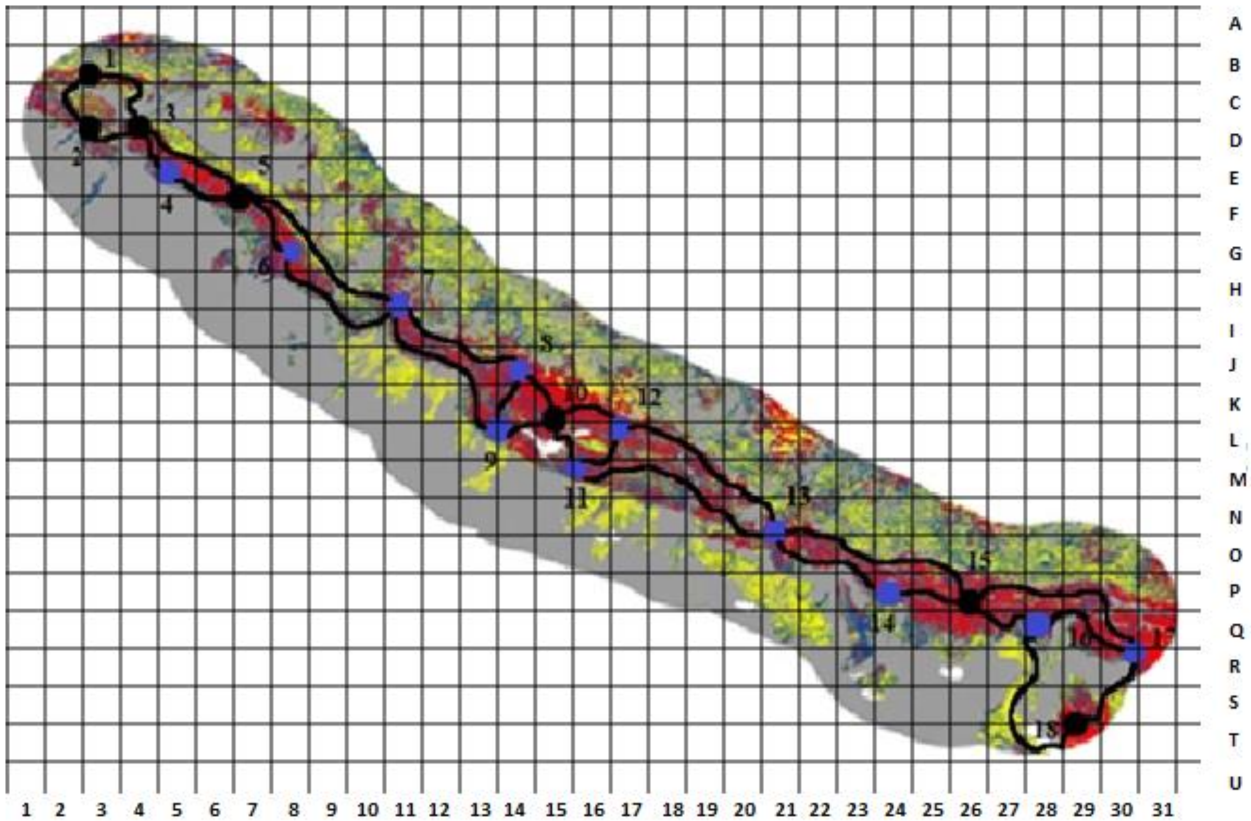


Figure 5-13: Set of grids overlaid on Results obtained through proposed model

Table 5-8: Matrix O, constructed using Figure 5-12 where "1" shows presence of tiger and "0" shows absence of tiger.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
A	0	0	0	0	0	0																									
B	0	1	1	1	1	0																									
C	0	1	1	1	1	1	0																								
D	0	1	1	1	1	1	1	0	0																						
E	0	0	0	1	1	1	1	1	1	0	0																				
F			0	1	1	1	1	1	1	1	1	1	0	0	0																
G				0	0	1	1	1	1	1	1	1	1	1	0	0	0														
H						0	1	1	1	1	1	1	1	1	1	1	0														
I							0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0									
J									0	0	0	1	1	1	1	1	1	1	1	1	1	0									
K										0	0	0	1	1	1	1	1	1	1	1	0	0									
L											0	0	0	0	1	1	1	1	1	0	0	0									
M												0	0	0	0	0	1	1	1	1	0	0	0	0	0						

N													0	0	0	0	0	1	1	1	1	0	1	1	0	0	0	0	0	0	0
O														0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0
P															0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Q																0	0	1	1	0	1	1	0	1	1	0	1	1	1	0	0
R																	0	0	0	0	1	1	0	0	0	0	1	1	1	1	0
S																		0	0	0	0	0	0	0	0	0	0	1	1	1	0
T																			0	0	0	0	0	0	0	0	1	1	1	1	0
U																															

Table 5-9: Matrix E, constructed using Figure 5-13 where "1" shows presence of tiger and "0" shows absence of tiger.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
A	0	0	0	0	0	0																									
B	0	1	1	1	1	0																									
C	0	1	1	1	0	1	0																								
D	0	1	1	1	1	1	1	0	0																						
E	0	0	0	1	1	1	1	1	0	0	0																				
F			0	1	1	1	1	1	1	1	1	1	0	0	0																
G				0	0	0	0	1	1	1	1	1	0	0	0	0	0														
H						0	0	1	1	1	1	1	1	1	1	0	0														
I							0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0									
J									0	0	1	1	1	1	1	1	1	1	1	1	0	0									
K										0	0	0	1	1	1	1	1	1	1	1	0	0									
L											0	0	1	1	1	1	1	1	1	1	0	0									
M												0	0	0	1	1	1	1	1	1	1	0	0	0	0						
N													0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0
O														0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0
P															0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	0
Q																0	0	0	1	0	1	1	0	1	1	1	1	1	1	1	0
R																	0	0	0	0	1	1	0	0	0	0	1	1	1	1	0
S																		0	0	0	0	0	0	0	0	0	1	1	1	1	0
T																			0	0	0	0	0	0	0	0	1	1	1	1	0
U																															

Two methodologies were used to determine the accuracy of a proposed model after obtaining images and constructing matrices. The first involved superimposing the images and determining accuracy through pixel overlaps. The second method involved comparing observed and expected matrices using grid overlaps and calculating the percentage of accuracy. The grid overlaps between the O and E matrices were calculated, and 24 out of 259 grids did not match, indicating that the proposed model is 90.73 percent accurate.

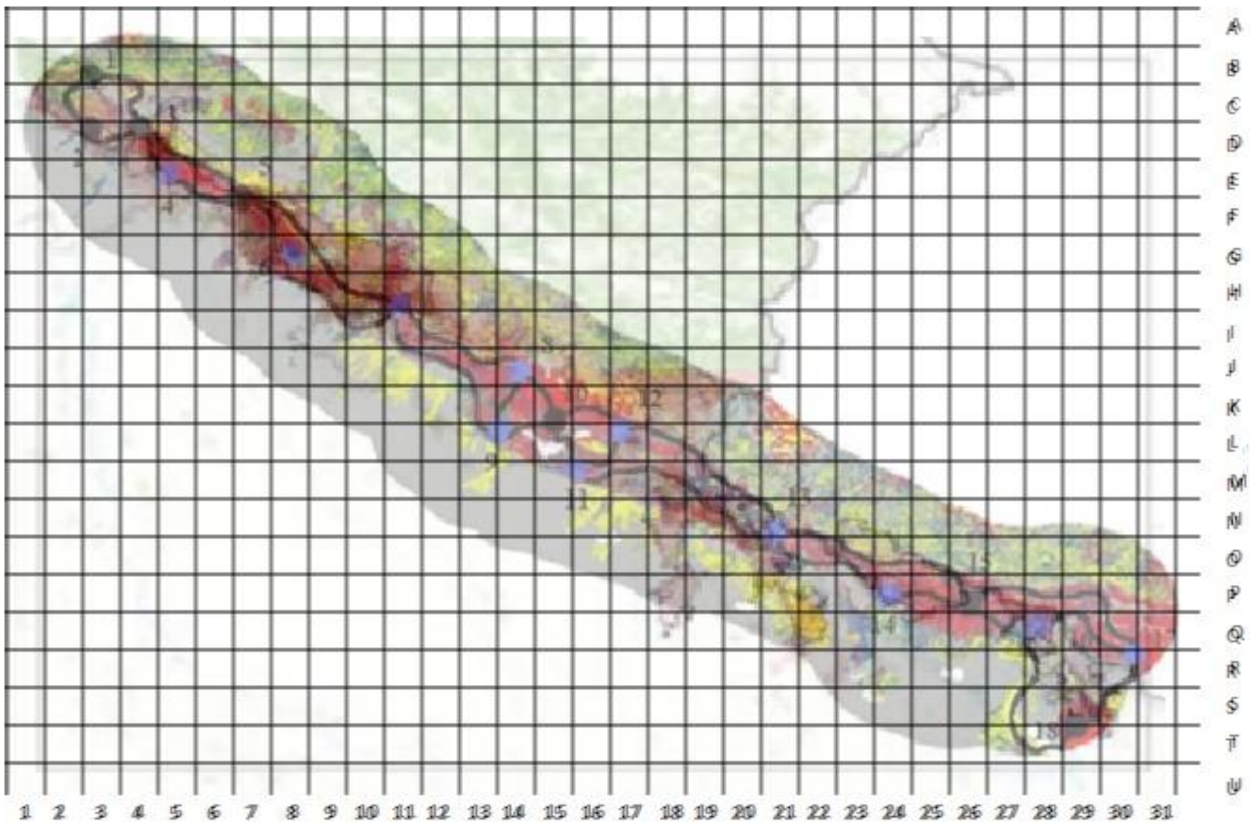


Figure 5-14: Superimposition of images to obtain the accuracy proposing 85.06% overlap.

Table 5-10: Difference between observed and expected Matrices (O - E), where "1" in the grids denotes that there exists a difference between the report map and the map obtained through proposed model.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
A																															
B																															
C					1																										
D																															
E									1																						
F																															
G						1	1						1	1																	

H							1									1															
I																	1														
J											1										1										
K																															
L													1	1						1											
M															1	1					1										
N																						1									
O																															
P																				1									1	1	
Q																		1								1				1	
R																															
S																											1				
T																															
U																															

Conclusion

The study's goal was to use the CPM to generate an appropriate tiger corridor network in the focus area. To achieve the goal, the following steps were taken: (i) obtain a tiger HSI in the Terai Arc landscape, (ii) use a computational approach to extract a tiger corridor network connecting different habitat patches (both PAs and potential habitat) in the landscape complex, and (iii) identify the most critical habitat patches and their underlying overlapping communities to focus conservation efforts on them.

The CPM was used to identify overlapping groups of habitat patches that sustain tiger populations and migration in the Terai Arc landscape complex. These overlapping communities are generated using clique graphs, which are built up of cliques produced from the investigation and study of habitat patch interactions. The HSI is one of the most extensively utilized methods for analyzing the landscape for habitats that support tiger populations and investigating connections between chosen habitat patches.

In comparison to the techniques of tiger conservation planning, GIS and Remote Sensing in combination with Network Analysis allows us to combine multiple geographical data and generate a spatial picture of the problem (Cantwell and Forman, 1993; Gastner and Newman, 2006). The integration of GIS allows us to manage spatial data across a vast region, and the capacity to integrate and analyze numerous spatial and non-spatial data sets is a significant step forward in understanding not just habitats but also the entire ecosystem of protected areas. The conservation strategy's main purpose is to identify potential tiger habitats and simulate the interplay of these habitat patches as tiger corridor linkages. The term "habitat patch" refers to locations outside of protected zones where tigers may dwell without interacting with human-dominated matrix, allowing tiny populations to establish metapopulations. The use of CPM assists us in obtaining the overlapping communities in the landscape produced by the tiger corridor network established by HSI, which is a crucial discovery of this work. Critical Habitat Patches in the terrain enable all populations to congregate.

The Tiger Habitat Suitability Map demonstrates that much of the Terai arc terrain has prospective tiger habitats, and it serves as a basis for connecting these patches, which have been calculated as a corridor network. The application of PC to the tiger corridor network has resulted in the establishment of twelve large habitat patches, which help in the preservation of interaction between vertices as well as cliques, and therefore the formation of key communities. In addition to the six most essential habitat patches have been discovered in the landscape through overlapping communities, all of which are vital to sustaining the landscape's continuity.

The findings and approach suggested by completion of this objective for identifying crucial landscape components using network analysis will be useful in building future conservation plans in the focus landscape and any other landscape of conservation concern.

Objective 2.1:

To create an algorithm and thus a function which would work on the interactions of all parameters to find the best paths to be designated as corridors.

All species experience the essential life event of dispersal from their original habitat. A few designated wildlife corridors are where these dispersals from the original region to a new range occur. Therefore, wildlife corridors may be characterized as landscape elements that permit animal dispersal for a variety of ecological purposes (Yumnam et al., 2014). When it comes to a species' life cycle and the ecological objectives that are achieved, it becomes especially species-specific. The corridor can therefore be characterized as being highly species-specific.

The preservation of wildlife corridors and their creation are essential for species conservation, according to several landscape studies and analyses. As aforementioned, since corridors are species-specific, solutions for their conservation and design must be as well. The species addressed in this investigation is the tiger (*Panthera Tigris Tigris*). The objective of this study is to develop a computer model for building wildlife corridors that considers temporal data and its impact on the overall network modelling of tiger corridors (Kshettry et al., 2020). One of the key considerations before developing a conservation strategy is the visualization of data, which would be very helpful in developing policies for landscape level conservation. Using a temporal representation of the data, the method described in this article constructs tiger corridor networks.

It might be argued that computational approaches are needed to simulate Tiger corridors between source and sink habitat regions. Due to the numerous aspects that must be deterministically studied and presented to design tiger corridor networks, such a computational method is necessary. These models also emphasize the important factors that ecologists must consider while planning corridors. The work goes through a few important computer science fundamental principles that must be used in such modelling. The model first covers using set theory to eliminate duplicate data, after which it looks at the amount to which certain qualities help or impede tiger mobility in the terrain. The analysis of these components is shown using a matrix form. A tensor representation method has been utilized because the matrix is made up of several additional matrices that were each calculated for a different parameter (Leonard et al., 2017; Romañach et al., 2016). One goal of the tensor approach is to show how temporal variations in landscape level data affects parameters, and the dispersal of species in the landscape.

An important study that indicates how the season influences conservation planning strategies in the target area is presented in the article. The results are created by applying three different seasonal settings to the central scene. All three seasons show how various seasons impact the curvature and geodesic distance of tiger dispersal. The study concludes that it is unsuccessful to create wildlife corridors just using GIS and remote sensing and that field research is necessary to create a better corridor model.

The study will aid in the better understanding by policymakers and stakeholders of the crucial components of tiger corridor modelling and monitoring for specific protection. Google Earth was used to map a landscape to show the model's capabilities.

Landscape for Study

The Rajaji National Park in the Indian state of Uttarakhand provided the terrain for this work. Figure 5-15 depicts the area that has been researched for modelling. The green part of the terrain stands in for the forest, while the light cyan water bodies, and grey lines for the highways.

Figure 5-15: Landscape for modelling with Habitat Patch 1 acting as the source habitat patch and Habitat Patch 2 acting as the sink habitat patch for tiger dispersal.

Methodology

Wildlife corridors are particularly species-specific. In order to construct tiger corridor networks in the target area, researchers are looking at the landscape features that either encourage or impede tiger dispersal. F set elements are used to represent the parameters. To deal with parameter duplication and eliminate it altogether, the concept of sets was developed. This serves as a good safeguard against inaccurate forecasts for the model (Biswas et al., 2022).

The model is kept simple and self-contained in this study by just looking at four parameters. Table 5-11 lists the parameters along with their respective encodings and comments.

Table 5-11: Modeling tiger corridor network parameters

Parameter	**Encoding**	**Remark**
Water	F_0	encourages tiger dispersal
Villages	F_1	Impedes tiger dispersal
Forest	F_2	encourages tiger dispersal
Roadways	F_3	Impedes tiger dispersal

Landscape parameter set F can be shown as:

$$F = \{F_0, F_1, F_2, F_3\} \text{ ---(10)}$$

The recommended model's next goal is to determine the size of the grid that divides the terrain after F is constructed. The grids given in this study are squares of length "x" that use "y" grids to completely cover the area "L" as follows:

$$y = L/x\hat{}2 \text{ ---(11)}$$

Landscape grids are comparable to picture pixels. Similar to how a tensor may describe the grid inside a landscape, a tensor can specify the pixels in a color image by specifying its resolution as:

$$|F| \; X \text{ data representing the grid ---(12)}$$

The cardinality of set F is denoted by |F|.

Given that the environment is represented by a set of "y" grids, it is possible to see the dispersed tiger in the scene moving across the grids. Each grid must either promote or restrict the tiger's dispersal. The researchers use the assumption that the presence of any element of F in the grid affects the grid's nature to promote or inhibits tiger dispersal. According to the degree of existence, promoting variables occupancy and inhibitory factors occupancy are determined. As a result, the degree is shown in the landscape as a percentage.

$$deg(F_p) = \text{degree of promoting factor "p"} = ((\text{area occupied by p})/(\text{total area of grid})) \; X \; 100 \text{ ---(13)}$$

$$deg(F_q) = \text{degree of inhibiting factor "q"} = ((\text{area occupied by q})/(\text{total area of grid})) \; X \; 100 \text{ ---(14)}$$

The total degree of a grid is determined by combining the following elements:

$$deg(G_{jk}) = {}^{(|F|-1)}\sum_{(d=0)} deg(F_d) \text{ ---(15)}$$

Each grid would have varying degrees of acceptability for permitting tigers to pass through it, based on the arguments and considerations presented above. By utilizing a similar tensor form as shown in equation (15), the degrees of support offered by a grid for the focus landscape may be described as a suitability matrix. The suitability matrix is a numerical representation of the qualitative characteristics of each grid and each T element, and it may be written as follows:

$$T_{jk} = deg(G_{ik}) \text{ ---(16)}$$

Using the suitability matrix, it is possible to identify the grids that would help tigers disperse from a source site. When the entire procedure described in this section is studied, it becomes clear that the available of parameters plays a vital role in identifying the optimal grids for tiger movement. The parameters depend heavily on the season for which the data is collected. The degree of each parameter's existence is affected by the data resolution, which is crucial. As the level of presence varies, the quantitative value of each grid would vary. The suitability matrix throughout the terrain would change as a result. It is argued that when season changes, the associated grid value vary, so does the curvature of the tiger corridor.

In the findings and discussion section, the present method is used to assess three potential seasons on the same area. In addition to the obtained results, a comparison analysis of shifting control curvatures is also found and presented.

Results And Discussion

The method described in the section above illustrates a crucial aspect of wildlife corridor design. Three separate seasons' data—winter, summer, and rainy—are applied to the ecosystem under examination. A sample of satellite-generated data was used to produce the data for this work's proposal of a computational model.

The outcomes of the preceding approach are shown in Figures 6-12, 13, and 14. Figure 5-12 displays the outcomes of using the model to analyze data from the summertime landscape. The results for the rainy season and the winter season are shown in Figures 6-13 and 6-14, respectively.

It is important to note that the conclusions reached are predicated on the idea that a dispersed tiger from Habitat Patch 1 must traverse the smallest geodesic distance to get to Habitat Patch 2.

The parameters listed in Table 5-11 are used as input for each form of data resolution, and the degree of their existence is calculated using equations 14 and 15. This illustrates how much inhibition or assistance for tiger movement occurs in each grid. The numbers differ for each resolution type, as the net area of a landscape feature in a region decreases as the resolution increases.

Each type of season uses the characteristics mentioned in Table 5-11 as input, and equations 16 and 17 are utilized to determine the extent of their presence. This demonstrates the degree to which each grid inhibits or facilitates tiger dispersal. Since the vegetation cover, land use land cover and biotic features of a landscape change with season, the figures vary for each season type.

In the collection of figures illustrating the model results, the yellow arc indicates the discovered tiger corridors, while the red circles represent habitat patches.

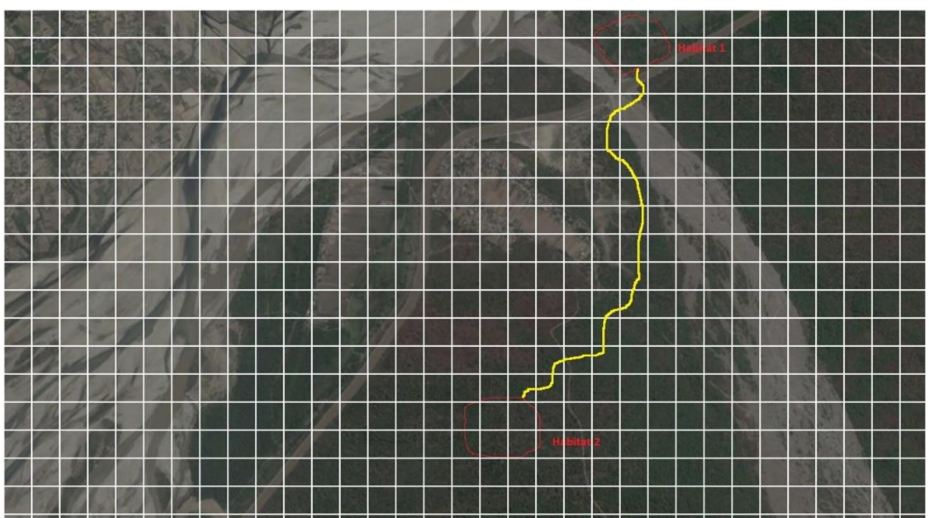


Figure 5-16: Tiger dispersal corridor, applying the model in the summer and getting the tensor over the terrain to go from Habitat Patch 1 to Habitat Patch 2.

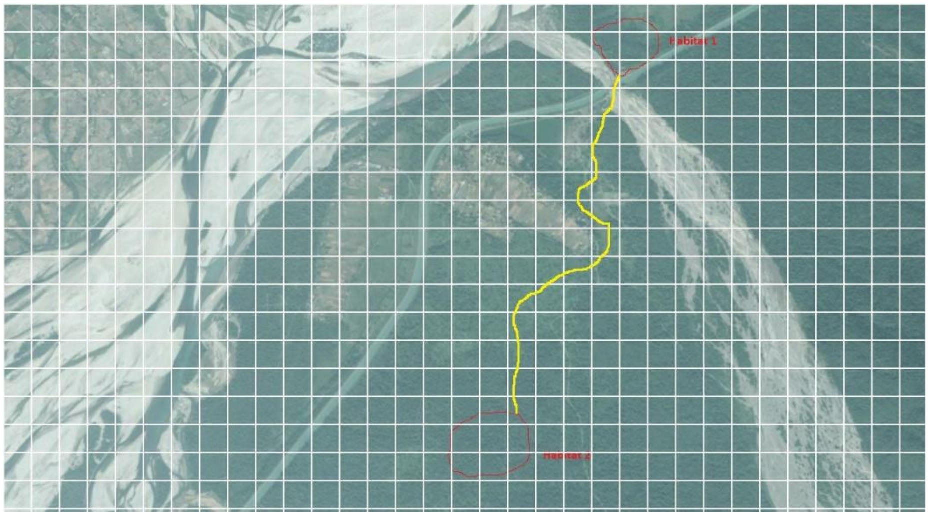


Figure 5-17: Tiger dispersal corridor, applying the model in the rainy and getting the tensor over the terrain to go from Habitat Patch 1 to Habitat Patch 2.

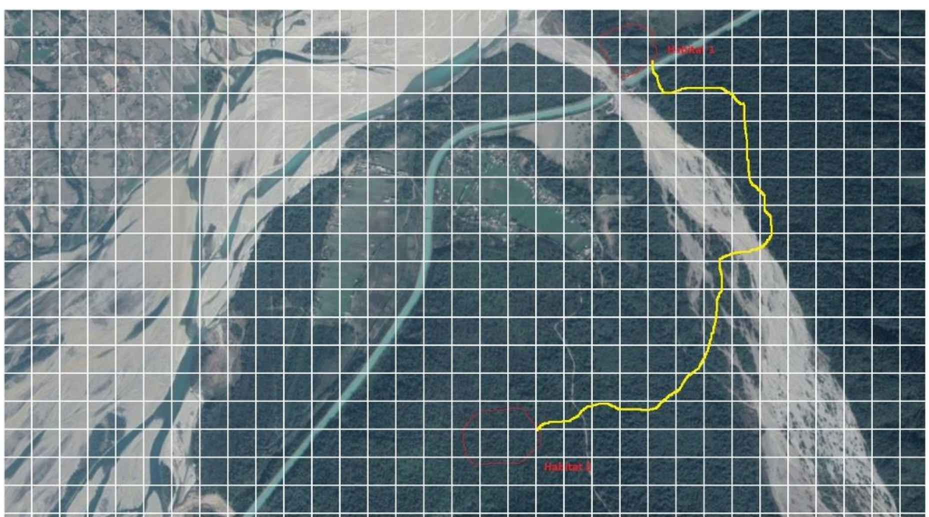


Figure 5-18: Tiger dispersal corridor, applying the model in the winter and getting the tensor over the terrain to go from Habitat Patch 1 to Habitat Patch 2.

To model Tiger corridor networks in a specific terrain, it is necessary to properly understand and analyze a few essential characteristics that the research has shown. The results show that when the seasons change, both the total geodesic distance and the curvature of the route alter. Therefore, based on temporal modelling, a more accurate model for creating tiger corridor networks may be created with more alternative corridors. It also implies that field research, GIS, and remote sensing data may be used to provide the best modelling for wildlife corridor networks.

One of the article's most important findings also implies that when the seasons change, it would be possible to explore dispersing species' perspectives more thoroughly. In this study, a unique feature of data encoding in tensor form is introduced. This feature may help to reduce the computational complexity of data analysis needed to construct Tiger corridor networks by reducing the net time and space complexity.

Conclusions

The results were obtained by applying very elementary Tiger dispersal logic. One may argue that the actual movement would be far more intricate and include the consideration of many more factors. The suggested model is distinctive in that it offers a basic computational framework for simulating tiger corridor networks using the tensor approach to data representation. If the model was built using real GIS and Remote Sensing data, it may be more effective and yield better results.

The recommended technique stresses the need for seasonal data variance in modelling wildlife corridor networks. The importance of wildlife corridor networks in preserving species should not be understated. The proposed model also suggests that temporal data should be considered when analyzing wildlife corridor networks. The results of this study show how the curve of tigers' dispersals may change depending on the season. These variations of curvature can be quite useful in figuring out how tigers move around the terrain. The research also shows that field data should be used to support corridor design in addition to GIS and remote sensing data. One of the work's primary conclusions is that field research is crucial for comprehending species dispersal patterns and for studying the topography to develop corridor networks.

Objective 2.2:

To create an algorithm and thus a function which would work on the Spatial resolution of data to find the best paths to be designated as corridors.

Dispersal of a species from its native area is a crucial life event for all species. These dispersals from the native area to a new range take place along some designated wildlife corridors. As a result, wildlife corridors can be defined as landscape components that allow the movement of animals for diverse ecological goals. It becomes particularly species-specific when it comes to the lifecycle of species and the ecological goals that are served. As a result, the corridor can be described as very species-specific (DeMatteo et al., 2017).

Various landscape research and analysis show that protecting and creating adequate wildlife corridors is critical for species conservation. As previously stated, because corridors are species-specific, corridor conservation and design solutions must be species-specific as well. Tigers *(Panthera Tigris Tigris)* are the species that have been targeted in this work. The goal of this research is to develop a computational model for creating wildlife corridors that considers data resolution and its influence on overall tiger corridor network modelling. The depiction of data, which would be highly useful in creating policies for landscape level conservation, is one of the crucial factors before strategizing for conservation. The technique presented in this study creates tiger corridor networks using a tensor representation of landscape data (Han et al., 2011).

It might be claimed that modelling Tiger corridors between source and sink habitat areas requires computational methodologies. The requirement for such a computational technique is because there are several factors that must be deterministically analyzed and presented to construct tiger corridor networks. Such models also highlight the criticals that ecologists must consider while designing corridors. The study discusses a few key computer science foundation aspects that must be applied to such modelling. Initially, the model discusses utilizing set theory to remove data duplication, and then it examines the extent to which various characteristics contribute to supporting or hindering tiger movement in the terrain. A matrix representation is used to depict the analysis of these factors. Because the matrix is a mixture of multiple other matrices derived for each parameter, a tensor representation technique has been used. One of the reasons for using the tensor technique is to demonstrate how data, parameters, and the flow of species in the landscape are all affected by data resolution.

The section presents essential research that demonstrates how resolution affects conservation planning tactics in the focus landscape. Three distinct resolution settings are applied to the focus landscape to produce the results. All three resolutions demonstrate how the curvature and geodesic distance of tigers' movement are affected by resolution. As a result, the study concludes that simply using GIS and remote sensing to build wildlife corridors is ineffective, and that field investigations are required to develop a better corridor model.

The research will help wildlife stakeholders and policymakers to better understand the important elements of tiger corridor modelling and monitoring for species protection. To demonstrate the model's functionality, a landscape was created using Google Earth.

Landscape for Study

The terrain used in this piece comes from Rajaji National Park in the Indian state of Uttarakhand. The region that has been investigated for modelling is shown in Figure 5-19. The forest area is represented by the green region in the landscape, water bodies are represented by light cyan, roads are represented by grey lines, and village regions are represented by polygons bordered by grey lines.

Figure 5-19: Landscape for modelling with Habitat patch 1 as the source habitat patch for tiger dispersal and Habitat Patch 2 as the sink habitat patch.

Methodology

Wildlife corridors, as discussed in the preceding sections, are very species-specific. The landscape characteristics that promote or restrict tiger dispersal are studied for the aim of modelling tiger corridor networks in the focal landscape. The parameters are represented as P set elements. The notion of sets was established to cope with parameter redundancy and eliminate any parameter repetition. This is useful for protecting the model against incorrect predictions.

Only four parameters are examined in this study to keep the model basic and self-contained. Table 5-12 shows the parameters with encodings and comments for each parameter.

Table 5-12: Parameters for modelling tiger corridor network

Parameter	Encoding	Remark
Forest	P_0	Supports tiger movement
Water	P_1	Supports tiger movement
Villages	P_2	Inhibits tiger movement
Roadways	P_3	Inhibits tiger movement

Set P of landscape parameters may be represented as:

$$P = \{P_0, P_1, P_2, P_3\} \text{ ---(17)}$$

Following the construction of P, the suggested model's next objective is to determine the grid size by which the landscape is split. The grids presented in this work are squares of length "n" that cover the whole landscape "A" with "m" grids, as follows:

$$m = A/n\text{^}2 \text{ ---(18)}$$

Landscape grids are analogous to pixels in an image. A tensor 3 * 3 resolution of the picture may specify the pixels in a color image, and similarly, a tensor can represent the grid within a landscape as:

$$|P| \; X \textit{ resolution of data representing the grid} \text{ ---(19)}$$

The cardinality of set P is denoted by |P|.

The dispersing tiger in the landscape may be thought to travel across the grids, as the landscape is represented by a collection of "m" grids. The movement of the tiger must be supported or inhibited by each grid. To keep the computational framework simple, the research assumes that the existence of any element of P in the grid determines whether the grid supports or prevents tiger dispersal. The degree of presence indicates how much of the grid is filled by promoting factors and how much is occupied by inhibitory factors. As a result, the degree is expressed as a percentage in the landscape.

$$deg(P_a) = \text{degree of promoting factor "a"} = ((\text{area occupied by a})/(\text{total area of grid})) \times 100 \quad \text{---(20)}$$

$$deg(P_b) = \text{degree of inhibiting factor "b"} = ((\text{area occupied by a})/(\text{total area of grid})) \times 100 \quad \text{---(21)}$$

The overall degree of a grid is calculated by adding all of the factors evaluated as:

$$deg(G_{ij}) = {}^{(|P|-1)}\sum_{(k=0)} deg(P_k) \quad \text{---(22)}$$

According to the above arguments and discussions, each grid would have varying degrees of suitability for allowing tigers to pass across it. The degrees of support provided by a grid for the focal landscape can be expressed as a suitability matrix, using an analogous tensor form as indicated in equation (xxii). The suitability matrix is a numerical representation of qualitative aspects of each grid, and each element of the S, the suitability matrix may be expressed as:

$$S_{ij} = deg(G_{ij}) \quad \text{---(23)}$$

The grids that would facilitate the tiger dispersal from a source point are identified using the suitability matrix. The whole process presented in this section may be examined, and it can be shown that most of the work involved in determining the best grids for tiger movement is dependent on data resolution. Data resolution is critical since it affects the degrees of presence of each parameter. The quantitative value of each grid would alter as the degree of presence changes. As a result, the suitability matrix throughout the landscape would shift. The curvature of the tiger corridor is argued to fluctuate with a change in net resolution and the accompanying grid value.

Three possible resolutions on the same landscape are examined with the current technique in the results and discussion section. A comparison analysis of shifting control curvatures is also discovered and reported in addition to the acquired results.

Result and Discussion

The technique outlined in the preceding section highlights a key feature of wildlife corridor design resolution. The process is applied to the environment under consideration with three distinct resolutions: 10 X 10, 5 X 5, and 3 X 3 square units. The data has been constructed for proposing a computational model in this work and is not satellite generated.

Figures 5-20, 5-21, and 5-22 depict the results of the preceding technique. Figure 5-20 shows the results of applying the model to a grid of 10 X 10 square units. Figures 5-21 and 5-22 depict the findings for 5 X 5 square units and 3 X 3 square units, respectively. It should be emphasized that the findings produced are based on the premise that the dispersing tiger from Habitat Patch 1 must travel the shortest geodesic distance to reach Habitat Patch 2.

The parameters listed in Table 5-12 are used as input for each form of data resolution, and the degree of their existence is calculated using equations xxiii and xxiv. This illustrates how much inhibition or assistance for tiger movement occurs in each grid. The numbers differ for each resolution type, as the net area of a landscape feature in a region decreases as the resolution increases.

The red circles in the collection of images explaining the model findings signify habitat patches, while the yellow arc denotes the obtained tiger corridors.

*Figure 5-20: Dispersal corridor for tiger, dispersing from Habitat Patch 1 and reaching Habitat Patch 2 using the model with a resolution of 10*10 sq. units and obtaining the tensor over the landscape.*

*Figure 5-21: Dispersal corridor for tiger, dispersing from Habitat Patch 1 and reaching Habitat Patch 2 using the model with a resolution of 5*5 sq. units and obtaining the tensor over the landscape.*

*Figure 5-22: Dispersal corridor for tiger, dispersing from Habitat Patch 1 and reaching Habitat Patch 2 using the model with a resolution of 3*3 sq. units and obtaining the tensor over the landscape.*

The foregoing findings reveal a few key facts that must be fully grasped and investigated to model Tiger corridor networks in a focused landscape. As can be observed from the findings, the overall geodesic distance as well as the curvature of the path reduces as the precision of data resolution increases. As a result, a more realistic model for building tiger corridor networks might be developed with increased resolution. It also suggests that the optimal modelling for wildlife corridor networks might be accomplished by combining field investigations with GIS and remote sensing data.

A crucial finding of the article also suggests that with higher data precision, the perspective of dispersing species might be better examined. The work introduces a novel feature of encoding data in tensor form, which may aid in decreasing the net time and space complexity related with the computational parts of data analysis to be provided for modelling Tiger corridor networks.

Conclusion

The findings were produced utilizing extremely basic Tiger dispersal logic. It may be argued that the real movement would be far more complex, including the examination of many more criteria. The proposed model is unique in that it presents a fundamental computational foundation for modelling tiger corridor networks utilizing the tensor approach to data representation. The model may be more promising and produce better results if it was based on actual GIS and Remote Sensing data.

For modelling wildlife corridor networks, the suggested method emphasizes the necessity of data resolution. Wildlife corridor networks are an important part of species protection and should be well researched. The suggested model also implies that while studying wildlife corridor networks, data resolution should be considered. The findings of this study demonstrate how data resolution might alter the curve of tiger's movement. These curvature gradients can be quite helpful in determining how tigers travel over the landscape. The analysis also demonstrates that corridor design should not just rely on GIS and Remote Sensing data but should also be backed up by field evidence. As a result, one of the work's main conclusions is that field research is essential for understanding species migration patterns and analyzing the terrain to create corridor networks.

Objective 3:

To create a machine intelligence approach which would help in the identification of the changes in LULC (Land Use Land Cover) and deduce the correct corridor design measures.

Many species' individuals spread from one habitat patch to the next for a variety of causes, including ecological variables and human disruptions (Fourcade, 2016). Dispersal outside of a species' natural range is a common occurrence and an important element of their life cycle (Montero-Pau and Serra, 2011). Depending on the terrain features of each focal landscape complex, such dispersals may be inhibited or facilitated. It is vital to understand the interaction of the species with the underlying landscape elements to research these dispersals, the possibility of dispersal, and dispersal patterns of individuals of various species.

Natural species dispersal happens in the wild. Species spread from their home region to another to avoid inbreeding, regulate food chain pressure, and retain other ecologically relevant aspects within the focal landscape (Bulte and Damania, 2008). As a result, species dispersal is a critical feature of nature that is required to maintain equilibrium among numerous phenomena and, as a result, to preserve ecological balance (Holloway and Miller, 2017). It might happen within a single Protected Area (PA) or across many PAs. Because both dispersals are virtually the same, they have a common ancestor. Cooperations, defections, support, and multilayer conflicts may occur in any focal landscape, facilitating or impeding species spread (Egyed and Grunbacher, 2004).

Landscape complexes exhibit a wide range of dynamic biotic and abiotic characteristics. These characteristics combine to generate a set of components that interact with the dispersing species and provide it with support on a positive or negative scale (Rsted et al., 2017). Individual dispersal of a species is thus an emergent process emerging from interaction with the landscape complex. Furthermore, each parameter interacts differently with various species, and each species receives a varied measure of support or inhibition. As a result, a species' movement and mobility patterns within a landscape may be argued to be unique to that species (Chassagneux et al., 2019). For example, the existence of a big chital *(Axis axis)* population in any landscape grid may not enable the mobility of an elephant *(Elephas maximus)*, while the dispersal of a tiger *(Panthera tigris tigris)* may. The preceding section illustrates how each species interacts with landscape variables in a distinctive manner, resulting in species-specific dispersal patterns in any focus area.

The goal of this study is to find and analyze tiger distribution patterns in a habitat with numerous important components of any terrain. The tiger is the main attraction. Following the life event models of tigers, such a model would need to comprehend why an individual disperses beyond of their natal range, which would be a critical goal. The knowledge gained regarding the cause for migration may be used to fulfil the expectations and desires of a dispersing tiger (Damodaran, 2007). These requests might possibly be recreated in order to learn more about the dispersing tiger's movement behaviour.

One approach to achieving the goal is to first split the terrain into equal-sized grids. As a result, each grid serves as a component of the landscape's matrix. The interactions in each grid are then simulated to generate a cost surface that is superimposed over the landscape matrix, yielding scores for each grid indicating whether it favors or hinders tiger movement across it. (Jones and Kaiser, 2005).

The primary purpose of this study is to propose a basic computational framework for better understanding and forecasting tiger distribution patterns in any area. Understanding these patterns can offer enough information on how tigers distribute in various sorts of settings. Knowing when, how, and where the tiger will disperse may provide many wildlife stakeholders with a foundation for designing and preparing conservation plans. An effective technique may be highly beneficial in minimizing various unlawful activities like poaching, hunting, and so on, as well as human-animal conflict in the dispersal landscape, resulting in greater species conservation. Cognitive definitions of a dispersing tiger's demands and the presence or absence of landscape quality in every grid of the landscape matrix complement the assertions stated in this study (Brady et al., 2009). As a result, the basic landscape structure influences every interaction.

The challenge of knowing tiger distribution patterns in a landscape is tackled as a cost allocation problem in this article. Dispersal weights are then used to integrate the reason why tigers depart from their original environment. The dispersal weights are determined by a cognitive evaluation of tiger needs based on dispersal causes (Kacprzak, 2019). It displays the dispersal coefficient for each landscape parameter, illustrating how much each property influences the cost distribution of the grid. Additionally, using a two-player prisoner's dilemma game, model the interaction of each attribute, and the payoffs are blended with the dispersal coefficients to offer a cost to each grid. The presence or absence of larger dominant tigers (henceforth called as co-predators in the work) in the grids is one of the most critical and changeable characteristics of the environment that impacts tiger dispersal (Cho, 2014). Only a few hardbound ratings are supplied, and the existence of co-predators is identified based on relative strengths, resulting in a secondary cost factor throughout the landscape

(Reddy et al., 2012). The final cost matrix for the full landscape complex is created by combining the initial matrix and secondary cost elements.

Several theories and strategies for building wildlife corridors have emerged in recent decades. The two well-known and widely accepted strategies for establishing wildlife corridors are based on either circuit theory or the Minimum Spanning Tree concepts. The theories both support and persuade the question, "What could be the best path that would support species movement in a given landscape?" They also advocate utilizing a comprehensive topography dataset and researching animal habitats to assist create dispersal corridors. They operate by detecting the presence or absence of focus characteristics in any landscape grid. Furthermore, animals are not required to go just along the corridors that have been built. Subject to availability and satisfaction of biological demands, animals may migrate over the terrain via routes that essentially do not capture the qualities of the most optimal corridors according to the design principles of the relevant theories. Field investigations demonstrate that dispersing animals abandon the corridors, implying that the two recommended corridor design solutions listed above do not account for all routes accessible to animal dispersal. The proposed solutions also fail to explain or react to problems about the behaviour of species in and around the corridors, which consider both the resident territorial populations in the landscape and the satellite tiger population in the region. The method presented in this paper gathers the importance of landscape features that are present or absent in each grid for cost estimation. As a result, a more practical and exact way of creating cost surfaces is created. The proposed model also takes into account co-predators, which is something that previous research has overlooked. Furthermore, the present model advises considering local movement and direction for dispersal rather than scanning the entire graph, which may not be the shortest but properly catches species departure from their goal path and then defines the important routes.

The following arguments ignore any real-world data obtained by a GIS technique and a normal field study. Because it focuses on the existence or absence of qualities in various grids in the complex and the ease of migration, the findings might serve as a model for conservationists and wildlife managers to employ when making judgements about tiger distribution patterns.

The next part lays the groundwork for the work's materials and methodology, and the hypothetical landscape that was utilized to develop and assess the mathematical model given in this study is detailed in further detail. Finally, the methodology for the study is discussed, and the remainder of the work is devoted to the study's findings, analysis, and conclusion.

Matrices, Dispersal Weights, and Game Theory

Using a few areas of mathematics, the current study proposes a model for realistic cost allocation for distributing tigers in a complicated landscape. This section discusses the essential principles of numerous disciplines in order to make the work self-contained.

Matrix: A matrix is a set of rows and columns with the same number of entries. Formally, a matrix's element arrangement is represented as follows:

$$A = \begin{bmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{bmatrix}_{mXn}$$

where the elements of the matrix A_{mXn} is denoted as $a_{ij} | \; i \, \epsilon \, \{1, 2, 3, \dots, m\}$ & $j \, \epsilon \, \{1, 2, 3, \dots, n\}$ and the order of the matrix is mXn, which signifies that there are m rows and n columns in the matrix (Pfaffel and Schlemm, 2012). The landscape is structured as a matrix with grids as its elements.

Dispersal Weights: The term "dispersal weight" refers to a set theoretic technique to ordering the components of any given set based on their probability and needs, as proposed in this work (Gutman, 2021). For a given set $A = \{a_1, a_2, \; a_3, \dots, a_n \}$ and a given set of parameters $B = \{b_1, b_2, b_3\}$ for deciding the importance of each element in A, the Dispersal weight M is given as:

$$M = rank(a_i) | \; a_i \epsilon \; A, \text{ where, } rank(a_i) = \; a_{i_{(b_1 \odot b_2 \odot b_3)}} | \; \odot \Rightarrow$$
$$operartion \; between \; elements \; of \; B. \text{ ---(24)}$$

The significance of dispersal weights has been addressed since they will be used to grade landscape elements depending on the cause of tiger dispersal.

Game Theory: Game theory has been utilized to simulate the interaction between landscape characteristics and dispersing tigers in this study (Webb 2007). A game is defined as a three-tuple $G = (P,\ \theta,\ \prod)$, where $P = \{P_1,\ P_2,\ P_3, \dots, P_n\}$ denotes the number of players, $\theta = \{\theta_1,\ \theta_2, \theta_3, \dots, \theta_m\}$ denotes the strategy set for each player, and $\prod$ denotes the associated payoff for each player, such that $\prod_{P_1\ X\ P_2\ X \dots X\ P_n} = \ \theta_{P_1}\ X\ \theta_{P_2}\ X\ \dots .\ X\ \theta_{P_n}$, where $\theta_i, i = \{1, 2, 3, \dots, n\}$ denotes the strategy chosen by player P_i from the strategy set θ for a move. Thus, when one player plays a certain strategy against the other, the payoff is the score they receive (Shanu et al., 2019).

There are several sorts of games that may be used to simulate interactions. In this experiment, a two-person prisoner dilemma game was employed to depict the binary interactions between the tigers and the terrain attributes. The game is depicted as follows:

$$G = (\{P_1, P_2\}, \{C, D\}, \{(R, R), (S, T), (T, S), (P, P)\}) \text{ ---(25)}$$

where $\{P_1, P_2\}$, present two players of the game. Next, $\{C, D\}$ represent the game's strategy set in which each player can either cooperate *(C)* or defect *(D)*. In a strategic form, the payoff matrix expressed in the form of a set in the above representation is expressed as:

$$\begin{array}{ccc} & & \underline{P2} \\ & & \begin{array}{cc}\underline{C} & \underline{D}\end{array} \\ \underline{P1} & \begin{array}{c}\underline{C}\\ \underline{D}\end{array} & \begin{bmatrix}(\boldsymbol{R},\boldsymbol{R}) & (\boldsymbol{S},\boldsymbol{T})\\ (\boldsymbol{T},\boldsymbol{S}) & (\boldsymbol{P},\boldsymbol{P})\end{bmatrix}\end{array}$$

where, *R* represents the reward for cooperation and has a numeric value of 3, *S* represents the sucker's payoff and has a numeric value of 0, *T* represents the reward for defect temptation and has a numeric value of 5, and *P* represents the punishment for mutual defection and has a numeric value of 1 (Hofbauer and Sigmund 1998; Webb 2007). As a result, the reward matrix may alternatively be represented numerically as:

$$\begin{array}{ccc} & & \underline{P2} \\ & & \begin{array}{cc}\underline{C} & \underline{D}\end{array} \\ \underline{P1} & \begin{array}{c}\underline{C}\\ \underline{D}\end{array} & \begin{bmatrix}(\mathbf{3},\mathbf{3}) & (\mathbf{0},\mathbf{5})\\ (\mathbf{5},\mathbf{0}) & (\mathbf{1},\mathbf{1})\end{bmatrix}\end{array}$$

The concepts of this work are centered on the binary relationship between tigers and the landscape qualities of each grid. These discussions were recorded using the two-person prisoner dilemma game (Shanu & Bhattacharya, 2018).

Hypothetical Landscape for the study

Figure 5-23 depicts the imaginary landscape utilized in this work for modelling reasons. Humans, prey animals, non-forested terrain, and water bodies are all important landscape factors to consider (Trisurat, 2010). Only a few critical areas are examined in order to show the concept and related mathematical framework. Many additional biotic and abiotic variables will be present in the terrain, and all of these characteristics must be taken into account while working on the tiger distribution pattern.

The specified forest zone comprises thick, moderately dense, open, and meadow-like forests. People represent the land utilized for agricultural, livestock grazing, and village settlements (Jhala et al., 2011). The prey base includes all desired species as well as damaged species that the tigers may consume. Wasteland, which is devoid of vegetation, is included in the non-forested landscape. The final water base characteristics analyzed encompass all water sources, from naturally flowing rivers to department-built waterholes. The landscape matrix is separated into significant pixels using a grid for evaluation and further observation of landscape elements. The model is designed to account for the presence or absence of dominant tigers over dispersing tigers, with each pixel of the landscape matrix representing a tiger habitat and territory in the hypothetical setting. As a result, the collection of parameters for each grid is displayed as:

$$G = \{WB, FA, HP, PB, NF\} \quad \text{---(26)}$$

where, WB represents water base, FA represents forested area, HP represents human presence, PB represents presence of a prey base and NF represents non-forested land.

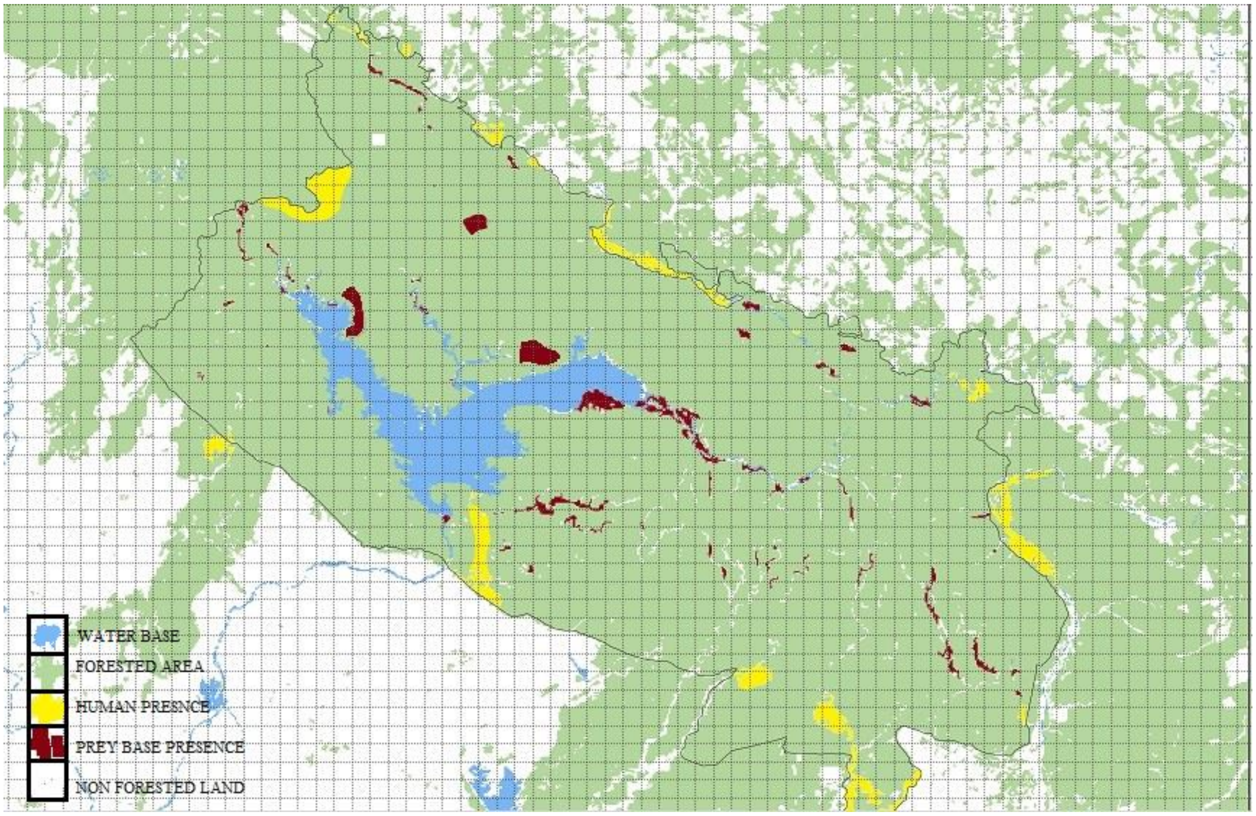


Figure 5-23: Hypothetical Landscape for the study.

Methodology

A segment of the landscape matrix including all of the qualities listed in the Hypothetical Landscape section is investigated with the boundary shown in Figure 5-24 to showcase the model proposed in this study. The study region was chosen using the landscape map in such a manner that it included all of the major study landscape features that would be employed in the proposed model. The imaginary map was built using GIS (Geographical Information System) and remote sensing from India's Terrai Arc Landscape. After analyzing the environment and placing grids on the map, the region that is most suited for exhibiting the proposed concept was picked.

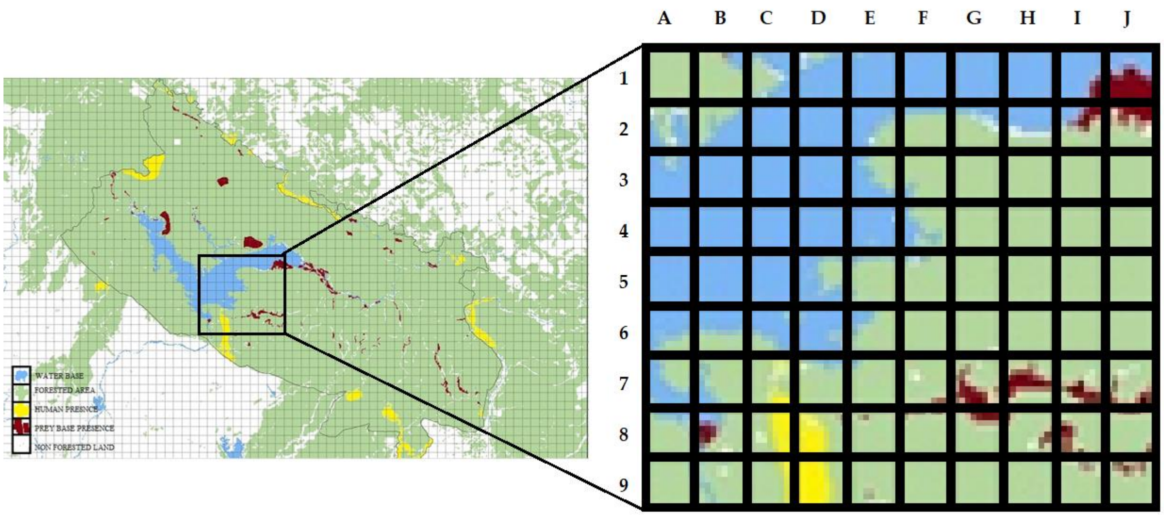


Figure 5-24: Region extracted from the landscape matrix with all defined components for Modeling.

The approach attempts to construct a cost matrix that may be disseminated throughout the terrain to better understand tiger distribution patterns. The cost matrix would be determined by the source and sink features of the grids in the focus landscape (Etherington, 2016). When discussing the source, the suggested work refers to the grids from which a member of a species begins to disseminate, while the other elements function as sinks. For example, if F3 is the source grid in Figure 5-20, the sink grids may be written as follows:

$$S = \{a_{ij} \mid i \in \{A, B, C, \dots, J\}, j \in \{1, 2, 3, \dots, 9\}, i \neq F \text{ and } j \neq 3 \quad \text{---(27)}$$

The previous explanation makes it evident that the costs of dispersal for each element of S must be calculated. All the abovementioned criteria are necessary during these evaluations, with the presence or absence of co-predators being one of the most crucial features (Presser and Luoma, 2013). The presence of co-predators in the area and environs is an important component in tiger dispersal. Figure 3 depicts an assumption for the selected landscape region, with 1 representing the existence of stronger co-predators or individuals, -1 showing the presence of lesser individuals, and 0 indicating the absence of any individual in the table.

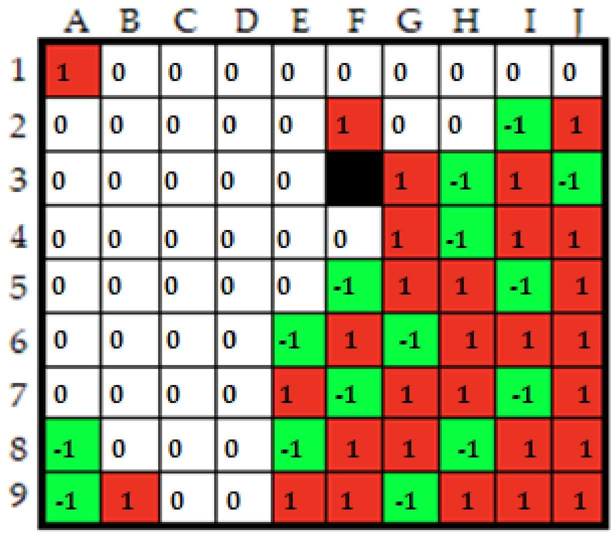


Figure 5-25: Presence/Absence of Co-predators with F3 as the source grid, where the red color with 1 indicates presence of a stronger predator than the dispersing individual, green with -1 represents the presence of a weaker predator than the dispersing individual.

To begin, the reason for an individual's dispersal is an important aspect in establishing their dispersal pattern. Four crucial life stages from the tiger life cycle that determine the tiger dispersal pattern are investigated for modelling purposes. These events provide for a better understanding of the dispersing individual's physical and cognitive requirements (Ramesh et al., 2009). It modifies the expenses associated with each grid while simulating the dispersal scenario and comprehending the dispersal trends. These events, the causes of dispersal, have been encoded in a way that is explained in Table 5-13 and is highly useful for modelling.

Table 5-13: Reasons for Dispersal.

Sl No.	Reason for Dispersal	Code
1	Dispersal for dominance	M1
2	Dispersal away from home	M2
3	Dispersal for Food	M3
4	Dispersal for Breeding	M4

Given the previous implications, the cost of each grid is computed by using the landscape complex features included in the grid, the reason of dispersal, and the presence/absence of co-predators. The cost of this job is governed by three criteria, which are shown below:

$$C_G = \left(\sum_{i=A,\ k=1}^{i=J,\ k=9} \alpha\, X \prod_{T,\ G_{ij}(M_k)} + (p \mid 0 \mid q)_{M_k}\right)_{k=1}^{k=4} \quad \text{---(29)}$$

where α indicates the dispersal coefficient based on the cause for tigers' dispersal. $\prod_{T,\ G_{ij}(M_k)}$ represents the payoff received by modelling a 2-Person's prisoner dilemma game between the dispersing tiger and each parameter of set *G* present in the grid G_{ij}, given the reason for dispersal M_k and $(p \mid 0 \mid q)_{M_k}$ represent the score received due to presence, absence as well as the dominance of co-predators in the grid.

To have a better understanding of the cost assessments outlined above, consider seeing the whole landscape as a network, with each grid acting as a vertex and the connections between the grid's eight neighborhoods functioning as edges (Tabassum et al., 2018). The advantageous relationships for tiger dispersal are determined by preferential movement in the suggested study work. The grid parameters or G components are prioritized over the network using dispersal weights, depending on the reason of dispersal, as illustrated in Table 5-14.

Table 5-14: Ranking of parameters based on Dispersal Weights.

Code	**WB**	**FA**	**HP**	**PB**	**NF**
M1	**3**	1	5	2	4
M2	2	3	5	1	4
M3	2	3	5	1	4
M4	2	1	5	3	4

This is used to calculate the dispersal coefficient α. Membership value or the dispersal coefficient has been obtained based on the rank of the parameters according to their needs as:

$$\alpha = \frac{n(G) - rank + 1}{n(G)} \quad \text{---(30)}$$

Range of α lies between 0 and 1. Earlier studies of the recent past have been utilized to get the values of α, based on various reasons for dispersal (Shanu et al., 2019). The values of α obtained on the application of dispersal weights are shown in Table 5-15.

Table 5-15: Value of α obtained using Table 5-14.

Code	WB	FA	HP	PB	NF
M1	0.6	1	0.2	0.8	0.4
M2	0.8	0.6	0.2	1	0.4
M3	0.8	0.6	0.2	1	0.4
M4	0.8	1	0.2	0.6	0.4

The interactions in the landscape are simulated using game theory after evaluating the degree of effect each element may have on the grid's cost (Turner, 1989). This study focuses on the interplay of dispersing tigers with landscape elements. As a result, the problem in this study is represented by the dispersing individual as one of the players in a two-person prisoner's dilemma game, with the landscape features as the other players (Shanu et al., 2019). As a result, the game's payoffs are as follows:

$$\prod_{Tiger,\ D}\big(Strategy(Tiger),\ \ Strategy(D)\big), D \in G \quad \text{---(31)}$$

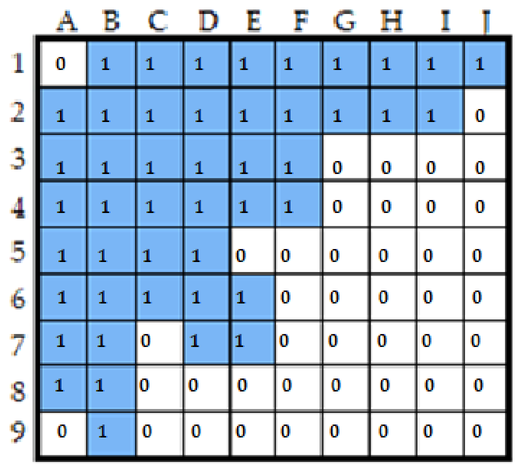
Set *G* contains elements that either assist or inhibit tiger movement in the landscape complex. Table 5-16 depicts the contribution of each parameter to the cost of any grid, as well as the degree of assistance for an individual's migration through the grid.

Table 5-16: Payoff of elements of G contributing to the grid costs.

Factor	Strategy of Factor	Strategy of Tiger	Associated score for grid	Remark (Johnsingh and Negi, 1998)
WB	Cooperate	Cooperate	3	Water is a supportive element for a species
FA	Cooperate	Cooperate	3	Forest cover supports presence and surviv of wild species
HP	Defect	Defect	-5	Any human presence hinders the flow species and usually neglected by species movement
PB	Cooperate	Defect	5	Prey base provides food elements to t moving tigers
NF	Defect	Defect	1	No effect other than restricting movement individuals

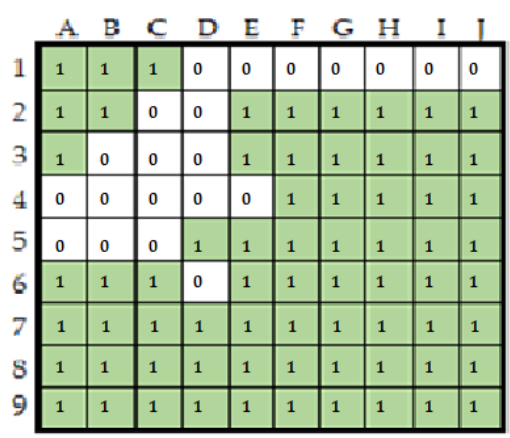
As previously stated, one of the most important aspects in influencing tiger dispersal is the presence or absence of co-predators; the work seeks to quantify the influence of this on the cost of a grid. Because interactions with co-predators can take numerous forms, utilizing game theory to analyze a dispersing tiger's interaction with co-predators may be difficult. Furthermore, while these encounters may be beneficial, they may also have negative repercussions such as injuries, weakened immune systems, and other conflict-related losses, all of which might limit an individual's mobility. The study gives interactions with stronger predators a high inhibitory discrete value of -10 and interactions with weaker predators a low supportive score of +3. The score has been set at 0 for regions with no co-predators.

To better understand tiger dispersal, the proposed technique was employed to undertake a detailed examination of landscape features for the estimation of grid costs over a landscape complex (Yumnam et al., 2014). The cost allocation is performed using the portion of the hypothetical landscape illustrated in Figure 5-24 as well as the example using F3 as the source. The images below show the presence and lack of parameters in landscape matrix grids. In each picture, 0 represents the lack of the parameter and 1 represents its presence.



	A	B	C	D	E	F	G	H	I	J
1	0	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	0
3	1	1	1	1	1	1	0	0	0	0
4	1	1	1	1	1	1	0	0	0	0
5	1	1	1	1	0	0	0	0	0	0
6	1	1	1	1	1	0	0	0	0	0
7	1	1	0	1	1	0	0	0	0	0
8	1	1	0	0	0	0	0	0	0	0
9	0	1	0	0	0	0	0	0	0	0

Figure 5-26: Presence/Absence of Water Body (WB), where blue and 1 represents the presence of WB and white with 0 represents the absence of WB.



	A	B	C	D	E	F	G	H	I	J
1	1	1	1	0	0	0	0	0	0	0
2	1	1	0	0	1	1	1	1	1	1
3	1	0	0	0	1	1	1	1	1	1
4	0	0	0	0	0	1	1	1	1	1
5	0	0	0	1	1	1	1	1	1	1
6	1	1	1	0	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1

Figure 5-27: Presence/Absence of Forest Area (FA), where green and 1 represents the presence of FA and white with 0 represents the absence of FA.

	A	B	C	D	E	F	G	H	I	J
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	1	1	0	0	0	0	0	0
8	0	0	1	1	0	0	0	0	0	0
9	0	0	1	1	0	0	0	0	0	0

Figure 5-28: Presence/Absence of Humans (HP), where yellow and 1 represents the presence of HP and white with 0 represents the absence of HP.

	A	B	C	D	E	F	G	H	I	J
1	0	0	0	0	0	0	0	0	1	1
2	0	0	0	0	0	0	0	0	1	1
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	1	1	1	1	1
8	0	1	0	0	0	1	1	1	1	1
9	0	0	0	0	0	0	0	0	1	1

Figure 5-29: Presence/Absence of Prey Base (PB), where brown with 1 represents the presence of PB and white with 0 represents the absence of PB.

	A	B	C	D	E	F	G	H	I	J
1	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	1	0	0	0	0	0

Figure 5-30: Presence/Absence of Non-Forested Area (NF), where pink represents the presence of NF and white represents the absence of NF.

The technique described above has been illustrated using one of the tiger dispersal scenarios, dispersal away from home (M2). Table 5-15 specifies the dispersal coefficients for the focal event, which are seen in Figure 5-31.

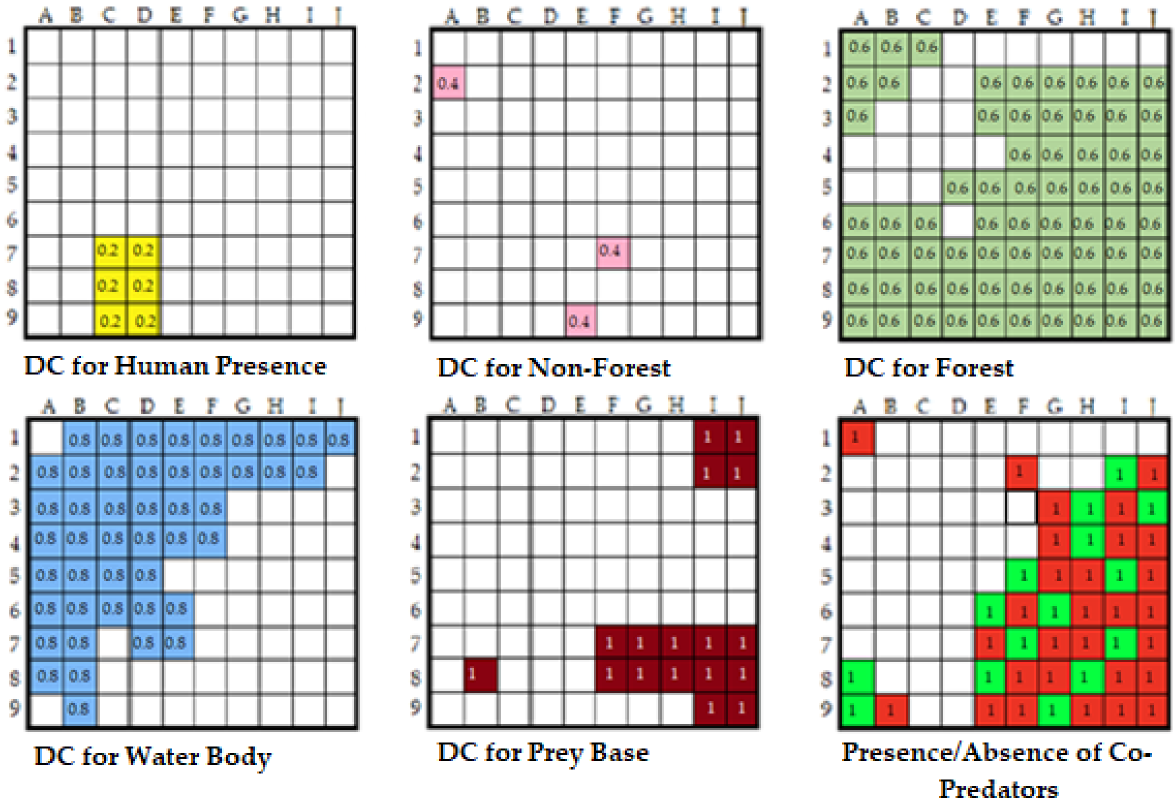


Figure 5-31: Dispersal coefficients for various landscape parameters according to Table 3 for the event of "dispersal away from home" for tigers.

The costs of each grid are further determined using equation 29, payoffs from Table 5-15, and the distinct payoffs for the presence/absence of Copredators (Epps et al., 2007). Using grid E7 as an example, the score is computed as:

$$C_{E7} = 0.8 * 3 + 0.6 * 3 + 0.2 * (-5) + 0 * 5 + 0 * 1 + 1 * (-10) = -6.8 \text{ ---(32)}$$

Similarly, the score for each grid is calculated by running a matrix simulation over all the grids, as illustrated in Figure 5-32 over the map. To make the model basic and informative, it is assumed that a tiger disperses for "dispersal away from home" from grid F3.

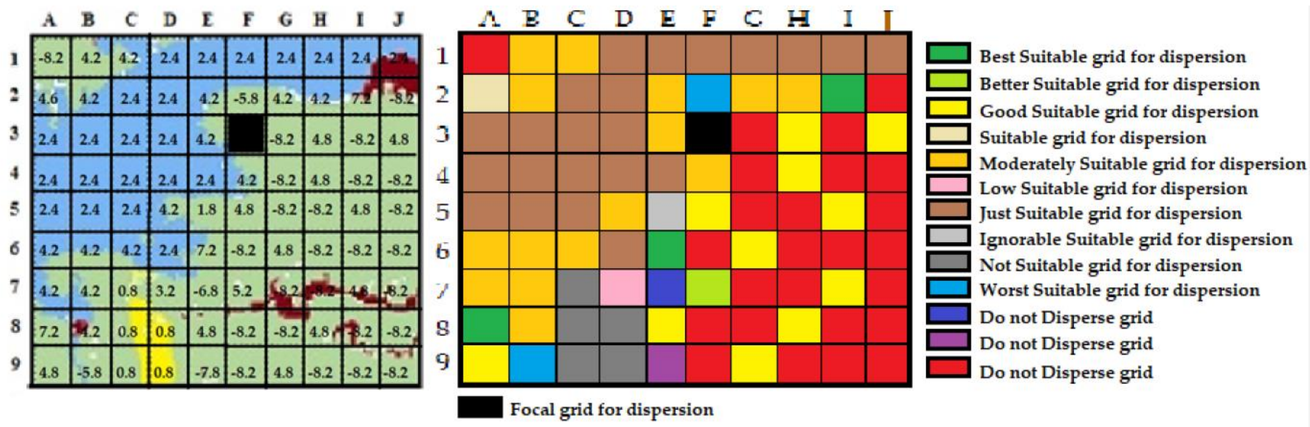


Figure 5-32: Cost of each grid for the life event of "Dispersal away from home" for tigers.

Figure 5-33 depicts the network for dispersal for the dispersing tiger throughout the whole landscape after the scores of each grid have been calculated and examined, as well as the tiger's dispersal from grid F3. The network is built on the concept of an 8-neighbourhood for each grid, so when a tiger reaches a grid, the model examines all 8 grids nearby and chooses which one is most suited for the subsequent degree of dispersal.

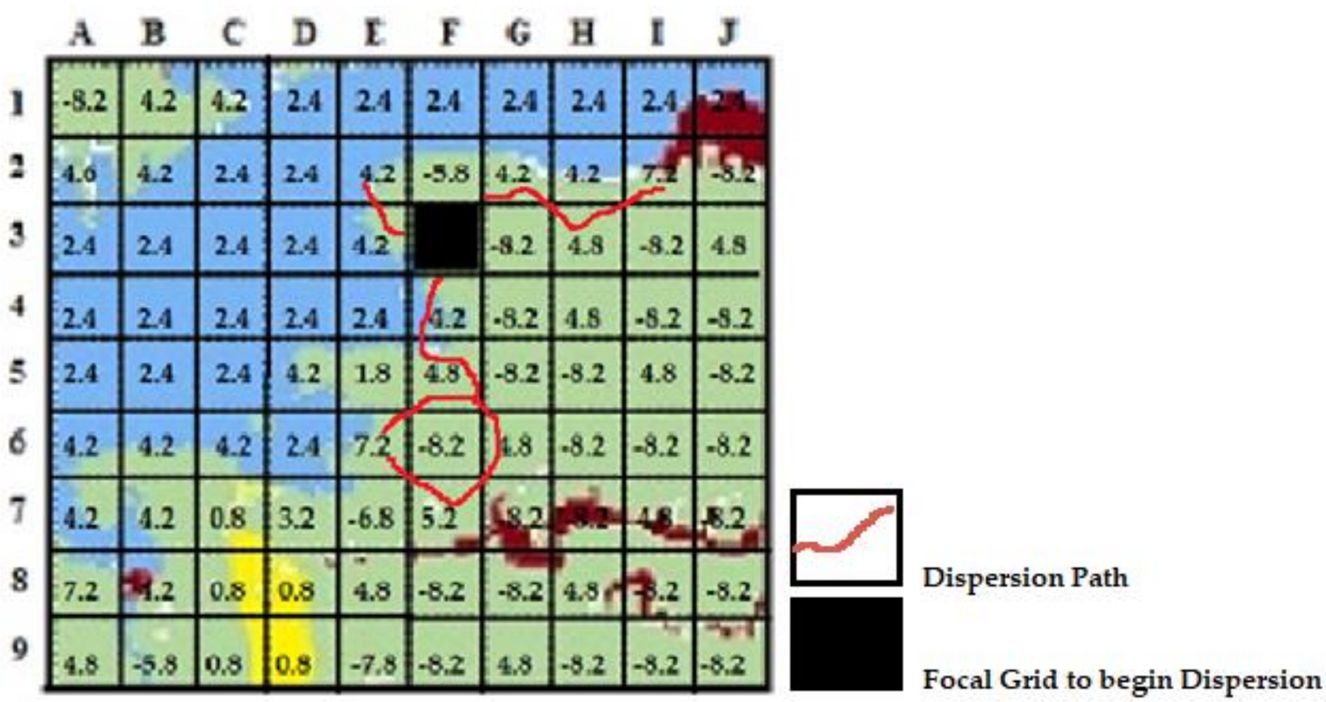


Figure 5-33: Dispersal network for the dispersing tiger for the event of "Dispersal away from home" from the grid F3.

The entire technique is used to the above-mentioned hypothetical scenario to present a computational framework for determining the tiger dispersal network and patterns. The same approach, when carried out with the assistance of satellite pictures and GIS, may be quite advantageous. When using GIS software such as ArcGIS or Qgis, the landscape photos and their respective .Shp files can be used by overlaying them with well-defined symmetric grids. Additionally, the "Identity" component of the tools may be used to categorize the grids' priority. Finally, utilizing geoprocessing and the defined equation presented in equation 29, the entire cost surface may be delivered throughout the terrain.

Results & Discussion

The scores are calculated by simulating each interaction between a dispersing tiger and a landscape parameter after obtaining the presence and absence details of the parameters in the landscape matrix for each of the four separate migration reasons, as described in Table 5-13. As mentioned in Table 5-15, the dispersal weight is computed using the sources of dispersal, and the value of the dispersal coefficient reflects this. In addition to the above listed criteria, the costs of co-predator presence are taken into account. Figures 5-34 to 5-37 show the final cost surface for all of the dispersal reasons explored in this work, which is calculated and shown as a matrix.

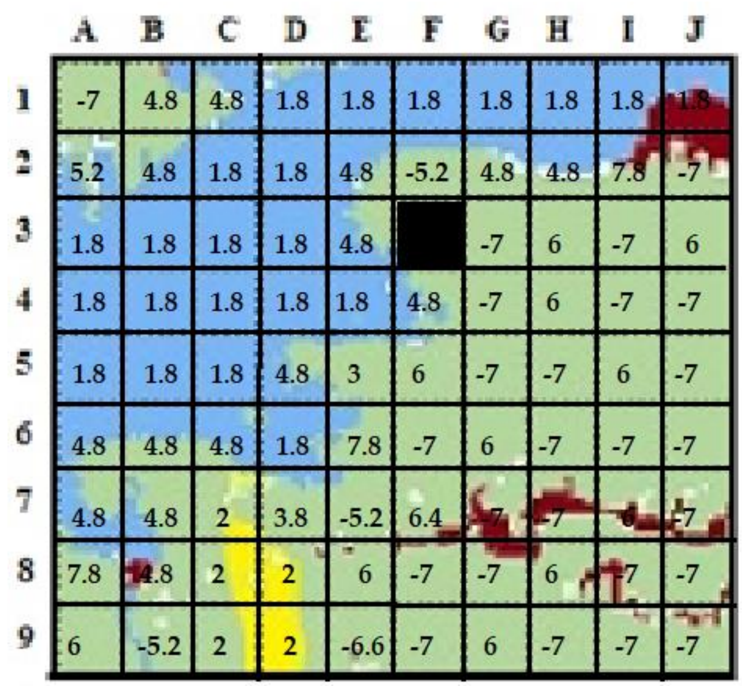


Figure 5-34: Cost surface over the landscape obtained for dispersal for dominance.

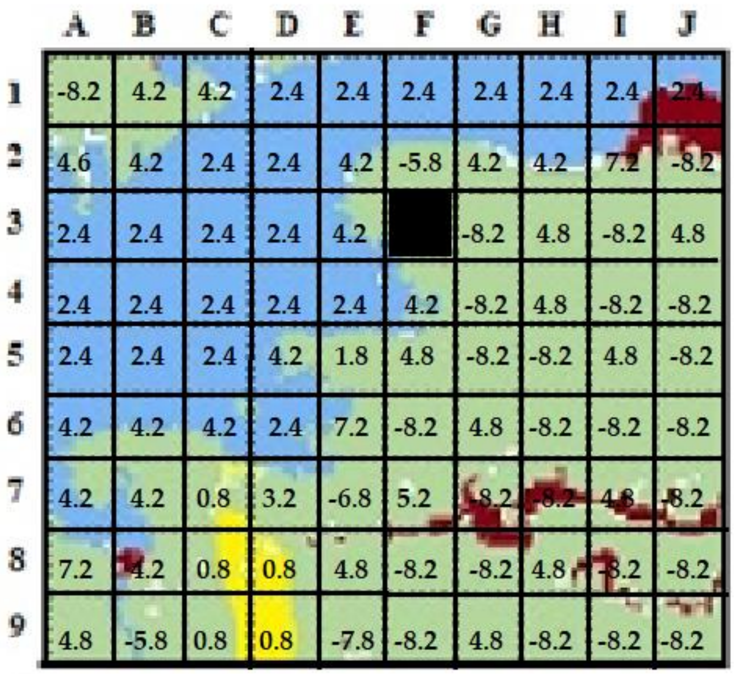


Figure 5-35: Cost surface over the landscape obtained for dispersal away from home.

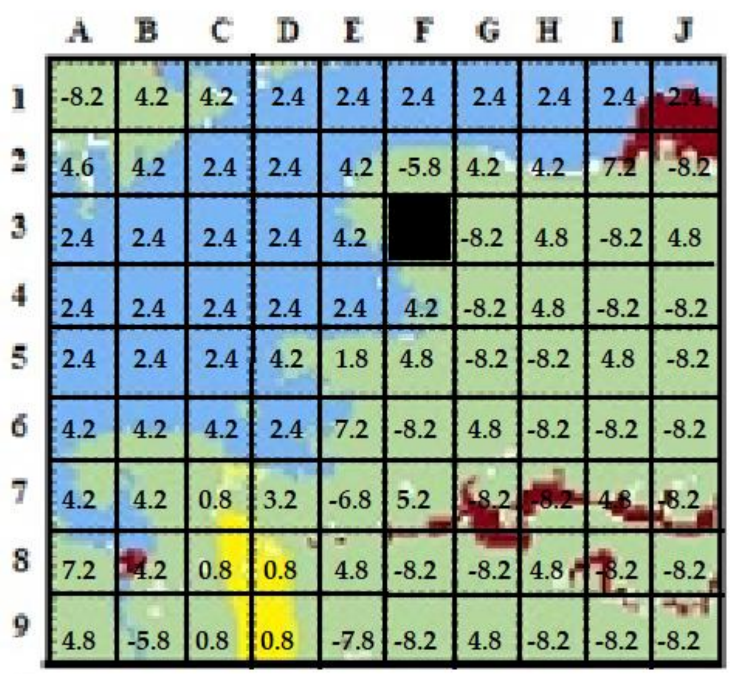


Figure 5-36: Cost surface over the landscape obtained for dispersal for food.

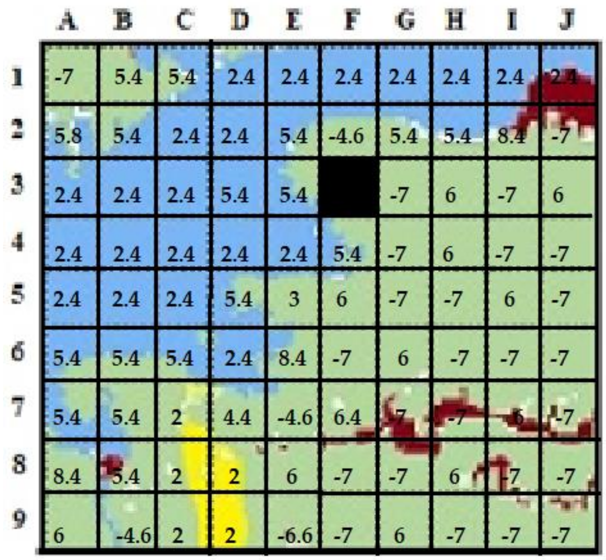


Figure 5-37: Cost surface over the landscape obtained for dispersal for breeding.

The proposed study provides a basic mathematical framework for evaluating the costs of a collection of landscape components that may aid or impede tiger dispersal from one area to another. The fundamental objective of the project is to provide a computer model to extract the cost for landscape grids, modelling tiger cognitive knowledge and behaviour, and utilizing it to learn about tiger dispersal patterns (Rifaie et al., 2015). An important outcome of this work is an in-depth analysis of the determinants and how tigers might use these parameters to disperse. The study also identifies critical grids where tiger dispersal may be tracked and seen as they depart their natural habitat. The proposed method provides a framework for developing a cost matrix over a landscape complex using game theory and the assumption that tigers and landscape elements interact deterministically. However, depending on the geography and surrounding conditions, the connection may alter. As a result, using just maps for game theoretic modelling would be one of the model's constraints. This might be improved if the work is integrated with field studies conducted in various landscapes. This has the potential to be extremely useful for animal stakeholders in terms of conservation and landscape design.

The primary findings of the study are provided in the form of a matrix, which is represented by a series of figures: Figures 5-34 to 5-37, which show various insights into tiger dispersal. Finding the cost surface begins with determining the reason for the tiger's departure from its native territory, which assists in determining the dispersing tiger's basic demands and, hence, the dispersal pattern. It also emphasizes the most critical grids in the landscape where tigers can disperse and settle, enabling greater attention to be paid to the connecting corridors. (Penjor et al., 2019; Minor and Urban, 2008).

The results demonstrate that there is a cost associated with each grid. The following is how the acquired costs in this work are linked to the tiger movement:

$$Cost\ of\ grid\ \propto Support\ for\ tiger\ movement \quad \text{---(33)}$$

As a result, the higher the cost, the more likely the tiger is to disperse through the grid.

After acquiring information on the tiger dispersal patterns using the costs associated with the landscape complex, the cost and the tiger dispersal pattern as a result of the expenses are investigated (Sharma et al., 2013). The study is depicted in Figure 5-38, which emphasizes numerous noteworthy findings. First, it shows that whether tigers leave their home region or for food, the expenses are the same, and hence the dispersal pattern is comparable. Then, with slight changes, it demonstrates a relationship between the cost and the dispersal pattern of tigers scattering for dominance or breeding. Furthermore, tigers migrating for dominance and breeding have more mobility options than tigers travelling for food or leaving their native zone. It also indicates that tigers leaving their original territory for food are either inexperienced and younger than the other dispersing tigers, or they are elderly and defeated.

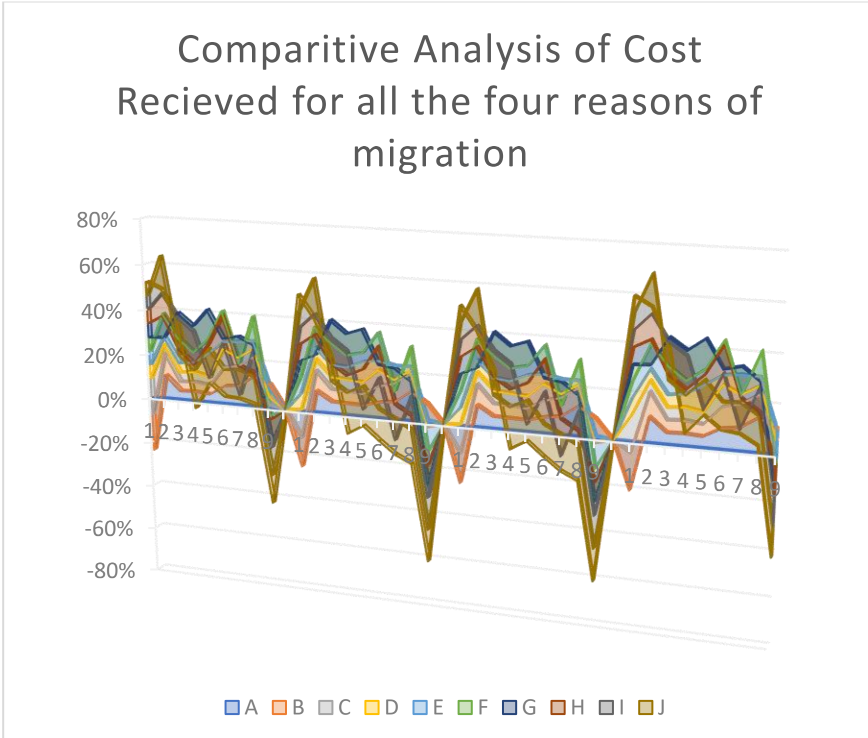


Figure 5-38: Analysis of results for all the 4 categories of movement.

The comparative study of expenses received for each of the four reasons of tiger migration (Meretsky et al., 2011) includes an evaluation of the dispersal costs over all grids. The visualization of the expenses data in Figure 5-38 shows that all migration-related reasons typically follow a similar trend with slight variations (Perkl, 2016). Figure 5-39 depicts a cumulative network map with the analysis on a map and a similarity in the dispersal trajectory for various sources of movement.

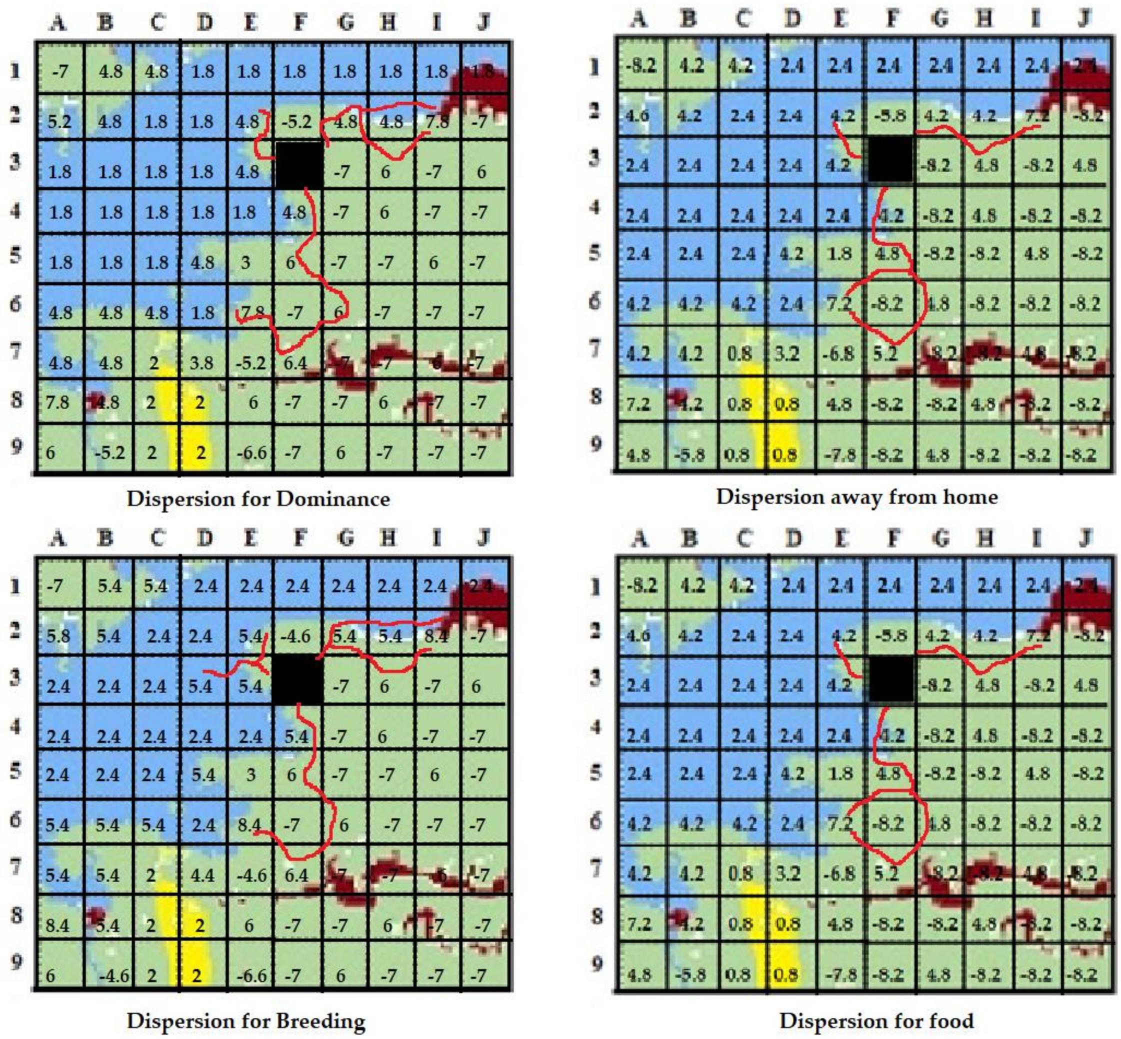


Figure 5-39: Cost surface with dispersal network for tigers, dispersing for various reasons within the landscape complex.

Comprehending species dispersal is essential for comprehending a range of conservation topics. Some of the main conservation principles linked with species distribution include wildlife corridor design, habitat suitability index, and other critical features. The construction of a cost surface over the landscape complex benefits not just in understanding but also in establishing dispersal patterns, which may subsequently be used for conservation. As previously discussed, a cost surface over a landscape matrix facilitates the creation of appropriate conservation models. Using an appropriate conservation model, the suggested approach tries to evaluate tigers' support and vulnerability as they disperse throughout a terrain. The appropriateness of a habitat or landscape for tiger survival and dispersal may be determined using the criticals supplied in the computational approach. Using these criticals would improve the precision of conservation plans and give a better model for target species conservation.

The capacity to derive the sensitivity of a grid for tiger distribution over it is another insight supplied by the recommended technique in this work. It is evident which grids help and which grids block tiger spread. As a result, the following is the relationship between grid costs and vulnerability:

$$cost\ of\ a\ grid \propto \frac{1}{vulnerability\ of\ the\ grid} \quad \text{---(34)}$$

Understanding the susceptibility of a grid is important because it illustrates grids that may require human involvement to aid tiger dispersal and hence conserve the species (Rathore et al., 2012). As a result, associated vulnerabilities might be regarded as a guiding notion for building optimal conservation strategies.

Several analogies and remarks presented above suggest the need to build the cost surface over a landscape matrix. All of the talks lead to the notion that locating a cost matrix and projecting it onto a surface aid in understanding how different species disperse throughout a complicated habitat and how they do so, which aids in conservation through the use of various models.

Conclusion

Using an iterative computational technique, the current work aims to generate a cost surface over the landscape complex, which shows the landscape complex as a matrix, and discover the tiger distribution pattern as well as their underlying scope of existence in a grid.

Using dispersal weights and game theory, this paper creates a cost surface over the landscape matrix that can be used to investigate actual tiger dispersal in any complicated habitat. The initial cost matrix was generated by simulating and integrating a game including landscape level features and tigers. The interactions of co-predators are also shown in a second cost matrix, which is merged with the first cost matrix to generate the landscape's final cost matrix. One of the primary elements that was overlooked in corridor design approaches such as circuit theory or game-graph theory was the presence of predators in the surrounding landscapes, which has been addressed in the suggested model. The proposed model in this work also includes the next-to-immediate grid where tigers can move while dispersing, making it more accurate and precise for wildlife stakeholders involved in conservation planning.

The cost surface design of the proposed model is largely focused on linear static interactions, ignoring some critical non-linear features such as the quantity of co-predation, the degree of cooperation or defection, and so on (Wikramanayake et al., 2008). The assignment is purposely kept simple to give a fundamental computational basis for extracting a cost surface in the tiger's attention landscape complicated. The absence of several interactions with separate co-predators in a single grid was a simplifying assumption in the study. The priority in this work has been to focus on cost matrix generation for dispersal patterns, thus improving the quality of interactions rather than the quantity of interactions. Second, the work focuses on learning about dispersal through a grid rather than understanding complexities within a grid. These two considerations excuse the failure to consider various interactions (Warneryd et al., 2020). These simplifications may not necessarily correspond to the cost surface scenario in the real world. With the tiger as the primary species, it is possible that the planned research would result in the publication of a computational template for cost surface design, which might be considerably enhanced by including field and GIS data from realistic situations.

Dispersal weights were used to identify the cost surface in the focal landscape complex, and game theory was used. The payoffs of the 2-person prisoner's dilemma game show that the cost surface only acts as a skeletal design. It is emphasized that the conclusions of this study need to be fine-tuned through suitable validation using actual field data to be useful for wildlife policy issues. A further type of constraint arises from a lack of understanding of the causes for the tiger's departure from its natural habitat. A range of causes, including a combination of variables, can drive species dispersal. In this study, just one motivation for creating a distinct cost surface was investigated. As a result, while they may be used to generate cost surfaces, they do not indicate how effectively these cost surfaces aid in issue identification (Croteau, 2010).

Most of the research focuses on computational techniques and concepts that may be utilized to construct a cost surface over any landscape complex to better understand dispersal patterns and apply them for conservation. It provides a fundamental computational basis that, when paired with reliable field data and GIS modelling, has the potential to be immensely valuable to wildlife conservationists and management (Rautela et al., 2022).

Chapter 6

CONCLUSION & FUTURE WORK

The understanding of ecosystems, animal behaviour, and the effects of human actions are all improved by computer applications and computations, according to the research presented in this report. The computational approaches include data analysis, GIS and Remote Sensing, algorithm design, code generation, etc. The study effort argues that computing is crucial for species conservation using several critical strategies. Few key highlights brought out from the study are concluded in this section with the future scopes.

The study aimed to use the CPM to generate an appropriate tiger corridor network in the Terai Arc landscape complex. The process involved obtaining a tiger Habitat Suitability Map (HSI) in the Terai Arc landscape, extracting a tiger corridor network connecting different habitat patches, and identifying the most critical habitat patches and their underlying overlapping communities to focus conservation efforts on them.

The CPM was used to identify overlapping groups of habitat patches that sustain tiger populations and migration in the Terai Arc landscape complex. These overlapping communities are generated using clique graphs, which are built up of cliques produced from the investigation and study of habitat patch interactions. The Tiger Habitat Suitability Map demonstrates that much of the Terai Arc terrain has prospective tiger habitats, and it serves as a basis for connecting these patches, which have been calculated as a corridor network.

The application of PC to the tiger corridor network has resulted in the establishment of twelve large habitat patches, which help in the preservation of interaction between vertices and cliques, and therefore the formation of key communities. In addition to the six most essential habitat patches, all of which are vital to sustaining the landscape's continuity, the findings and approach suggested by completion of this objective will be useful in building future conservation plans in the focus landscape and any other landscape of conservation concern.

Using dispersal weights and game theory, this paper creates a cost surface over the landscape matrix that can be used to investigate actual tiger dispersal in any complicated habitat. The initial cost matrix was generated by simulating and integrating a game including landscape level features and tigers. The interactions of co-predators are also shown in a second cost matrix, which is merged with the first cost matrix to generate the landscape's final cost matrix. One of the primary elements that was overlooked in corridor design approaches such as circuit theory or game-graph theory was the presence of predators in the surrounding landscapes, which has been addressed in the suggested model.

However, the cost surface design of the proposed model is largely focused on linear static interactions, ignoring some critical non-linear features such as the quantity of co-predation, the degree of cooperation or defection, and so on. The assignment is purposely kept simple to give a fundamental computational basis for extracting a cost surface in the tiger's attention landscape complicated. The study's conclusions need to be fine-tuned through suitable validation using actual field data to be useful for wildlife policy issues.

A further constraint arises from a lack of understanding of the causes for the tiger's departure from its natural habitat. While they may be used to generate cost surfaces, they do not indicate how effectively these cost surfaces aid in issue identification. Most research focuses on computational techniques and concepts that can be utilized to construct a cost surface over any landscape complex to better understand dispersal patterns and apply them for conservation.

Data gathering and analysis are made possible by computation, which allows for the gathering, storing, and analysis of enormous volumes of ecological and biological data. To handle data from diverse sources, including GPS trackers, camera traps, sound sensors, and remote sensing satellites, researchers employ computational techniques. These facts support the tracking of ecological trends such as habitat changes, species numbers, and migratory patterns. Modelling and Simulation: Scientists can comprehend complex ecological systems and forecast how they could react to various events by using computational models and simulations. Modelling, for instance, may be used to foretell the spread of illnesses, the effects of climate change on the distribution of species, and the efficacy of conservation measures. Mapping and GIS: To produce accurate maps and geographical analysis, Geographic Information Systems (GIS) significantly rely on computing. These resources are essential for locating significant habitats, creating animal corridors, and organizing conservation initiatives in particular areas. Population Dynamics: Computational models help to understand how species populations change over time, taking into account things like migratory patterns, mortality rates, and the effects of human activity. To maintain the long-term viability of species, these models assist in making management decisions. Genetic Analysis: By analyzing DNA sequences to examine population genetics, genetic diversity, and the relatedness of individuals within a species, computation helps genetic research. Understanding gene flow, inbreeding, and the possible implications of genetic bottlenecks requires knowledge of this information. To find patterns and make predictions, machine learning and artificial intelligence systems may analyze large data sets. These technologies can aid in species conservation by predicting poaching episodes, locating illicit wildlife trafficking networks, and even determining the danger of extinction. Studies on animal behaviour are aided by computation, which processes data from sensors and tracking equipment. This aids in the understanding of animal behaviour, including foraging, migratory patterns, and interactions with their surroundings. Outreach and Communication: Computational tools, like websites, smartphone applications, and social media platforms, make it easier to inform the public about conservation initiatives. These resources inspire support for conservation efforts, increase awareness, and include the public in citizen scientific projects. Decision Support Systems: Computation aids in the creation of decision support systems that guide decision-making in the areas of land use, habitat protection, and wildlife management by policymakers, conservation groups, and land managers. Efficiency and cost-effectiveness: Conservationists may use computation to prioritize conservation efforts, optimize resource allocation, and plan interventions more effectively, saving time and resources.

The area of species conservation has been fundamentally changed by computers, allowing practitioners and academics to collect, examine, and interpret data in ways that were before impossible. The long-term sustainability of biodiversity depends on the capacity to conserve species, safeguard ecosystems, and make wise decisions.

This study proposes a computational template for building tiger corridors by parametrizing landscape complex elements. It suggests adding more parameters to make the model more realistic and considering obstacles to tiger movement and potential corridors. The network structure model can be designed to be more adaptable to changing land use and land cover dynamics, useful for real-time study of tiger corridors. It is important to design a realistic corridor network considering territorial populations outside Protected Areas, as a significant population of tigers in the focal landscape reside outside these areas. The basic template presented in this work should be enhanced to account for these populations.

The field of wildlife corridor design is a promising avenue at the intersection of technology and conservation. Future trends include data-driven conservation, which uses machine learning and data analytics to process large datasets like satellite imagery, GPS tracking, and biodiversity records to identify optimal locations for wildlife corridors. Remote sensing and GIS can be used to map and monitor wildlife habitats, while connectivity modeling can simulate animal movement patterns to predict changes in the landscape.

Corridor design optimization involves using optimization algorithms to design and plan wildlife corridors efficiently, considering factors such as landscape connectivity, habitat suitability, and minimizing potential barriers. Sensor networks and IoT devices can monitor wildlife movement in real-time, providing valuable data for understanding animal use and identifying challenges. Virtual reality and augmented reality can help public awareness and stakeholder buy-in.

Blockchain technology can create transparent and tamper-proof systems for tracking and validating conservation efforts, especially when dealing with multiple stakeholders and funding sources. Community engagement and crowdsourcing can enhance the effectiveness of conservation initiatives. Tools to assist policymakers and conservationists in making informed decisions can be developed, demonstrating the ecological and economic benefits of maintaining or establishing wildlife corridors.

Climate change resilience can be integrated into wildlife corridor planning, predicting how climate shifts may affect species distribution and adjusting corridor designs accordingly. Robotic and drone technology can be explored for monitoring wildlife corridors, collecting data, and assisting in habitat restoration activities. This dynamic field has the potential to make significant contributions to biodiversity conservation and ecosystem resilience.

The 5 major results of the work include:

1. Development of Computational Models for Tiger Corridor Design: The work presents the development of computational models for designing wildlife corridors specifically tailored

for tigers in various landscapes. These models utilize complex network analysis and machine intelligence techniques to identify suitable habitats, assess landscape connectivity, and design effective corridors to facilitate tiger movement and dispersal.

2. Utilization of Complex Network Analysis in Wildlife Conservation: The work demonstrates the application of complex network analysis in wildlife conservation, particularly in the context of designing wildlife corridors. By employing graph theory and computational tools, the study explores habitat suitability, landscape connectivity, and species dispersal patterns, providing insights into effective conservation strategies for maintaining biodiversity and promoting species survival.
3. Species-Specific Corridor Planning Strategies: The research highlights the importance of species-specific corridor planning strategies, focusing on the conservation of tigers as a focal species. Through computational modeling and analysis, the study develops tailored approaches to identify critical tiger habitats, assess landscape connectivity, and design corridors that facilitate gene flow and population viability.
4. Accuracy of Computational Models: The work evaluates the accuracy and effectiveness of the proposed computational models by comparing their results with empirical data on tiger populations. The models demonstrate high accuracy in predicting suitable habitat areas, identifying landscape connectivity patterns, and designing corridors aligned with conservation goals.
5. Practical Implications for Conservation Management: The research provides practical implications for conservation management by offering a systematic framework for planning and implementing wildlife corridors. By integrating computational techniques with ecological principles, the study offers valuable insights into the design, optimization, and evaluation of wildlife corridors to support tiger conservation efforts and broader biodiversity conservation goals.

The study's utility for wildlife researchers and forest managers is profound, particularly in the realm of tiger conservation and habitat management. By leveraging complex network analysis (CNA) and machine intelligence (MI), the research offers a groundbreaking approach to designing wildlife corridors, especially tailored to the needs of tiger populations. Wildlife corridors, essential for maintaining genetic diversity, facilitating migration, and ensuring access to vital resources, are meticulously crafted using computational models that consider diverse ecological factors and temporal variations. These corridors not only enhance tiger population viability but also contribute to the overall health and resilience of ecosystems. Through sophisticated techniques such as the Clique Percolation Method (CPM) and habitat suitability index (HSI) modeling, the study provides a systematic framework for identifying critical habitat patches and establishing connectivity between them. By integrating data from GIS, remote sensing, and ecological field studies, the research bridges the gap between theoretical network analysis and practical conservation efforts, empowering wildlife managers with actionable insights for effective corridor planning and landscape management. Furthermore, the study's emphasis on species-specific corridor design underscores its relevance for tailored conservation strategies, ensuring the long-term survival of endangered species like tigers while fostering interdisciplinary collaboration and advancing the frontiers of conservation science.

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List of Published Work

Journal Publications

[1] Shanu S., Sastry H.G., Marriboyina V. (2021) Optimal solution approach on large-scale data to avoid deadlocks in resource allocations, Materials Today: Proceedings.

[2] Rautela N., Shanu S., Agarwal A., Bhattacharya S., Roy A. (2022) Geospatial modelling of overlapping habitats for identification of tiger corridor networks in the Terai Arc landscape of India, Geocarto International.

[3] Shanu S, Agarwal A. (2023) A Computational Model for Determining Tiger Dispersal and Related Patterns in a Landscape Complex. Sustainability. 2023; 15(11):8539.

[4] Shanu, S., Agarwal, A., Rautela, N., & Chaudhary, H. (2023). Designing Data-Resolution Dependent Wildlife Corridor Networks for Tigers Using a Tensor-Based Computational Model. Journal of Mines, Metals and Fuels, 71(4), 552–556.

[5] Shanu, S., Agarwal, A. (2023). A Decision Support System for Modelling Wildlife Corridors in India. Biomed J Sci & Tech Res 52(1)-2023. BJSTR.

[6] Shanu S, Agrawal A (2023) An Application to Wildlife Corridor Designing in Central India-Eastern Ghats Landscape, India, Using Simplicial-Complexes in Community-Structures. J Atmos Earth Sci 7: 043.

[7] Shanu S, Idiculla J, Qureshi Q, Jhala Y V, Aggarwal A, Dimri P, Bhattacharya S (2019) A graph theoretic approach for modelling tiger corridor network in Central India-Eastern Ghats landscape complex, India, Ecological Informatics Volume 50, March 2019, Pages 76-85.

Book Chapters

[1] Shanu, S. (2022). Technology Versus Tradition: Game Theoretic Model for Human-Animal Conflict in the Evolution of Digital Society. In: Choudhury, A., Singh, T.P., Biswas, A., Anand, M. (eds) Evolution of Digitized Societies Through Advanced Technologies. Advanced Technologies and Societal Change. Springer, Singapore.

Conferences

[1] International Conference on Data Analytics and Computing (ICDAC 2022).

[2] International Conference on Production and Industrial Design (CPIE 2023).

Details of Journal Publications:

Table 1: Details of Publication Associated with the work.

Publication	**DOI**	**Link**	**Indexing**	**Impact Factor**
Shanu S, Agarwal A. A Computational Model for Determining Tiger Dispersal and Related Patterns in a Landscape Complex. Sustainability. 2023; 15(11):8539.	https://doi.org/10.3390/su15118539	https://www.mdpi.com/2071-1050/15/11/8539	Scopus, SCIE	3.89
Shanu, S., Agarwal, A., Rautela, N., & Chaudhary, H. (2023). Designing Data-Resolution Dependent Wildlife Corridor Networks for Tigers Using a	https://doi.org/10.18311/jmmf/2023/33937	https://www.informaticsjournals.com/index.php/jmmf/article/view/33937	SCI	0.11

Tensor-Based Computational Model. Journal of Mines, Metals and Fuels, 71(4), 552–556.				
Rautela N., Shanu S., Agarwal A., Bhattacharya S., Roy A. (2022) Geospatial modelling of overlapping habitats for identification of tiger corridor networks in the Terai Arc landscape of India, Geocarto International.	https://doi.org/10.1080/10106049.2022.2095444	https://www.tandfonline.com/doi/abs/10.1080/10106049.2022.2095444	Scopus, SSCI	3.45
Shanu, S., Agarwal, A. (2023). A Decision Support System for Modelling Wildlife Corridors in India. Biomed J	https://doi.org/10.26717/BJSTR.2023.52.008196	https://biomedres.us/pdfs/BJSTR.MS.ID.008196.pdf	SIS	1.229

Sci & Tech Res 52(1)-2023. BJSTR.				
Shanu S., Sastry H.G., Marriboyina V. (2021) Optimal solution approach on large-scale data to avoid deadlocks in resource allocations, Materials Today: Proceedings.	https://doi.org/10.1016/j.matpr.2021.06.357	https://www.sciencedirect.com/science/article/pii/S2214785321047519	Scopus	2.59
Shanu S, Agrawal A (2023) An Application to Wildlife Corridor Designing in Central India-Eastern Ghats Landscape, India, Using Simplicial-Complexes in Community-Structures. J	https://doi.org/10.24966/AES-8780/100043	https://www.heraldopenaccess.us/journals/journal-of-atmospheric-earth-sciences	WOS	1.06

Atmos Earth Sci 7: 043.				
Shanu S, Idiculla J, Qureshi Q, Jhala Y V, Aggarwal A, Dimri P, Bhattacharya S (2019) A graph theoretic approach for modelling tiger corridor network in Central India-Eastern Ghats landscape complex, India, Ecological Informatics Volume 50, March 2019, Pages 76-85	https://doi.org/10.1016/j.ecoinf.2019.01.002	https://www.sciencedirect.com/science/article/abs/pii/S1574954118301444?via%3Dihub	SCI	5.1

Details of Conferences

Table 2: Details of Conference presentations Associated with the work.

Paper Title	Authors	Conference Name	Type of Conference	Indexing of Conference	Remark
Designing Data-resolution Dependent Wildlife Corridor Networks for Tigers using a Tensor-based Computational Model	S. Shanu & A. Aggarwal	International Conference on Data Analytics and Computing (ICDAC 2022)	International	Scopus	
Designing Temporal Data Dependent Wildlife Corridor Networks for Tigers using a Tensor-based Computational Model	S. Shanu & A. Aggarwal	International Conference on Production and Industrial Design (CPIE 2023)	International	Scopus	Best Paper Award received.

Copyrights

Table 3: List of Copyrights Associated with the work.

SL. NO.	PRODUCT TITLE	COPYRIGHT NUMBER	DOMAIN	USING AGENCY	YEAR
1.	ANIMETER	SW-15074/2021	REM	WII (Wildlife Institute of India)	2021

2.	AWC: An Automated Wildlife Camera Trap Image Species Segregation Tool	18731/2022-CO/SW	Wildlife	WII (Wildlife Institute of India)	2022
3.	FEEL: Feature Extraction based Emotional Personality Learning Tool	18737/2022-CO/SW	Cognitive Science	Psychology based agency	2022
4.	IBS	7643/2023-CO/SW	Surveillance	Security Agencies	2023

Granted Patent

Table 4: List of Patent Associated with the work.

SL. NO.	PRODUCT TITLE	PATENT NUMBER	APPLICATION NUMBER	DATE OF FILING	DATE OF GRANT
1.	COMPUTER-IMPLEMENTED METHOD AND SYSTEM TO PROVIDE A NON-DETERMINISTIC FRAMEWORK TO DETERMINE A PATROLLING PATH	485619	201811009124	13/03/2018	19/12/2023

APPENDIX A: Calculations for the relevance of the prey

The Analytic Hierarchy Process (AHP) is a powerful tool for managing complex decision-making dynamics. It helps management authorities set needs and make the best choice by decreasing complex choices to develop pairwise correlations and synthesizing outcomes. The AHP also helps in catching both abstract and target parts of a choice and checks the consistency of managers' assessments, reducing inclination in the dynamic decision-making process. The AHP involves problem and goal definition, a chain of importance from head to least level, and a list of choices. Once the problem, goal and AHP structure have been identified, we construct a set of pairwise comparison matrix $(N \text{ X } N)$; where N denotes the number of parameters considered for the processing, for every component in the level quickly above by utilizing relative scale estimation appeared in table. The pairwise comparisons are done in terms of which element dominates the other. Hierarchical synthesis was used to weight the Eigen vector entries corresponding to those in the next lower level of hierarchy, which provides the state of dominance, after obtaining the comparison matrix. After all of the pairwise comparisons have been completed, the accuracy is calculated by calculating the consistency index *(CI)* as follows:

$$CI = \frac{(\lambda_{max} - n)}{(N-1)}$$

Where *N* is the matrix size. Judgment consistency is estimated by taking the consistency ratio (*CR*) of *CI* with appropriate values in Table 1 and Table 2. If the CR does not exceed 0.10, it is permissible. If it is higher, the decision must be improved. Repetition of steps taken at all stages of the hierarchy aids in improving accuracy of judgement. In a linear additive model, the vector values computed by synthesized matrices of different layers are used in allotting weights to different input groups and input layers.

Table 1: AHP preferences Pairwise comparison scale

Numerical Rating	**Verbal Judgments of preferences**
9	Extremely preferred
8	Very strongly to extremely

7	Very strongly preferred
6	Strongly to very strongly preferred
5	Strongly preferred
4	Moderately to strongly preferred
3	Moderately preferred
2	Equally to moderately preferred
1	Equally preferred

Table 2: Average random consistency (RI)

Size of Matrix	1	2	3	4	5	6	7	8	9	10
Random Consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table. 3: Pair-wise comparison matrix of LULC (Spotted deer)

	Grassland	**Sal mixed moist**	**Dry deciduous**	**Sal forest**	**Scrub**	**Plantation**	**Degraded forest**	**Pine**	**Himalayan**	**Sub alpine**	**Agriculture**	**Settlement**	**Water body**
Grassland	1	2	2	4	5	6	7	9	9	9	9	9	9
Sal mixed moist deciduous	0.5	1	2	3	4	5	6	7	8	8	9	9	9
Dry deciduous	0.5	0.5	1	2	3	4	5	6	7	8	8	9	9
Sal forest	0.25	0.33	0.5	1	2	3	4	5	6	7	8	8	9

Scrub	0.2	0.25	0.33	0.5	1	2	3	4	5	6	7	8	9
Plantation	0.17	0.2	0.25	0.33	0.5	1	2	3	4	5	6	7	8
Degraded forest	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3	4	5	6	7
Pine	0.11	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3	4	5	6
Himalayan moist temperate	0.11	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3	4	5
Sub alpine	0.11	0.13	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3	4
Agriculture	0.11	0.11	0.13	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3
Settlement	0.11	0.11	0.11	0.13	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2
Water body	0.11	0.11	0.11	0.11	0.11	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1
Total	3.43	5.18	7.07	11.95	16.83	22.72	29.59	38.45	46.28	54.08	62.83	71.5	81

Table 4: The synthesized matrix of LULC

	Grassland	Sal mixed mois	Dry deciduous	Sal forest	Scrub	Plantation	Himalayan moi	Pine	Degraded fores	Sub alpine	Agriculture	Settlement	Water body	Priority Vecto
Grassland	0.2	0.3	0.2	0.3	0.3	0.2	0.24	0.23	0.19	0.17	0.1	0.1	0.1	0.2
Sal mixed moist deciduous	0.1	0.1	0.2	0.2	0.2	0.2	0.20	0.18	0.17	0.15	0.1	0.1	0.1	0.1
Dry deciduous	0.1	0.1	0.1	0.1	0.1	0.1	0.17	0.16	0.15	0.15	0.1	0.1	0.1	0.1
Sal forest	0.0	0.0	0.0	0.0	0.1	0.1	0.14	0.13	0.13	0.13	0.1	0.1	0.1	0.1
Scrub	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.10	0.11	0.11	0.1	0.1	0.1	0.0
Plantation	0.0	0.0	0.0	0.0	0.0	0.0	0.07	0.08	0.09	0.09	0.1	0.1	0.1	0.0
Himalayan moist temperate	0.0	0.0	0.0	0.0	0.0	0.0	0.03	0.05	0.06	0.07	0.0	0.0	0.0	0.0
Pine	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.03	0.04	0.06	0.0	0.0	0.0	0.0
Degraded forest	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.02	0.04	0.0	0.0	0.0	0.0
Sub alpine	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.02	0.0	0.0	0.0	0.0
Agriculture	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.01	0.0	0.0	0.0	0.0
Settlement	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.01	0.0	0.0	0.0	0.0
Water body	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0

λ_{max} = 14.33708; Consistency index (CI)= 0.111; Consistency Ratio(CR) = 0.074781

Table 5: Pair-wise comparison matrix of Forest density

	Low density	Medium density	High density	Very high density
Low density	1	2	7	8
Medium density	0.5	1	4	7
High density	0.14	0.25	1	3
Very high density	0.13	0.14	0.33	1
Total	1.77	3.39	12.33	19

Table 6: Synthesis matrix of Forest density

	Low density	Medium density	High density	Very high density	Priority Vector
Low density	0.57	0.59	0.57	0.42	0.54
Medium density	0.28	0.29	0.32	0.37	0.32
High density	0.08	0.07	0.08	0.16	0.10
Very high density	0.07	0.04	0.03	0.05	0.05

λ_{max} = 4.10; Consistency index (CI)= 0.03 ; Consistency Ratio(CR) = 0.02

Table 7: Pair-wise matrix of Aspect

	South	South east	East	South west	North	North east	North west	West
South	1	2	2	3	6	6	7	9
South east	0.5	1	2	3	5	6	7	8
East	0.5	0.5	1	3	4	5	6	8
South west	0.3	0.3	0.3	1	4	5	7	8
North	0.2	0.2	0.3	0.3	1	3	2	2
North east	0.2	0.2	0.2	0.2	0.3	1	2	2
North west	0.1	0.1	0.2	0.1	0.5	0.5	1	2
West	0.1	0.1	0.1	0.1	0.5	0.5	0.5	1
Total	**2.92**	**4.47**	**6.08**	**10.72**	**21.33**	**27**	**32.50**	**40**

Table 8: Synthesis matrix of Aspect

	South	South east	East	South west	North	North east	North west	West	Priority vector
South	0.34	0.45	0.33	0.28	0.28	0.22	0.22	0.23	0.29
South east	0.17	0.22	0.33	0.28	0.23	0.22	0.22	0.20	0.23
East	0.17	0.11	0.16	0.28	0.19	0.19	0.18	0.20	0.19
South west	0.11	0.07	0.05	0.09	0.19	0.19	0.22	0.20	0.14
North	0.06	0.04	0.04	0.02	0.05	0.11	0.06	0.05	0.05
North east	0.06	0.04	0.03	0.02	0.02	0.04	0.06	0.05	0.04
North west	0.05	0.03	0.03	0.01	0.02	0.02	0.03	0.05	0.03
West	0.04	0.03	0.02	0.01	0.02	0.02	0.02	0.03	0.02

$\lambda_{max} =$ 8.46; Consistency index (CI)= 0.07; Consistency Ratio(CR) = 0.04

Table 9: Pair-wise matrix of Slope (degree) (where 1(0-15), 2(15-30), 3(30-45), 4(45-75)

	3	**4**	**2**	**1**
3	1	2	7	9
4	0.5	1	7	8
2	0.14	0.14	1	2
1	0.11	0.13	0.5	1
Total	1.75	3.27	15.50	20

Table 10: Synthesis matrix of Slope

	3	4	2	1	Priority Vecto
3	0.57	0.61	0.45	0.45	0.52
4	0.29	0.31	0.45	0.4	0.36
2	0.08	0.04	0.06	0.1	0.07
1	0.06	0.04	0.03	0.05	0.05

$\lambda_{max} =$ 7; Consistency index (CI)= 0.12; Consistency Ratio(CR) = 0.09

Table 11: Pair-wise matrix among different layers

	LULC	Forest density	Drainage	Slope	Aspect	Road	Settlement	Railway
LULC	1	2	3	4	5	7	8	9
Forest densit	0.5	1	2	4	5	6	7	8
Drainage	0.33	0.5	1	2	4	5	6	7
Slope	0.25	0.25	0.5	1	2	4	5	6
Aspect	0.2	0.2	0.25	0.5	1	3	4	6
Road	0.14	0.17	0.2	0.25	0.33	1	3	4
Settlement	0.13	0.14	0.17	0.2	0.25	0.33	1	2
Railway	0.11	0.13	0.14	0.17	0.17	0.25	0.5	1
Total	2.66	4.38	7.26	12.12	17.75	26.58	34.5	43

Table 12: Synthesis matrix of different layers

	LULC	Forest dens	Drainage	Slope	Aspect	Road	Settlemen	Railway	Priority Vector
LULC	0.38	0.46	0.41	0.33	0.28	0.26	0.23	0.21	0.32
Forest density	0.19	0.23	0.28	0.33	0.28	0.23	0.20	0.19	0.24
Drainage	0.13	0.11	0.14	0.17	0.23	0.19	0.17	0.16	0.16
Slope	0.09	0.06	0.07	0.08	0.11	0.15	0.14	0.14	0.11
Aspect	0.08	0.05	0.03	0.04	0.06	0.11	0.12	0.14	0.08
Road	0.05	0.04	0.03	0.02	0.02	0.04	0.09	0.09	0.05
Settlement	0.05	0.03	0.02	0.02	0.01	0.01	0.03	0.05	0.03
Railway	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.02

$\lambda_{max} =$ 8.57; Consistency index (CI)= 0.081; Consistency Ratio(CR) = 0.057

Table 13: Pairwise comparison matrix of LULC (Sambar)

	Sal mixed moist	**Sal forest**	**Pine**	**Grassland**	**Himalayan**	**Dry deciduous**	**Planation**	**Scrub**	**Degraded forest**	**Sub alpine**	**Agriculture**	**Settlement**	**Water body**
Sal mixed moist deciduous	1	2	3	3	4	5	6	7	8	8	9	9	9
Sal forest	0.5	1	2	3	3	5	6	7	8	8	9	9	9
Pine	0.33	0.5	1	2	3	4	5	6	7	8	8	9	9
Grassland	0.33	0.33	0.5	1	2	4	5	5	6	7	8	8	9
Himalayan moist temperate	0.25	0.33	0.33	0.5	1	2	3	4	5	6	7	8	9
Dry deciduous	0.20	0.2	0.25	0.25	0.5	1	2	3	4	6	6	7	8
Planation	0.17	0.17	0.2	0.2	0.33	0.5	1	2	4	5	5	6	7
Scrub	0.14	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3	4	5	6
Degraded forest	0.13	0.13	0.14	0.17	0.2	0.25	0.25	0.5	1	2	3	4	5
Sub alpine	0.13	0.13	0.13	0.14	0.17	0.17	0.2	0.33	0.5	1	2	3	4
Agriculture	0.11	0.11	0.13	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3

Settlement	0.11	0.11	0.11	0.13	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2
Water body	0.11	0.11	0.11	0.11	0.11	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1
Total	3.51	5.26	8.07	10.82	14.83	22.68	29.46	36.45	46.28	55.08	62.83	71.5	81

Table 14: Synthesized-matrix of LULC

	Sal mixed moist	**Sal forest**	**Pine**	**Grassland**	**Himalayan**	**Dry deciduous**	**Planation**	**Scrub**	**Degraded forest**	**Sub alpine**	**Agriculture**	**Settlement**	**Water body**	**Priority Vector**
Sal mixed moist deciduous	0.28	0.38	0.37	0.28	0.27	0.22	0.20	0.19	0.17	0.15	0.14	0.13	0.11	0.22
Sal forest	0.14	0.19	0.25	0.28	0.20	0.22	0.20	0.19	0.17	0.15	0.14	0.13	0.11	0.18
Pine	0.09	0.10	0.12	0.18	0.20	0.18	0.17	0.16	0.15	0.15	0.13	0.13	0.11	0.14
Grassland	0.09	0.06	0.06	0.09	0.13	0.18	0.17	0.14	0.13	0.13	0.13	0.11	0.11	0.12
Himalayan moist temperate	0.07	0.06	0.04	0.05	0.07	0.09	0.10	0.11	0.11	0.11	0.11	0.11	0.11	0.09
Dry deciduous	0.06	0.04	0.03	0.02	0.03	0.04	0.07	0.08	0.09	0.11	0.10	0.10	0.10	0.07
Planation	0.05	0.03	0.02	0.02	0.02	0.02	0.03	0.05	0.09	0.09	0.08	0.08	0.09	0.05

Scrub	0.04	0.03	0.02	0.02	0.02	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.07	0.04
Degraded forest	0.04	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.04	0.05	0.06	0.06	0.03
Sub alpine	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.02
Agriculture	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.02
Settlement	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Water body	0.03	0.02	0.01	0.01	0.01	0.01	0.005	0.005	0.004	0.005	0.01	0.01	0.01	0.01

λ_{max} = 14.93; Consistency index (CI)= 0.12; Consistency Ratio(CR) = 0.08

Table 15: Pair-wise matrix of forest density

	Very High	**High**	**Medium**	**Low density**
Very High density	1	2	8	8
High density	0.5	1	7	8
Medium	0.13	0.14	1	2
Low density	0.13	0.13	0.5	1
Total	1.75	3.27	16.5	19

Table 16: Synthesized matrix of Forest density

	Very High density	High density	Medium	Low density	Priority vector
Very High density	0.57	0.61	0.48	0.42	0.52
High density	0.29	0.31	0.42	0.42	0.36
Medium	0.07	0.04	0.06	0.11	0.07
Low density	0.07	0.04	0.03	0.05	0.05

λ_{max} = 4.10; Consistency index (CI)=0.03 ; Consistency Ratio(CR) = 0.03

Table 17: Pair-wise matrix of Aspect

	South	South east	East	South west	North	North east	North west	West
South	1	2	2	3	6	6	7	9
South east	0.5	1	2	3	5	6	7	8
East	0.5	0.5	1	3	4	5	6	8
South west	0.3	0.3	0.3	1	4	5	7	8
North	0.2	0.2	0.3	0.3	1	3	2	2
North east	0.2	0.2	0.2	0.2	0.3	1	2	2
North west	0.1	0.1	0.2	0.1	0.5	0.5	1	2
West	0.1	0.1	0.1	0.1	0.5	0.5	0.5	1
Total	**2.92**	**4.47**	**6.08**	**10.72**	**21.33**	**27**	**32.50**	**40**

Table 18: Synthesized matrix of Aspect

	South	South east	East	South west	North	North east	North west	West	Priority vector
South	0.34	0.45	0.33	0.28	0.28	0.22	0.22	0.23	0.29
South east	0.17	0.22	0.33	0.28	0.23	0.22	0.22	0.20	0.23
East	0.17	0.11	0.16	0.28	0.19	0.19	0.18	0.20	0.19
South west	0.11	0.07	0.05	0.09	0.19	0.19	0.22	0.20	0.14
North	0.06	0.04	0.04	0.02	0.05	0.11	0.06	0.05	0.05
North east	0.06	0.04	0.03	0.02	0.02	0.04	0.06	0.05	0.04
North west	0.05	0.03	0.03	0.01	0.02	0.02	0.03	0.05	0.03
West	0.04	0.03	0.02	0.01	0.02	0.02	0.02	0.03	0.02

λ_{max} = 8.46; Consistency index (CI)= 0.07; Consistency Ratio(CR) = 0.04

Table 19: Pair-wise comparison matrix of Slope (degree) (where 1(0-15), 2(15-30), 3(30-45), 4(45-75)

Slope	3	4	2	1
3	1	2	7	9
4	0.5	1	7	8
2	0.14	0.14	1	2
1	0.11	0.13	0.5	1
Total	1.75	3.27	15.5	20

Table 20: Synthesized matrix of Slope

	3	4	2	1	Priority Vector
3	0.57	0.61	0.45	0.45	0.52
4	0.29	0.31	0.45	0.4	0.36
2	0.08	0.04	0.06	0.1	0.07
1	0.06	0.04	0.03	0.05	0.05

λ_{max} = 4.08; Consistency index (CI)=0.02 ; Consistency Ratio(CR) = 0.03

Table 21: Pair-wise comparison matrix of different layers

	LULC	Forest density	Drainage	Slope	Aspect	Road	Settlement	Railway
LULC	1	2	3	4	5	7	9	9

Forest density	0.5	1	2	2	5	7	8	9
Drainage	0.33	0.5	1	2	4	5	6	9
Slope	0.25	0.5	0.5	1	3	5	6	8
Aspect	0.2	0.2	0.25	0.33	1	3	4	8
Road	0.14	0.14	0.2	0.2	0.33	1	2	2
Settlement	0.11	0.13	0.17	0.17	0.25	0.5	1	2
Railway	0.11	0.11	0.11	0.13	0.13	0.5	0.5	1
Total	2.65	4.58	7.23	9.83	18.71	29	36.5	48

Table 22: Synthesized – matrix of different layers

	Forest density	**LULC**	**Drainage**	**Slope**	**Aspect**	**Road**	**Settlement**	**Railway**	**Priority Vector**
LULC	0.38	0.44	0.42	0.41	0.27	0.24	0.25	0.19	0.32
Forest density	.19	0.22	0.28	0.20	0.27	0.24	0.22	0.19	0.23
Drainage	0.13	0.11	0.14	0.20	0.21	0.17	0.16	0.19	0.16
Slope	0.09	0.11	0.07	0.10	0.16	0.17	0.16	0.17	0.13
Aspect	0.08	0.04	0.03	0.03	0.05	0.10	0.11	0.17	0.08
Road	0.05	0.03	0.03	0.02	0.02	0.03	0.05	0.04	0.04
Settlement	0.04	0.03	0.02	0.02	0.01	0.02	0.03	0.04	0.03
Railway	0.04	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02

λ_{max} =0.063; Consistency index (CI)=0.048; Consistency Ratio(CR) = 0.04

Table 23: Pair-wise comparison matrix of LULC (Barking deer)

	Sal mixed moist	**Sal forest**	**Dry deciduous**	**Grassland**	**Pine forest**	**Himalayan moist**	**Plantation**	**Scrub**	**Sub alpine**	**Degraded forest**	**Agriculture**	**Settlement**	**Water body**
Sal mixed moist deciduous	1	2	3	3	4	5	6	7	8	8	9	9	9
Sal forest	0.5	1	2	3	4	5	6	7	8	8	9	9	9
Dry deciduous	0.33	0.5	1	2	3	4	5	6	7	8	9	9	9
Grassland	0.33	0.33	0.5	1	2	3	4	5	6	7	8	8	9
Pine forest	0.25	0.25	0.33	0.5	1	2	3	4	5	6	7	8	9
Himalayan moist temperate	0.2	0.2	0.25	0.33	0.5	1	2	3	4	6	6	7	8
Plantation	0.17	0.17	0.2	0.25	0.33	0.5	1	2	4	5	5	6	7
Scrub	0.14	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3	4	5	6
Sub alpine	0.13	0.13	0.14	0.17	0.2	0.25	0.25	0.5	1	2	3	4	5
Degraded forest	0.13	0.13	0.13	0.14	0.17	0.17	0.2	0.33	0.5	1	2	3	4

Agriculture	0.11	0.11	0.11	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3
Settlement	0.11	0.11	0.11	0.13	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2
Water body	0.11	0.11	0.11	0.11	0.11	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1
Total	3.51	5.18	8.05	10.95	15.83	21.68	28.46	36.45	46.28	55.08	63.83	71.5	81

Table 24: Synthesized- matrix of LULC

	Sal mixed moist	**Sal forest**	**Dry deciduous**	**Grassland**	**Pine forest**	**Himalayan moist**	**Plantation**	**Scrub**	**Sub alpine**	**Degraded forest**	**Agriculture**	**Settlement**	**Water body**	**Priority Vector**
Sal mixed moist deciduous	0.28	0.39	0.37	0.27	0.25	0.23	0.21	0.19	0.17	0.15	0.14	0.13	0.11	0.22
Sal forest	0.14	0.19	0.25	0.27	0.25	0.23	0.21	0.19	0.17	0.15	0.14	0.13	0.11	0.19
Dry deciduous	0.09	0.10	0.12	0.18	0.19	0.18	0.18	0.16	0.15	0.15	0.14	0.13	0.11	0.15
Grassland	0.09	0.06	0.06	0.09	0.13	0.14	0.14	0.14	0.13	0.13	0.13	0.11	0.11	0.11
Pine forest	0.07	0.05	0.04	0.05	0.06	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.09
Himalayan moist temperate	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.08	0.09	0.11	0.09	0.10	0.10	0.07

Plantation	0.05	0.03	0.02	0.02	0.02	0.02	0.04	0.05	0.09	0.09	0.08	0.08	0.09	0.05
Scrub	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.05	0.06	0.07	0.07	0.04
Sub alpine	0.04	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.04	0.05	0.06	0.06	0.03
Degraded forest	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.02
Agriculture	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.02
Settlement	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Water body	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01

λ_{max} =14.35; Consistency index (CI)=0.11; Consistency Ratio(CR) = 0.07

Table 25: Pair-wise comparison matrix of forest density

	High density	**Medium density**	**Very high density**	**Low density**
High density	1	2	7	9
Medium density	0.5	1	6	8
Very high density	0.14	0.17	1	2
Low density	0.11	0.13	0.5	1
Total	1.75	3.29	14.5	20

Table 26: Synthesized matrix of density

	High density	Medium density	Very high density	Low density	Priority vector
High density	0.57	0.61	0.48	0.45	0.53
Medium density	0.29	0.30	0.41	0.4	0.35
Very high density	0.08	0.05	0.07	0.1	0.08
Low density	0.06	0.04	0.03	0.05	0.05

λ_{max} = 4.06 ; Consistency index (CI)=0.02 ; Consistency Ratio(CR) = 0.02

Table 27: Pair-wise comparison matrix of Aspect

	South	South east	East	South west	North	North east	North west	West
South	1	1	2	2	3	4	4	5
South east	1.0	1	2	3	3	4	4	5
East	0.5	2.0	1	2	2	3	4	5
South west	0.5	0.3	0.5	1	2	2	3	4
North	0.3	0.3	0.5	0.5	1	2	2	3
North east	0.3	0.3	0.3	0.5	0.5	1	2	2

North west	0.3	0.3	0.3	0.3	0.5	0.5	1	2
West	0.2	0.2	0.2	0.3	0.3	0.5	0.5	1
Total	4.0	5.4	6.8	9.6	12.3	17.0	20.5	27.0

Table 28: Synthesized matrix of Aspect

	South	**South east**	**East**	**South west**	**North**	**North east**	**North west**	**West**	**Priority**
South	0.25	0.19	0.29	0.21	0.24	0.24	0.20	0.19	0.22
South east	0.25	0.19	0.29	0.31	0.24	0.24	0.20	0.19	0.24
East	0.12	0.37	0.15	0.21	0.16	0.18	0.20	0.19	0.20
South west	0.12	0.06	0.07	0.10	0.16	0.12	0.15	0.15	0.12
North	0.08	0.06	0.07	0.05	0.08	0.12	0.10	0.11	0.08
North east	0.06	0.05	0.05	0.05	0.04	0.06	0.10	0.07	0.06
North west	0.06	0.05	0.04	0.03	0.04	0.03	0.05	0.07	0.05
West	0.05	0.04	0.03	0.03	0.03	0.03	0.02	0.04	0.03

λ_{max} = 8.45; Consistency index (CI)= 0.06; Consistency Ratio(CR) = 0.04

Table 29: Pair-wise comparison matrix of Slope

	3	**4**	**2**	**1**
3	1	2	8	8
4	0.5	1	8	8

2	0.13	0.13	1	2
1	0.11	0.11	0.5	1
Total	1.74	3.24	17.5	19

Table 30: Synthesized matrix of Slope

	2	**1**	**3**	**4**	**Priority Vector**
2	0.58	0.62	0.46	0.42	0.52
1	0.29	0.31	0.46	0.42	0.37
3	0.07	0.04	0.06	0.11	0.07
4	0.06	0.03	0.03	0.05	0.04

λ_{max} = 4.05; Consistency index (CI)= 0.01 ; Consistency Ratio(CR) = 0.02

Table 31: Pair-wise comparison matrix among different layers

	LULC	**Forest**	**Drainage**	**Slope**	**Aspect**	**Road**	**Settlement**	**Railway**
LULC	1	2	3	4	5	7	9	9
Forest density	0.5	1	2	2	5	7	8	9
Drainage	0.33	0.5	1	2	4	5	6	8
Slope	0.25	0.5	0.5	1	3	5	6	8
Aspect	0.2	0.2	0.25	0.33	1	3	3	6
Road	0.14	0.14	0.2	0.2	0.33	1	2	2
Settlement	0.11	0.13	0.17	0.17	0.33	0.5	1	2
Railway	0.11	0.11	0.13	0.13	0.17	0.5	0.5	1
Total	2.65	4.58	7.24	9.83	18.83	29	35.5	45

Table 32: Synthesized- matrix of different layers

	LULC	Forest density	Drainage	Slope	Aspect	Road	Settlement	Railway	Priority Vector
LULC	0.38	0.44	0.41	0.41	0.27	0.24	0.25	0.20	0.32
Forest density	0.19	0.22	0.28	0.20	0.27	0.24	0.23	0.20	0.23
Drainage	0.13	0.11	0.14	0.20	0.21	0.17	0.17	0.18	0.16
Slope	0.09	0.11	0.07	0.10	0.16	0.17	0.17	0.18	0.13
Aspect	0.08	0.04	0.03	0.03	0.05	0.10	0.08	0.13	0.07
Road	0.05	0.03	0.03	0.02	0.02	0.03	0.06	0.04	0.04
Settlement	0.04	0.03	0.02	0.02	0.02	0.02	0.03	0.04	0.03
Railway	0.04	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02

λ_{max} =7.33; Consistency index (CI)=0.05; Consistency Ratio(CR) = 0.04

Table 33: Pair-wise comparison matrix of LULC (Wild boar)

	Sal mixed moist de	Sal forest	Dry deciduous	Grassland	Scrub	Plantation	Pine	Agriculture	Himalayan moist te	Degraded forest	Sub alpine	Settlement	Water body
Sal mixed moist decidu	1	2	2	3	4	5	6	7	8	8	9	9	9
Sal forest	0.5	1	2	3	4	5	6	7	8	8	9	9	9
Dry deciduous	0.5	0.5	1	2	3	4	5	6	7	8	9	9	9
Grassland	0.33	0.33	0.5	1	2	3	4	5	6	7	8	8	9
Scrub	0.25	0.25	0.33	0.5	1	2	3	4	5	6	7	8	9
Plantation	0.2	0.2	0.25	0.33	0.5	1	2	3	4	6	6	7	8
Pine	0.17	0.17	0.2	0.25	0.33	0.5	1	2	4	5	5	6	7
Himalayan moist temp	0.14	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3	4	5	6
Subalpine	0.13	0.13	0.14	0.17	0.2	0.25	0.25	0.5	1	2	3	4	5
Degraded forest	0.13	0.13	0.13	0.14	0.17	0.17	0.2	0.33	0.5	1	2	3	4
Agriculture	0.11	0.11	0.11	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2	3
Settlement	0.11	0.11	0.11	0.13	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1	2
Water body	0.11	0.11	0.11	0.11	0.11	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1
Total	3.68	5.18	7.05	10.95	15.83	21.68	28.46	36.45	46.28	55.08	63.83	72	81

Table 34: Synthesized- matrix of LULC

	Sal mixed moist deci	Sal forest	Dry deciduous	Grassland	Scrub	Plantation	Pine	Himalayan moist ter	Subalpine	Degraded forest	Agriculture	Settlement	Water body	Priority Vector
Sal mixed moist decidu	0.27	0.39	0.28	0.27	0.25	0.23	0.21	0.19	0.17	0.15	0.14	0.13	0.11	0.22
Sal forest	0.14	0.19	0.28	0.27	0.25	0.23	0.21	0.19	0.17	0.15	0.14	0.13	0.11	0.19
Dry deciduous	0.14	0.10	0.14	0.18	0.19	0.18	0.18	0.16	0.15	0.15	0.14	0.13	0.11	0.15
Grassland	0.09	0.06	0.07	0.09	0.13	0.14	0.14	0.14	0.13	0.13	0.13	0.11	0.11	0.11
Scrub	0.07	0.05	0.05	0.05	0.06	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.09
Plantation	0.05	0.04	0.04	0.03	0.03	0.05	0.07	0.08	0.09	0.11	0.09	0.10	0.10	0.07
Pine	0.05	0.03	0.03	0.02	0.02	0.02	0.04	0.05	0.09	0.09	0.08	0.08	0.09	0.05
Himalayan moist temp	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.05	0.06	0.07	0.07	0.04
Subalpine	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.04	0.05	0.06	0.06	0.03
Degraded forest	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.02
Agriculture	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.02
Settlement	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Water body	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01

Table 35: Pair-wise comparison matrix of forest density

	Low density	Medium density	High density	Very high density
Low density	1	2	3	7
Medium density	0.5	1	3	7
High density	0.33	0.33	1	3
Very high density	0.14	0.14	0.33	1
Total	1.98	3.48	7.33	18

Table 36: Synthesized matrix of density

	Low density	Medium density	High density	Very high density	Priority Vector
Low density	0.51	0.58	0.41	0.39	0.47
Medium density	0.25	0.29	0.41	0.39	0.33
High density	0.17	0.10	0.14	0.17	0.14
Very high density	0.07	0.04	0.05	0.06	0.05

λ_{max} = 4.06; Consistency index (CI)=0.022; Consistency Ratio(CR) = 0.02

Table 37: Pair-wise comparison matrix of Aspect

	South	**South**	**East**	**South west**	**North**	**North**	**North west**	**West**
South	**1**	**2**	**2**	**3**	**6**	**6**	**7**	**8**
South east	**0.5**	**1**	**2**	**3**	**5**	**5**	**7**	**8**
East	**0.5**	**2**	**1**	**3**	**4**	**5**	**6**	**7**
South west	**0.33**	**0.33**	**0.33**	**1**	**4**	**5**	**7**	**7**
North	**0.17**	**0.2**	**0.25**	**0.25**	**1**	**3**	**2**	**2**
North east	**0.17**	**0.2**	**0.2**	**0.2**	**0.33**	**1**	**2**	**2**
North west	**0.14**	**0.14**	**0.17**	**0.14**	**0.5**	**0.5**	**1**	**2**
West	**0.13**	**0.13**	**0.14**	**0.14**	**0.5**	**0.5**	**0.5**	**1**
Total	**2.93**	**6**	**6.09**	**10.74**	**21.33**	**26**	**32.5**	**37**

Table 38: Synthesized matrix of Aspect

	South	South east	East	South west	North	North east	North west	West	Priority vector
South	0.34	0.34	0.33	0.28	0.28	0.22	0.22	0.23	0.28
South east	0.17	0.17	0.33	0.28	0.23	0.22	0.22	0.2	0.23
East	0.17	0.34	0.16	0.28	0.19	0.19	0.18	0.2	0.21
South west	0.11	0.06	0.05	0.09	0.19	0.19	0.22	0.2	0.14
North	0.06	0.03	0.04	0.02	0.05	0.11	0.06	0.05	0.05
North east	0.06	0.03	0.03	0.02	0.02	0.04	0.06	0.05	0.04
North west	0.05	0.02	0.03	0.01	0.02	0.02	0.03	0.05	0.03
West	0.04	0.02	0.02	0.01	0.02	0.02	0.02	0.03	0.02

λ_{max} = 11.70 ; Consistency index (CI)=0.52; Consistency Ratio(CR) = 0.37

Table 39: Pair-wise comparison matrix of Slope

	1	2	3	4
1	1	2	4	6
2	0.5	1	3	5
3	0.25	0.33	1	2
4	0.17	0.2	0.5	1
Total	1.92	3.53	8.5	14

Table 40: Synthesized matrix of Slope

	1	2	3	4	Priority Vector
1	0.52	0.57	0.47	0.43	0.52
2	0.26	0.28	0.35	0.36	0.36
3	0.13	0.09	0.12	0.14	0.07
4	0.09	0.06	0.06	0.07	0.05

$\lambda_{max} = 4.35$; Consistency index (CI)=0.01; Consistency Ratio(CR) = 0.01

Table 41: Pair-wise comparison matrix of different layers

	LULC	Forest density	Drainage	Slope	Aspect	Road	Settlement	Railway
LULC	1	2	3	4	5	7	9	9
Forest density	0.5	1	2	2	5	7	8	9
Drainage	0.33	0.5	1	2	4	5	6	8
Slope	0.25	0.5	0.5	1	3	5	6	8
Aspect	0.2	0.2	0.25	0.33	1	2	2	2
Road	0.14	0.14	0.2	0.2	0.5	1	2	2
Settlement	0.11	0.13	0.17	0.17	0.5	0.5	1	2
Railway	0.11	0.11	0.13	0.13	0.5	0.5	0.5	1
Total	2.65	4.58	7.24	9.83	19.5	28	34.5	41

Table 42: Synthesized matrix of different layers

	Forest density	LULC	Drainage	Slope	Aspect	Road	Settlement	Railway	Priority vector
LULC	0.38	0.44	0.41	0.41	0.26	0.24	0.26	0.22	0.33
Forest density	0.19	0.22	0.28	0.20	0.26	0.24	0.23	0.22	0.23
Drainage	0.13	0.11	0.14	0.20	0.21	0.17	0.17	0.20	0.17
Slope	0.09	0.11	0.07	0.10	0.15	0.17	0.17	0.20	0.13
Aspect	0.08	0.04	0.03	0.03	0.05	0.10	0.06	0.05	0.06
Road	0.05	0.03	0.03	0.02	0.03	0.03	0.06	0.05	0.04
Settlement	0.04	0.03	0.02	0.02	0.03	0.02	0.03	0.05	0.03
Railway	0.04	0.02	0.02	0.01	0.03	0.02	0.01	0.02	0.02

λ_{max} = 8.6; Consistency index (CI)=0.08; Consistency Ratio(CR) = 0.06

Table 43: Pair-wise comparison matrix of LULC(Blue bull)

	Grassland	Dry deciduous	Sal mixed moist	Plantation	Degraded forest	Sal forest	Scrub	Pine forest	Himalayan	Agriculture	Sub alpine	Settlement	Water body
Grassland	1	2	3	3	4	4	6	8	8	8	9	9	9
Dry deciduous	0.5	1	2	3	3	4	5	8	8	7	8	9	9
Sal mixed moist deciduous	0.33	0.5	1	2	3	4	5	7	7	7	8	9	9
Plantation	0.33	0.33	0.5	1	2	4	5	7	7	7	8	9	9
Degraded forest	0.25	0.33	0.33	0.5	1	2	4	6	6	7	8	8	9

Sal forest	0.25	0.25	0.25	0.25	0.5	1	2	3	4	5	6	7	8
Scrub	0.17	0.2	0.2	0.2	0.25	0.5	1	2	4	5	6	7	8
Pine forest	0.125	0.13	0.14	0.14	0.17	0.33	0.5	1	3	3	4	6	7
Himalayan moist temperate	0.125	0.13	0.14	0.14	0.17	0.25	0.25	0.33	1	2	3	4	5
Agriculture	0.125	0.14	0.14	0.14	0.14	0.2	0.2	0.33	0.5	1	2	3	4
Sub alpine	0.11	0.125	0.125	0.125	0.125	0.17	0.17	0.25	0.33	0.5	1	2	3
Settlement	0.11	0.11	0.11	0.11	0.125	0.14	0.14	0.17	0.25	0.33	0.5	1	2
Water body	0.11	0.11	0.11	0.11	0.11	0.13	0.13	0.14	0.2	0.25	0.33	0.5	1
Total	3.54	5.36	8.06	10.73	14.59	20.72	29.38	43.23	49.28	53.08	63.83	74.5	83

Table 44: Synthesized matrix

	Grassland	Dry deciduous	Sal mixed moist deciduous	Scrub	Degraded forest	Plantation	Sal forest	Pine forest	Himalayan moist temperat	Agriculture	Sub alpine	Settlement	Water body	Priority Vector
Grassland	0.28	0.37	0.37	0.28	0.27	0.19	0.20	0.19	0.16	0.15	0.14	0.12	0.11	0.22
Dry deciduous	0.14	0.19	0.25	0.28	0.21	0.19	0.17	0.19	0.16	0.13	0.13	0.12	0.11	0.17
Sal mixed moist deciduous	0.09	0.09	0.12	0.19	0.21	0.19	0.17	0.16	0.14	0.13	0.13	0.12	0.11	0.14
Scrub	0.09	0.06	0.06	0.09	0.14	0.19	0.17	0.16	0.14	0.13	0.13	0.12	0.11	0.12
Degraded forest	0.07	0.06	0.04	0.05	0.07	0.10	0.14	0.14	0.12	0.13	0.13	0.11	0.11	0.10
Plantation	0.07	0.05	0.03	0.02	0.03	0.05	0.07	0.07	0.08	0.09	0.09	0.09	0.10	0.07
Sal forest	0.05	0.04	0.02	0.02	0.02	0.02	0.03	0.05	0.08	0.09	0.09	0.09	0.10	0.05
Pine forest	0.04	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.06	0.06	0.06	0.08	0.08	0.04
Himalayan moist temperate	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.04	0.05	0.05	0.06	0.03
Agriculture	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.02
Sub alpine	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.02
Settlement	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.01
Water body	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01

λ_{max} =24.08; Consistency index (CI)=0.92; Consistency Ratio(CR) = 0.62

Table 45: Pair-wise comparison matrix of forest density

	Low density	**Medium density**	**High density**	**Very high density**
Low density	1	2	7	9
Medium density	0.5	1	6	8
High density	0.14	0.17	1	2

Very high density	0.11	0.13	0.5	1
Total	1.75	3.29	14.5	20

Table 46: Synthesized matrix of forest density

	Low density	**Medium density**	**High density**	**Very high density**	**Priority vector**
Low density	0.57	0.61	0.48	0.45	0.53
Medium density	0.29	0.30	0.41	0.4	0.35
High density	0.08	0.05	0.07	0.1	0.08
Very high density	0.06	0.04	0.03	0.05	0.05

λ_{max} = 4.06 ; Consistency index (CI)=0.02 ; Consistency Ratio(CR) = 0.02

Table 47: Pair-wise comparison matrix of Aspect

	East	**South east**	**South**	**South west**	**North**	**North east**	**North west**	**West**	**Priority Vector**
East	0.25	0.19	0.29	0.21	0.24	0.24	0.20	0.19	0.22
South east	0.25	0.19	0.29	0.31	0.24	0.24	0.20	0.19	0.24
South	0.12	0.37	0.15	0.21	0.16	0.18	0.20	0.19	0.20
South west	0.12	0.06	0.07	0.10	0.16	0.12	0.15	0.15	0.12
North	0.08	0.06	0.07	0.05	0.08	0.12	0.10	0.11	0.08

North east	0.06	0.05	0.05	0.05	0.04	0.06	0.10	0.07	0.06
North west	0.06	0.05	0.04	0.03	0.04	0.03	0.05	0.07	0.05
West	0.05	0.04	0.03	0.03	0.03	0.03	0.02	0.04	0.03

Table 48: Synthesized matrix of Aspect

	East	**South east**	**South**	**South west**	**North**	**North east**	**North**	**West**
East	1	1	2	2	3	4	4	5
South east	1.0	1	2	3	3	4	4	5
South	0.5	2.0	1	2	2	3	4	5
South west	0.5	0.3	0.5	1	2	2	3	4
North	0.3	0.3	0.5	0.5	1	2	2	3
North east	0.3	0.3	0.3	0.5	0.5	1	2	2
North west	0.3	0.3	0.3	0.3	0.5	0.5	1	2
West	0.2	0.2	0.2	0.3	0.3	0.5	0.5	1
Total	4.0	5.4	6.8	9.6	12.3	17.0	20.5	27.0

λ_{max} = 8.45; Consistency index (CI)= 0.06; Consistency Ratio(CR) = 0.04

Table 49: Pair-wise comparison matrix of Slope

	2	1	3	4
2	1	2	8	9
1	0.5	1	8	9
3	0.13	0.13	1	2
4	0.11	0.11	0.5	1
Total	1.74	3.24	17.5	21

Table 50: Synthesized matrix of Slope

	2	1	3	4	Priority Vector
2	0.58	0.62	0.46	0.43	0.52
1	0.29	0.31	0.46	0.43	0.36
3	0.07	0.04	0.06	0.10	0.07
4	0.06	0.03	0.03	0.05	0.05

$\lambda_{max} =$ 4.11; Consistency index (CI)= 0.04 ; Consistency Ratio(CR) = 0.04

Table 51: Pair-wise comparison matrix of different layers

	LULC	Forest density	Drainage	Slope	Aspect	Road	Settlement	Railway
LULC	1	2	3	4	5	7	9	9
Forest density	0.5	1	2	2	5	7	9	9
Drainage	0.33	0.5	1	2	4	5	6	9
Slope	0.25	0.5	0.5	1	4	5	6	8
Aspect	0.2	0.2	0.25	0.25	1	3	4	8

Road	0.14	0.14	0.2	0.2	0.33	1	2	2
Settlement	0.11	0.11	0.17	0.17	0.25	0.5	1	2
Railway	0.11	0.11	0.11	0.13	0.13	0.5	0.5	1
Total	2.65	4.57	7.23	9.74	19.71	29	37.5	48

Table 52: Synthesized matrix of different layers

	Forest	**LULC**	**Drainage**	**Slope**	**Aspect**	**Road**	**Settlement**	**Railway**	**Priority**
Forest density	0.38	0.44	0.42	0.41	0.25	0.24	0.24	0.19	0.34
LULC	0.19	0.22	0.28	0.21	0.25	0.24	0.24	0.19	0.23
Drainage	0.13	0.11	0.14	0.21	0.20	0.17	0.16	0.19	0.16
Slope	0.09	0.11	0.07	0.10	0.20	0.17	0.16	0.17	0.13
Aspect	0.08	0.04	0.03	0.03	0.05	0.10	0.11	0.17	0.06
Road	0.05	0.03	0.03	0.02	0.02	0.03	0.05	0.04	0.03
Settlement	0.04	0.02	0.02	0.02	0.01	0.02	0.03	0.04	0.02
Railway	0.04	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02

λ_{max} = 7.35; Consistency index (CI)=0.05; Consistency Ratio(CR) = 0.03

Table 53: Pair-wise comparison matrix of different layers (Tiger)

	Sambar	**Spotted deer**	**Barking deer**	**Wild boar**	**Blue bull**
Sambar	1	2	5	7	8
Spotted deer	0.5	1	4	7	8

Barking deer	0.2	0.25	1	7	8
Wild boar	0.14	0.14	0.14	1	6
Blue bull	0.13	0.13	0.13	0.17	1
Total	1.97	3.52	10.27	22.17	31

Table 54: Synthesized matrix of different layers

	Sambar	**Spotted deer**	**Barking deer**	**Wild boar**	**Blue bull**	**Priority vector**
Sambar	0.51	0.57	0.49	0.32	0.26	0.43
Spotted deer	0.25	0.28	0.39	0.32	0.26	0.3
Barking deer	0.1	0.07	0.07	0.32	0.26	0.17
Wild boar	0.07	0.04	0.04	0.05	0.19	0.07
Blue bull	0.06	0.04	0.04	0.01	0.03	0.03

λ_{max} = 5.29; Consistency index (CI)=0.07; Consistency Ratio(CR) = 0.06

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