Graph theory based analysis of forest connectivity in Western Himalayas

Thesis submitted to the Andhra University, Visakhapatnam in partial fulfilment of the requirement for the award of

Master of Technology in Remote Sensing and Geographic Information System

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CERTIFICATE

This is to certify that Mr. **M.Ramprakash** has carried out the thesis entitled "Graph theory based analysis of forest connectivity in Western Himalayas" in partial fulfilment for the award of degree of Master of Technology (M. Tech.) in Remote Sensing and GIS. The thesis has been carried out in Forestry and Ecology Department and is the original work of the candidate under the guidance of **Dr. Arijit Roy**, Scientist/Engineer-F, Forestry and Ecology Department, Indian Institute of Remote Sensing, Dehradun, India.

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Abstract

Landscape connectivity play a vital role in maintaining the viability and survival of the species through the movement of organisms, genetic interchange and other ecological flows. Fragmentation due to land use change has resulted in disruption of the connectivity among natural landscape. Due to ever increasing natural areas coming under human influence, analysis of forest connectivity is vital for conservation of endemic biodiversity. Graph theory is among the best method for studying network in landscape owing to its capability to handle large datasets. Considering the individual forest patches as nodes, graphs estimate the interactions among the habitats as links in GIS environment. The study was conducted to estimate the changes in the connectivity pattern over Western Himalayas over three decades (1985 – 2014) using an open source software (Conefor 2.6) using all pairs shortest path algorithm. It is of utmost importance to study spatial pattern analysis while studying connectivity pattern. Patch analyst 5.1 was used to find the changes in spatial pattern over the three decades.

Critical areas for conservation were identified and the increase in fragmentation was observed. It was also observed that the level of connectivity decreased through time as a result of fragmentation. Of the landscape connectivity indices used, PC (Probability of Connectivity) was found to be the best performing index for its ability to include the topographical position of the patch in the landscape. Level of connectivity of *Abies pindrow, Betula utilis* and *Taxus wallichiana* were studied. The potential distribution of these species were modelled through species distribution modelling (Maxent 3.3.3k), with the help of presence only data. Then, the highly distributed patches were used for connectivity analysis of the focal species. Jackknife evaluation was used to find the best performing environmental variables. The resulting network of these species was visualized to estimate the level of connectivity. The graph constructed was 300 meter thresholded planar graph. 300 meter was taken as threshold distance as these wind dispersed (anemochory) species cannot disperse beyond 300 meters. The resultant networks were scale-free networks. Normally, it is desired to have a scale-free network for habitats as a single large hub can be declared as a protected area and more importance can be given to it for conservation. The nodes and the links can be analysed using a threshold to estimate the critical node or forest/natural area patches which are key to movement of species in event of climate change.

Keywords: Landscape connectivity, Graph theory, Network analysis, fragmentation, dispersal

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Abbreviations

AWF	Area Weighted Flux
AWiFS	Advanced Wide Field Sensor
DEM	Digital Elevation Model
F	Flux
H	Harary index
IGBP	ISRO Geosphere-Biosphere Programme
IIC	Integral Index of Connectivity
LCP	Landscape Coincidence Probability
LISS	Linear Imaging Self-Scanning
LULC	Land Use Land Cover
MAR	Mean Annual Rainfall
MAT	Mean Annual Temperature
Maxent	Maximum Entropy
MSS	Multi Spectral Scanner
NC	Number of Components
NL	Number of Links
PC	Probability of Connectivity

Chapter – 1 Introduction

'Nature, the earth herself, is the only panacea'

-Henry David Thoreau, 1859

Natural ecosystems of our earth are experiencing changes that are unprecedented in historic times. Destruction and degradation of these natural habitats by humankind has widespread and profound implications on biological diversity and their sustainability. Such activities are not a new phenomenon; but the rate at which it takes place causes great alarm. Along with the loss of natural habitats, maintaining and conserving biodiversity in current human dominated landscapes have become a challenge. In many landscapes, large tracts of forest no longer exist. Remnants of the natural habitat occur as a mosaic of large and small forest patches. This problem can be sorted out with the help of connectivity study. Forest patch connectivity is a practical measure that responds directly to the isolating effects of habitat fragmentation. Connectivity analysis along with spatial pattern analysis fulfils the uphill task of analysing the landscape at its own scale.

1.1 Landscape ecology

Movement of animals, water and wind as a result of these the flow of materials, energy and nutrients are the central theme in landscape ecology (Hobbs, 1993). Landscape ecology is now a well-established disciple that tries to integrate the understanding of ecosystems at entire landscape scale. Thus, landscape ecology provides a broad framework for exploring the ecological function of habitat fragments and the benefits of connectivity and energy interchange between fragments in sustaining population (Forman, 1995). In other words, landscape ecology seeks to understand the structure of landscape, the way they function and change over time. The flow of energy and matter (both biotic and abiotic) between the patches depends on three factors i.e., wind, water and animals (Forman, 1995). Movement of species is not only critical for the survival of local population but also to the ecological function of the landscape. In the past decades, tremendous progress had been made in this field and also rapid progress are made day by day. Wu and Hobbs (2002) had identified ecological flow between forest patches and spatial pattern as emerging fields of landscape ecology.

1.2 Patch connectivity

According to Forman (1995), there are two main components that influence potential connectivity for a particular species, community or ecological process – a structural component and a behavioural component. The structural component of connectivity is determined by the spatial arrangement of different types of habitats in the landscape. It is influenced by factors such as the continuity of suitable habitat, the extent and length of gaps, the distance to be traversed, and the presence of alternative pathways or network properties (Collinge and Forman, 1998).

The behavioural component of connectivity relates to the behavioural response of individuals and species to the physical structure of the landscape. It is influenced by factors such as the scale at which a species perceives and moves within the environment, its habitat requirements and degree of habitat specialization, its tolerance of disturbed habitats, the life stage and timing of dispersal movements, and the species' response to predators and competitors (Harrison, 1992). The following figure portrays the true nature of connectivity which can help to enhance the diversity through gene pool flows.

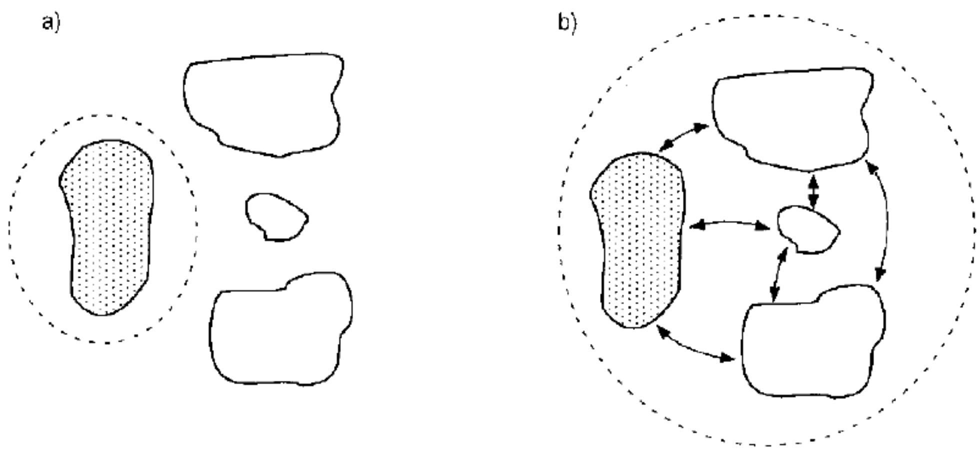


Figure 1.1 a) Isolated forest patches, b) Connected forest patches which can help in conservation of biodiversity cited from Forman (1995).

After the introduction of landscape connectivity as a new field in landscape ecology, some modelling studies were done to measure the movement of resources among patches over the entire landscape (Doak et al, 1992; Demers et al., 1995; Schippers et al., 1996; Schumaker, 1996). Dispersal success defined as proportion of individuals which immigrate into new habitat patches was simulated using classified GIS maps (Schippers et al., 1996) and predicted by analysing the potential of landscape indices (Schumar, 1996). Search time defined as the number of movement steps required to find a new habitat patch was used to quantify connectivity (Doak et al., 1992). Spatial population distribution assumed to be indirect measures of connectivity was investigated by With et al. (1997). Other than modelling approaches, few empirical studies like functional distances (Petit and Burel, 1998a; Petit and Burel, 1998b) and movement measurements like mark-release recapture (Pither and Taylor, 1998) were performed. After all these preliminary studies, landscape connectivity took a new dimension when Urban and Keitt (2001), introduced graph theory into connectivity analysis in landscape ecology.

1.3 Graph theory

1.3.1 History

Graph theory had its beginning in 1736 when Euler considered the (general case of the) Königsberg bridge problem: The (Eulerian) path should cross over each of the seven bridges exactly once and the aim was to find a nice path across the seven Köningsberg bridges. In 1859, Sir William Rowan Hamilton developed a toy based on finding a path visiting all cities in a graph exactly once and sold it to a toy maker in Dublin. It took another 200 years to write the first book on graph theory. This was "Theorie der endlichen und unendlichenGraphen" by Konig in 1936.

Since then graph theory has developed into an extensive and popular branch of mathematics, which has been applied to many problems in mathematics, computer science, and other scientific and not-so-scientific areas. But now graph theory is used for finding communities in networks where we want to detect hierarchies of substructures and their sizes can become quite big. Some of the common uses of graph theory in our daily life are ranking (ordering) hyperlinks or to find the shortest path home in a GPS.

1.3.2 Graphs

The fundamental concept of graph theory as mentioned by Diestel (2005), is the graph, which (despite the name) is best thought of as a mathematical object rather than a diagram, even though graphs have a very natural graphical representation. A graph – usually denoted G(V,E) or G = (V,E) – consists of set of vertices V together with a set of edges E. Vertices are also known as nodes, points and (in social networks) as actors, agents or players. Edges are also known as lines and (in social networks) as ties or links. An edge e = (u, v) is defined by the unordered pair of vertices that serve as its end points. Two vertices u and v are adjacent if there exists an edge (u, v) that connects them. An edge e = (u, u) that links a vertex to itself is known as a self-loop or reflexive tie. The number of vertices in a graph is usually denoted n while the number of edges is usually denoted m.

As an example, the graph depicted in the figure below mentioned in Diestel (2005) has vertex set V= {a, b, c, d, e, f} and edge set E = {(a, b), (b, c), (c, d), (c, e), (d, e), (e, f)}.

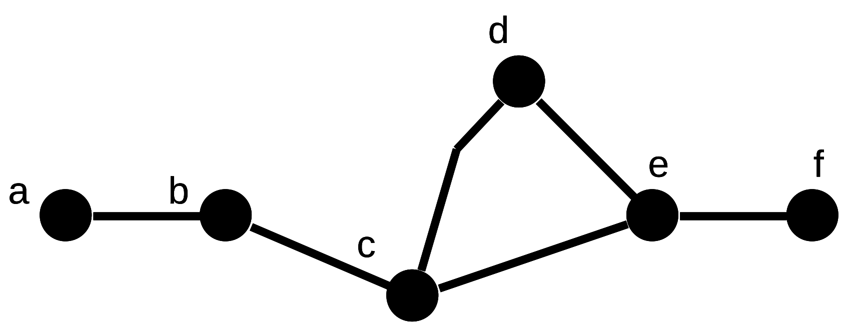


Figure 1.2 Example of a simple graph

Table 1.1 Terminologies in graph theory

Graph	Finite set of dots(vertices or nodes) and connecting links(edges)
Vertex	Dot in the graph where edges meet
Edge	Used to connect pairs of vertices
Weights	Assigned to edges depending upon the problem being solved
Loop	Special type of edge that connects a vertex to itself

Degree of a Vertex	Number of edges meeting a particular vertex
Path	Sequence of vertices using the edges
Circuit	Path that begins and ends at the same vertex
Connected graphs	Paths existing between any vertex to any other vertex
Unconnected graphs	No path between any two vertices in the graph
Component	Subgraph where a path exists from one node to every other node within that subgraph
Directed graphs	Edges symbolizing ordered relationship between two nodes
Undirected graphs	Edges that do not have any ordered relationship between the nodes

1.3.3 Basic concepts

Here are the following terminologies from Ruohonen (2008) that explain the basic concepts of graphs:

- The two vertices u and v are end vertices of the edge (u, v).
- Edges that have the same end vertices are parallel.
- An edge of the form (v, v) is a loop.
- A graph is simple if it has no parallel edges or loops.
- A graph with no edges (i.e. E is empty) is empty.
- A graph with no vertices (i.e. V and E are empty) is a null graph.
- A graph with only one vertex is trivial.
- Edges are adjacent if they share a common end vertex.
- Two vertices u and v are adjacent if they are connected by an edge, in other words, (u, v) is an edge.
- The degree of the vertex v, written as d (v), is the number of edges with v as an end vertex.
- A pendant vertex is a vertex whose degree is 1.
- An edge that has a pendant vertex as an end vertex is a pendant edge.
- An isolated vertex is a vertex whose degree is 0.

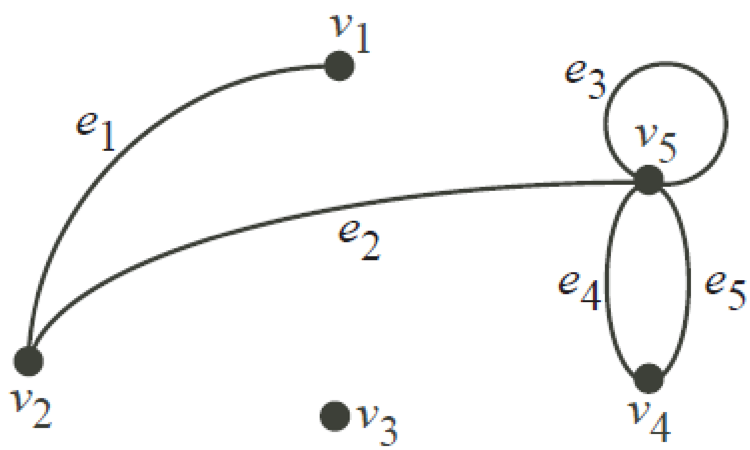


Figure 1.3 Graph showing vertices and edges

- v4 and v5 are end vertices of e5.
- e4 and e5 are parallel.
- e3 is a loop.
- The graph is not simple.
- e1 and e2 are adjacent.
- v1 and v2 are adjacent.
- The degree of v1 is 1 so it is a pendant vertex.
- e1 is a pendant edge.
- The degree of v5 is 5.
- The degree of v4 is 2.
- The degree of v3 is 0 so it is an isolated vertex.

1.4 Graph theory in landscape ecology

After the introduction of graph theory in landscape ecology (Urban and Kiett, 2000), lots of improvement had been made in the field but the recent plot is the integration of connectivity for biodiversity conservation and landscape planning (Ng et al., 2013). Landscape connectivity had been analysed through the development of many indices that quantify the connectivity through graph theory that assesses the individual importance of forest patches to uphold its ecological fluxes. Some of the indices are Number of Links, Number of Components, Harary index, Landscape Coincidence Probability, Class Coincidence Probability, Betweeness Centrality, Integral Index of Connectivity, Flux, Area Weighted Flux, Probability of Connectivity (Saura and Torne, 2009). A step further leads to new technique, where habitat availability (total area of the landscape) which plays a major role in quantifying connectivity near to perfection. Indices like Integral Index of Connectivity and Probability of Connectivity are used to calculate habitat availability (Saura and Pascaul-Hortal, 2007). Still deep research had divided these indices into flux, intra and connector (Saura and Rubio, 2010) which are explained in the forthcoming chapters. The dynamics of the landscape was studied by constructing a network with the help of graph theory (Liu et al., 2014a).

1.5 Integration of modelling in connectivity analysis

Species distribution models can be used as a tool for getting information about the spatial distribution of any species which may be really difficult to obtain in rugged and difficult terrains. The outputs of these models can also be used in monitoring areas for the suitability to endangered species, through various spatial and non spatial habitat variables (Davis et al., 1990). Kushwaha et al. (2004) and Zarri et al. (2008) had stated that the outputs of these models can be used for the assessment of environmental impacts. The quickest, most cost-effective and accurate way for identification of suitable habitats is through the application of geospatial technologies, which include remote sensing and geographic information system (GIS) combined with the global positioning system (GPS).

1.6 Need for this study

Key issues hampering the conservation of biological diversity are habitat loss and fragmentation (Allen, 1980). The undying process of habitat loss and fragmentation has some serious implications for the conservation of flora and fauna throughout the world.

Indigenous flora and fauna are facing the verge of population decline and extinction owing to the continuation of climate change and fragmentation of natural habitats. Climate change pushes the current forest site to new environmental changes which are not fit for the indigenous, endemic species and the fragmentation leads to reduction in the size of habitats. Forest connectivity ensures diversity to be maintained through the possibility of gene flow (dispersal). Thus, landscape conservation is to be promoted through connectivity of remaining forest habitat patches. Graph theory had found its place in the network analysis of forest connectivity owing to its capability to handle large datasets.

Connectivity loss is a major threat for conservation of biodiversity and the maintenance of ecological functions of the landscape. Forest fragmentation has been said to be the major contributor in connectivity losses. Fragmentation in forest habitats occur mainly due to the changes that happen in land use policies. Landscape connectivity facilitates the movement of organisms, genetic interchange and other ecological flows that are critical for the viability and survival of species and for the conservation of biodiversity in general. This has led to an increasing interest in considering connectivity for landscape management and conservation planning purposes.

In this context, graph structures have been shown to be a powerful and effective way of both representing the landscape pattern and performing complex analysis regarding landscape connectivity. Graph theory offers the ability to identify patches that are very important to habitat connectivity and thus to long term population persistence across the landscape (Minor and Urban, 2007).

The area of research in this study was taken as Western Himalayas. Himalayas known as the water tower of the earth supports nearly 50% of the flowering plants of India whereas 30% is endemic to the region. Dividing it into eastern and western Himalayas, it supports 8000 and 5000 flowering species respectively (Rao, 1994). Western Himalayas, owing to its diversity of ecosystems are facing a serious problem of habitat loss, degradation and fragmentation. The region with a large area and huge fragmentation problem along with a large list of climate sensitive and endangered species will be a perfect one to study the connectivity which is the first time to incorporate in this region. *Abies pindrow, Betula utilis* and *Taxus wallichiana* were chosen to study the level of connectivity for species level study. The dispersal of these species are wind-driven, so their dispersal distance can be used as such for the study. Also, these species are native to Himalayas and climate sensitive which will be a major issue to tackle species survival.

The focus of this study is on the importance of landscape connectivity for the conservation of biodiversity with the integration of spatial pattern analysis and connectivity analysis.

1.7 Research Questions

- What will be the spatial pattern in time domain with regard to fragmentation of forests?
- How does the spatial distribution changes with respect to climate?
- What are the best connectivity indices and how far it helps to address the issue of connectivity?

1.8 Research objectives

- To study the changes in landscape pattern in time domain to analyze the fragmentation effect
- To obtain and address the potential distribution of endangered tree species.
- To find the critical nodes for connectivity in terms of structural as well as functional level of connectivity

1.9 Structure of Thesis

The thesis has been structured into following six chapters:

Introduction: The introduction throws light on the study background and has its roots upon and the need for the study addressing the rationale and the objectives of the thesis.

Review of Literature: This chapter includes the various studies in which the current research is based upon and which refines the research questions cited above and provides way for obtaining solutions to them.

Study Area and Materials: The detailed description of the study area is illustrated in this chapter where the background of the study area is explained, which lies as the basis for understanding the rationale along with information about the materials used for this study.

Methods: This chapter explains the systematic way of solving the research questions which includes the various methods involved in the study.

Results and Discussion: The research outcomes are discussed extensively in this chapter.

Conclusions and Recommendations: Based on the outcomes and the discussions, conclusions and recommendations are provided to the scientific community and the research utilizing population.

Chapter – 2 Review of literature

2.1 Western Himalayas

Western Himalaya is commonly referred to the western half of the Himalayan Mountains, stretching from Afghanistan to Nepal. The region is well known for its diverse natural ecosystems which are present in large stretches. The western Himalayas are generally drier than the eastern Himalayas (Singh and Singh, 1987). The forest group present over this region includes Tropical Moist Deciduous forest, Tropical Dry Deciduous forest, Montane Subtropical Pine forest, Montane Subtropical Dry Evergreen forest, Montane Himalayan Temperate forest, Montane Himalayan Dry Temperate forest, Sub-Alpine forest, Moist Alpine scrub and Dry Alpine scrub (Champion and Seth, 1968).There is a high spatial variation in the forest types as a result of altitude and aspect (Hajra and Rao, 1990).

2.2 Landscape Ecology

The term landscape ecology was coined and elaborated by German bio geographer Carl Troll in 1950 (Turner, 2005). Landscape ecology considers "the development and dynamics of spatial heterogeneity and its effects on ecological processes, and the conservation of spatial heterogeneity (Risser, 1984). Landscape ecology is now a well-established field which provides a strong conceptual and theoretical basis for understanding the landscape – its structure, function and change (Forman and Godron, 1986).The importance of dispersal and movement of species through the landscape have been emphasised in the developments in metapopulation biology and landscape ecology, with species populations interacting dynamically through landscape- scale movements (Taylor et al., 1993; Hanski and Gilpin, 1997; Vos et al., 2001).The restriction of gene flow and dispersal results in isolated populations, which leads to the loss of genetic material (Keyghobadi, 2007).Christensen et al. (1996) had stated that interactions at ecosystems level should be considered rather than focusing on patch level. The importance of dispersal for survival of species has increased due to the tremendous anthropogenic pressure and fragmentation. In situations like this, research done at landscape level prove efficient for management as well as conservation, by linking patterns of connectivity and their disturbances in dynamic landscapes.

Forman and Godron (1986) had stated that the combination of both habitat patches and its functional connection between them is known as habitat networks. Habitat networks help to analyse spatial processes whereas the habitat itself helps to analyse spatial pattern. The central importance in the current study goes to the relation between spatial patterns and processes. Spatial pattern and patch composition are mentioned as the key features for population persistence in a fragmented landscape. Spatial patterns leads to the study of habitat fragmentation while spatial processes leads to a much wider term called landscape connectivity. The gap between landscape connectivity and landscape spatial pattern may discriminate recolonization of species (Kindlmann and Burel, 2008). It is common for fragmented populations to get extinct locally (Fahrig and Merriam, 1994) and the reintroduction of these populations is critical for the normal functioning of the ecosystem (Hanski and Hanski, 1999). Thus there is a necessity of network of patches (that can help in connectivity) for the individuals of population to disperse (Bowne and Bowers, 2004).Stability and diversity of the landscape can be maintained by connectivity between forest patches (Galpern et al., 2011).

2.3 Habitat fragmentation

Forest fragmentation is a landscape-level process in which mainly due to human activity and sometimes due to topography, large forest areas are divided into small, complex and isolated fragments (Harris, 1984). It will be potentially difficult for some species to cope up with changes in their habitat in a highly fragmented landscape and in the shifts of species distributions in response to changes to climate (Araujo et al., 2004; Kharouba and Kerr, 2010).Wilcove et al. (1998) has emphasized that habitat loss and fragmentation are the primary threats to biodiversity. Habitat loss, more than fragmentation has a significant negative impact on biodiversity (Fahrig, 2003). But the negative effects can be enlarged by fragmentation to a great extent (Monkkonen and Reunanen, 1999).Also it is stated that fragmentation is the starting phase of habitat loss (Faaborg et al., 1995; Jaeger, 2000). Barriers made by humans in the name of development, such as railways and roadways begin the process of fragmentation. Species instead of moving between a single forest patch are forced to move between small and scattered patches. Situations, like this constitutes the main reason behind gene flow reduction (Allentoft and O'Brein, 2010). The shrinking size of the patch and increased effect of isolation often has a strong bearing on the frequency and intensity of disturbances of fire in forest patches (Baker, 1989). Growing evidence had stated that habitat fragmentation may contribute to substantial loss in biodiversity, both regionally and globally (Fahrig, 2003; Krauss et al., 2010).

Terborgh (1989) had stated that forest fragmentation causes decline in biodiversity more predominantly in human dominated forest areas. Fragmentation has a lots of negative effects on forest such as Population decline and extinction (Donovan and Flather, 2002), Loss of genetic diversity (Gibbs, 2001), Encroachment (Vos et al., 2001), Density reduction in forests (Haddad and Baum, 1999), Reduction in growth rate (Foppen et al., 1999), Disruption of biotic interactions, reducing seed setting and increasing the rate of parasitism (Kruess and Tscharntke, 2000) and Invasive and exotic species invasion (Minor et al., 2009). The results from fragmentation indices and aggregation indices at the landscape metric level witnessed the increase in fragmentation of the forest habitats from 1991 to 2006 and a 91.3% of connectivity loss because of this spatial pattern change (Liu et al., 2014b). This explains the need for a connectivity study integrated with fragmentation analysis.

Three inferences can be drawn easily from the following figure. They state that fragmentation

- Causes overall loss in habitat
- Reduction in size of habitat and
- Chances of patch isolation is increased

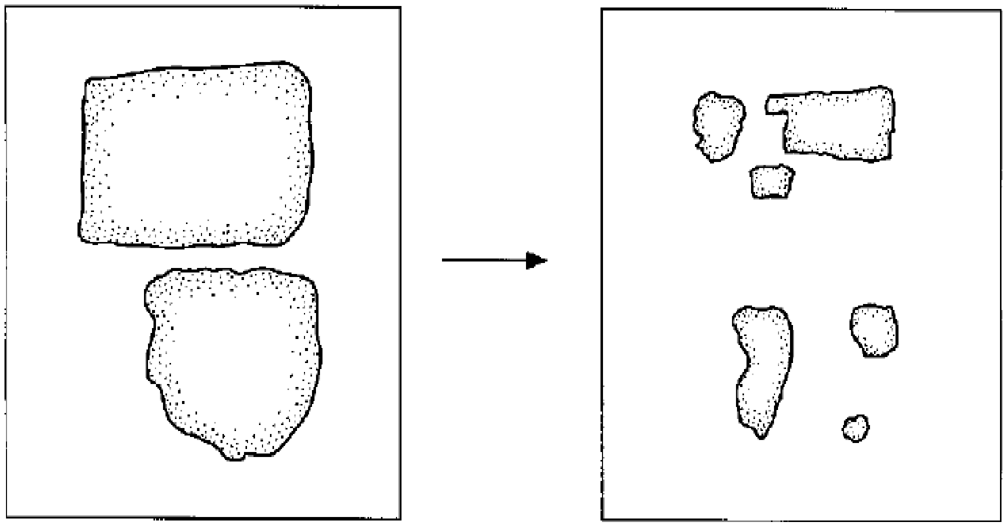


Figure 2.1 The process of habitat fragmentation given by Bennett (1998).

2.4 Landscape connectivity

The concept of landscape connectivity was introduced by Merriam (1984) and he defined it as "the degree to which absolute isolation is prevented by landscape elements which allow organisms to move among patches". A key topic in ecological research is connectivity which has the potential to mitigate the effects of habitat fragmentation (Anderson and Jenkins, 2006; Bailey, 2007). Landscape connectivity is considered to be of paramount importance for the survival of populations (Pain et al., 2000; Briers, 2002).Maintaining connectivity and mitigating the fragmentation of habitat may be critical for landscape process such as gene flow and dispersal (Crooks and Sanjayan, 2006). Landscape connectivity has been identified to monitor the impacts on biodiversity by habitat loss and fragmentation (Heller and Zavaleta, 2009). Conversely, Minor and Urban (2008) species invasion, and the spread of pests and pathogens are process that can be managed by reducing connectivity.

Landscape connectivity can be defined as" the extent to which the landscape allows movement among patches" (Taylor et al., 1993). Two types of connectivity seen in theory are Structural and Functional connectivity (Watts et al., 2005). Dispersal distances and the behavioural response of individuals or species to the physical structure of the landscape (functional connectivity) may be taken into account in the analysis in addition to the spatial arrangement of the habitat (structural connectivity) (Tischendorf and Fahrig, 2000; Theobald, 2006). Functional measure of connectivity can be divided into two: one the potential connectivity just with some information about dispersal ability and the second one with a much elaborated details about the number of individuals moving in and out of patches (Calabrese and Fagan, 2004). Leitao et al. (2006) suggested that landscape connectivity could be considered as an emergent from the interaction of landscape structure and landscape function. The following figure explains the context of connectivity both structurally and functionally.

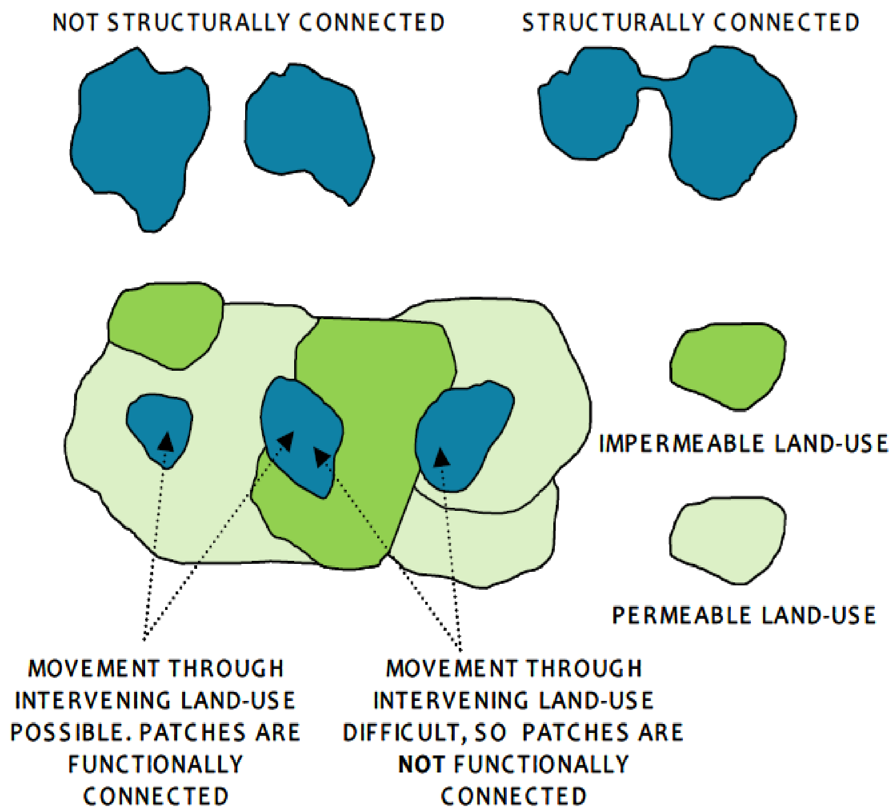


Figure 2.2 Difference between structural and functional connectivity described by Briers et al. (unpublished report).

There is a great confusion between the terminologies "landscape connectivity" and "patch connectivity". Landscape connectivity represents the connectivity of the entire landscape and used in connectivity analysis whereas patch connectivity represents the connectivity as an attribute of a patch in metapopulation studies (Tischendorf and Fahrig, 2001). Crooks and Sanjayan (2006) had promoted habitat networks through improving the connectivity between remaining patches for the long-term persistence and ability to adapt to environmental change. Geospatial assessment of landscape level forest connectivity is realized as one of the important frameworks to prioritize the biodiversity conservation strategies. Dalang and Hersperger (2012) has observed through a study in Switzerland's dry grasslands that improvement in connectivity through reduction in edge-to-edge distance can prove as an effective alternative for compensation to create new habitat patches for losses. A study conducted in Mediterranean forests suggested that patches with high diversity of seed fluxes leads to high species richness (Martin-Queller and Saura, 2013). A suggestion has been made to consider landscape connectivity as an important measure for ecosystem services and the results suggest that ecosystem services get reduced due to decrease in both habitat size and habitat connectivity (Ng et al., 2013).

Graph structures and the algorithms based on it have been shown to be a powerful and effective tool for representing the landscape pattern as a network of functionally interconnected patches and performing complex analysis regarding landscape connectivity. (Bunn et al., 2000; Ricotta et al., 2000; Urban and Keitt, 2001; Jordan et al., 2003; Pascual-Hortal and Saura, 2006; Pascual-Hortal and Saura, 2008).Calabrese and Fagan (2004) have suggested that graph-theoretical indices possess the most important analysis for conservation problems that require characterization of connectivity at relatively large scales with modest data requirements. For species survival in a heterogeneous landscape, connectivity is an important component (Bowne et al., 2006).

2.5 Habitat Availability

Pascual-Hortal and Saura (2006) had suggested that landscape connectivity should be considered within the wider concept of habitat availability (reachability) in order to be successfully integrated in landscape conservation planning applications. For a habitat to be available for a species, it should be both abundant and well connected. This is the basic concept of habitat availability. Thus, it is based in considering a patch itself as a space where connectivity occurs (intra-patch connectivity), integrating habitat patch area and connectivity between different patches (inter-patch connectivity) into a single measure (Pascual-Hortal and Saura, 2006). Saura and Pascual-Hortal (2007) had introduced two new indices named Integral Index of Connectivity and Probability of Connectivity to find the habitat loss and to identify most critical habitat areas for maintenance of landscape connectivity. According to Saura and Rubio (2010), these indices can be partitioned into intra, flux and connector which represents intra-patch connectivity, dispersal flux through the connections of one patch with the rest of patches and patch contributing connectivity between other habitat patches (stepping stone) respectively.

Connector fraction is not redundant with any other indices (Baranyi et al., 2011) and the only index which measures the link type along with patch importance (Saura and Rubio, 2010). Few ecologists like Neel (2008), Pascual-Hortal and Saura (2008), Garcia-Feced et al. (2011), Awade et al. (2012) had used habitat availability indices in the past. Habitat availability indices have been analysed for an Atlantic rainforest bird (*Pyriglena leucoptera)* for inputs as planning conservation strategies in terms of how much habitat should be available for this particular species to favour its occurrence in fragmented landscapes (Awade et al., 2012).

2.6 Graph theory

Graph theory is the study of graphs, which are mathematical structures used to model pairwise relations between objects. The recognition of the solution to complex systems has led to the new branch in mathematics called graph theory (Harary, 1969; Aldous and Wilson; 2000). Graph theory has become a popular tool for modelling the functional connectivity of landscapes. Although graph theory is a newcomer to landscape ecology, it has been widely used for its diverse applications in natural and social sciences, where the resulting models are variously called graphs or networks. Unlike the traditional population data, this method does not require long term population data (Urban and Keitt, 2001). Pereira et al. (2011) had claimed that land-use planning can be done with a help from landscape graphs.

According to landscape ecology, a graph is a mathematical representation of a landscape (Urban and Keitt, 2001; Bodin and Norberg, 2007). With the help of graph theory, habitat and their interactions can be represented as nodes and links in GIS environment. It is not a data demanding tool (Saura and Rubio, 2010). Bunn et al. (2000) and Galpern et al. (2011) had explained nodes as habitat patches and links as the distance between these habitat patches. The continuity of patches connected by links is called as a path (Urban and Keitt, 2001). The ability of an organism to disperse from one patch to another is represented as the length of the links (Bodin and Norberg, 2007).The link distance can be Euclidean or effective corresponding to least cost pathway (Rothley and Rae, 2005; Fall et al., 2007).

A useful property of landscape graphs is that they can be scaled to represent an increasing potential for landscape connectivity (Bunn et al., 2000; Brooks, 2006; Treml et al., 2008). This process is called thresholding, where resource patches are connected and understood to represent a component, when the length of the links connecting patches is below a threshold value. In simple words, nodes will be connected by links only when the distance between two patches does not exceed the maximum dispersal distance of the species under consideration. Building a landscape graph at successive threshold values has been called a scalar analysis of landscape connectivity (Brooks, 2003). A recent study done by Foltete et al., (2014) had introduced the use of graph theory in landscape level decision-support process, other than just prioritisation of patches.

There have been few studies done in the past with the help of different connectivity indices through graph theory. Firstly, the need for connectivity measures to assess the capacity of landscape to support viable species survival was specified (Moilanen and Hanski, 2000). While Saura (2010) compared indices to find the best index, Proulx et al. (2005) used Betweenness Centrality (BC) for his study. Equivalent Connected Area (ECA) index corresponding to PC and IIC indices calculated for four different thresholds showed the importance of connectivity at the patch level and the least-cost pathways increased with the increase in dispersal distance (Liu et al., 2014a). An optimal threshold distance of 250 m was found out and top 5 patches of the optimal component (145 patches) were identified, with the help of graph indices IIC and LCP, for individual important patches for potential connectivity (Devi et al., 2013).Till date, nearly 60 different indices for graph-theoretic connectivity analysis have been published (Rayfield et al., 2011). There is still a great lack of knowledge about the use of these indices in species occurrence especially in fragmented landscapes (Galpern et al. 2011).

2.7 Graph theory models

Environmental system models had a problem of inclusion of more variables to achieve perfection of system behaviours; but it may also include errors of parameters used (Ascough et al., 2008). Thus, simpler models can be used to eliminate these errors. But a simpler model may fail to predict and represent the key processes due to its simplifications (Nihoul, 1994). Scientists put forward that spatial explicit graph theory based models balance the difference between the above said two arguments for evaluating landscape management scenarios (Bodin and Norberg, 2007; Bunn et al., 2000; Calabrese and Fagan, 2004; Keitt et al., 1997; Laita et al., 2011; Minor and Urban, 2008; Pascual-Hortal and Saura, 2006; Rayfield et al., 2011).

Graph theory models make up the network graph through representing habitat networks as a series of nodes (patches) and edges (links) (Urban and Keitt, 2001; Pascual-Hortal and Saura, 2006). Based on the Euclidean distance, if dispersal is possible, then two nodes are considered to be linked. The degree of connectivity of the patches can be found out by the indices developed based on graph theory (Saura and Pascual-Hortal, 2007). The indices vary from simple (no. of links between patches) to complex (no. of shortest paths between connected patches). These models also evaluate the relative contribution of individual habitat patches to overall network connectivity (Saura and Rubio, 2010). A diagram depicting a simple graph representing the habitat patches and links have been shown in figure 2.3.

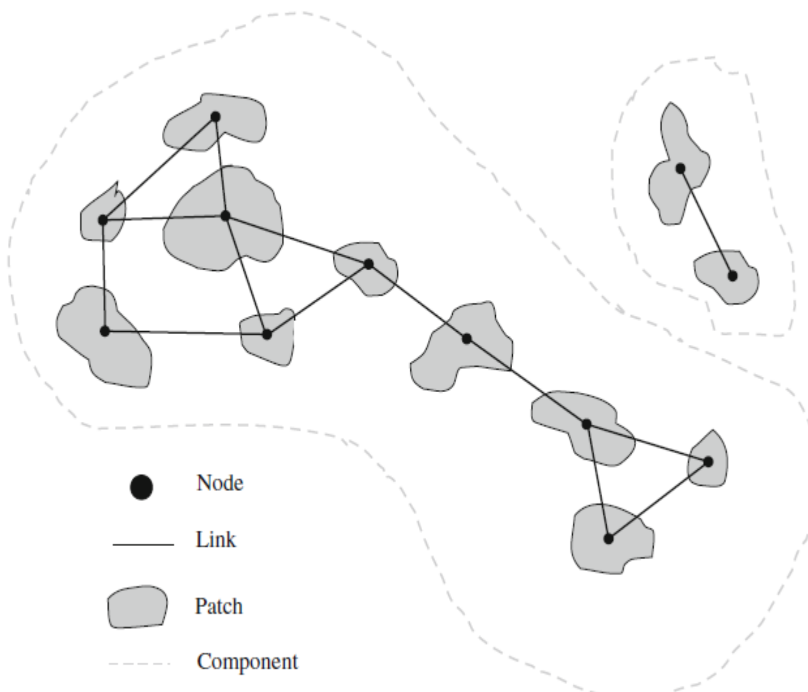


Figure 2.3 Habitat network expressed as graph networks cited from Eros et al. (2012).

Baranyi et al., (2011) had stated that the variability in the patch ranking system by the different indices done by three different aspects: 1. Amount of flux a patch is estimated to receive, 2. Degree to which a patch is valuable to uphold the connectivity between other habitat areas different from itself, and 3. Patch attributes (e.g. habitat area).Graph based models are appealing in landscape ecology studies because they provide a spatial representation of the graph data structure constructed and also offers a well-developed mathematical framework for quantifying the impacts of management decisions for landscape connectivity (Urban et al., 2009). The graph once constructed can be made available to compute connectivity metrics at either the entire network, or at component level or at individual patch level (Rayfield et al., 2011). Information about the biology of the species obtained from secondary source or empirical observations can be used to validate the graph models (Andersson and Bodin, 2009; Minor and Urban, 2008).

A major advantage of these graphs is that they can be displayed as maps, allowing researchers to interpret the spatial configuration of the network under analysis (Bergsten and Zetterberg, 2013). Euclidean and least cost distance models are compared for a ground beetle in grassland mosaic and conformed that both these models calculated the distances similarly, but not so reliable for long distances than shorter ones (Szabo et al., 2012). Thus, graphs can be used to analyse large landscapes at a single time unlike the other models which are largely data dependent and memory specific. The computational cost of network analysis in graphs in desktop configuration is limited. Thus, parallel computation helps save time in this kind of analysis (Foltete et al., 2012).

2.8 Application of graph theory in ecology

Urban and Keitt (2001) had introduced graph theory into metapopulation study in conservation biology. By representing the data structure as graph, they found the importance of individual patches to overall landscape connectivity. It was found out that population persistence of Mexican Spotted Owl can be maintained despite substantial losses of habitat area, as long as connectivity is maintained. Graphs have been used to represent spatial relationships among patches of landscape (Urban and Keitt, 2001) and among individuals (Fortuna et al., 2008) for focal species. Forests of European continent were simulated into habitat networks and the links between them were represented in two time series to reveal the changes in connectivity over time (Saura et al., 2011).

Graph analyses can be effectively implemented in conservation biology with empirical dispersal data and validated with independent field data (Urban et al., 2009). Zetterberg et al., 2010 used Betweenness Centrality(BC) index to capture important stepping stone patches of European common toad and stressed the importance of spatially explicit and geographically defined representations of the network. Graph theory was used in metapopulation context by comparing the dispersal abilities of American mink and prothonotary warblers and it was suggested that very little data would be enough for graph theory based models, unlike other modelling techniques which are data intensive (Bunn et al., 2000). A model was built to design the connected reserve network using graph theory approach and tested with its application in the protection of rare and endangered bird species of Cache river basin, USA (Wang and Onal, 2011). Network analysis with the help of landscape graph of forest patches found out that highway construction in Bereg forests of Ukraine will have deleterious consequences on forest-dwelling carabids (Vasas et al., 2009).

Graph theory analysis was carried out along with land cover permeability and least-cost analysis for nuthatch, a forest dwelling bird in Galicia region of Spain. Key connectivity areas were identified and most of those areas were situated outside the forest patches and it was suggested to implement biodiversity-friendly measures (Rubio et al., 2012). Landscape connectivity was assessed for three different scenarios of forest systems in western United States (Theobald et al., 2011). The potential of landscape graphs in the topological analysis of stream networks with a concept based framework proves that graphs can be a useful tool in quantifying freshwater ecosystems (Eros et al., 2012). Graph theory has been applied to J-walk output (movement ability of female bears) obtained from black bear in Texas and the conservation sites were found out (Morzillo et al., 2011). A network was built for the daily movement threshold of Thorn-tailed Rayadito, Chile to find occupancy of these birds and the result suggested that inclusion of patch area and connectivity greatly increases the models' accuracy (Vergara et al., 2010). Structural and functional connectivity components were integrated using a graph theory based connectivity measure with a study undertaken for European otter and the key elements for the functional one was found to be channel straightening and fragmentation in riparian forests (Van Looy et al., 2014).

2.9 Habitat Modelling

The presence or absences of a species in any habitat are the two initial objectives in habitat conservation planning (Peterson and Dunham, 2003). The development of predictive habitat models in the recent years helps us greatly to address these issues. First and foremost, these models can help us to detect the occurrence of the rare or endangered species in any terrain that are difficult to access (Pearce et al., 2001). The most standard approach to habitat modelling is based on the presence – absence data (Woolf et al., 2002; Niedzialkowska et al., 2006). Even though, based on coarse scaled allowing coarse habitat inferences and predictions, they most importantly, overlook the biological details which are very important for species conservation. These models produce two kinds of useful outputs by exploring the relationships between species occurrences and environmental variables. The first important kind of result is the estimates of probability that species might occur at given unrecorded locations and the second is the prediction of area suitability for species. There has been a great increase in advocating the empirical models for conservation planning (e.g. Margules & Nicholls, 1987; Cocks & Baird, 1989; Arau jo & Williams, 2000; Williams & Arau´ jo, 2000, 2002; Polasky & Solow, 2001; Arau jo et al., 2004).

2.10 MaxEnt modelling

Maxent works in the maximum-entropy principle which is the approximation that satisfies any constraints on the unknown distribution that we are aware of, and subject to those constraints, the distribution should have maximum entropy (Jaynes, 1957). The unknown probability distribution, which we denote π, is over a finite set X (no. of pixels). The individual elements of X is denoted as points. The distribution π assigns a non-negative probability π(x) to each point x, and these probabilities sum to 1. Our approximation of π is also a probability distribution, and we denote it π. The entropy of π is defined as

$$H(\pi) = -\sum_{x \in X} \pi(x) \ln \pi(x)$$

where, ln is the natural logarithm. The entropy is nonnegative and is at most the natural log of the number of elements in X. Entropy is defined as "a measure of how much choice is involved in the selection of an event" (Shannon, 1948).Thus a probability distribution with higher entropy involves less constraints and vice versa.

2.11 Integration of MaxEnt modelling with landscape connectivity

A recent study had mentioned the use of geographic distribution model for *Lonchophylla peracchii*, a forest-dependent bat species to find the range of occurrence of the species in South-eastern Brazil (Teixeira et al., 2014). Species distribution models have been in use in the field of ecology for so long but with the help of their outcome, connectivity analysis is rising as a new field. Connectivity study for a common frog (*Rana temporaria*) in Europe was done by integrating maximum entropy modelling and graph theory approach (Decout et al., 2010). The common frog was once again used as a case study to explore and provide a graph connectivity analysis framework that integrates habitat suitability and dispersal responses to landscape permeability (Decout et al., 2012).

Chapter – 3 Study Area and Materials

3.1 Study Area

Western Himalayan region that belongs to the Indian states of Himachal Pradesh, Jammu and Kashmir and Uttarakhand were chosen for connectivity analysis. Earlier workers (Clarke, 1898) recognized two botanical regions, viz., the western and the eastern Himalaya. The western region has diverse forest types but is drier than its eastern counterpart.

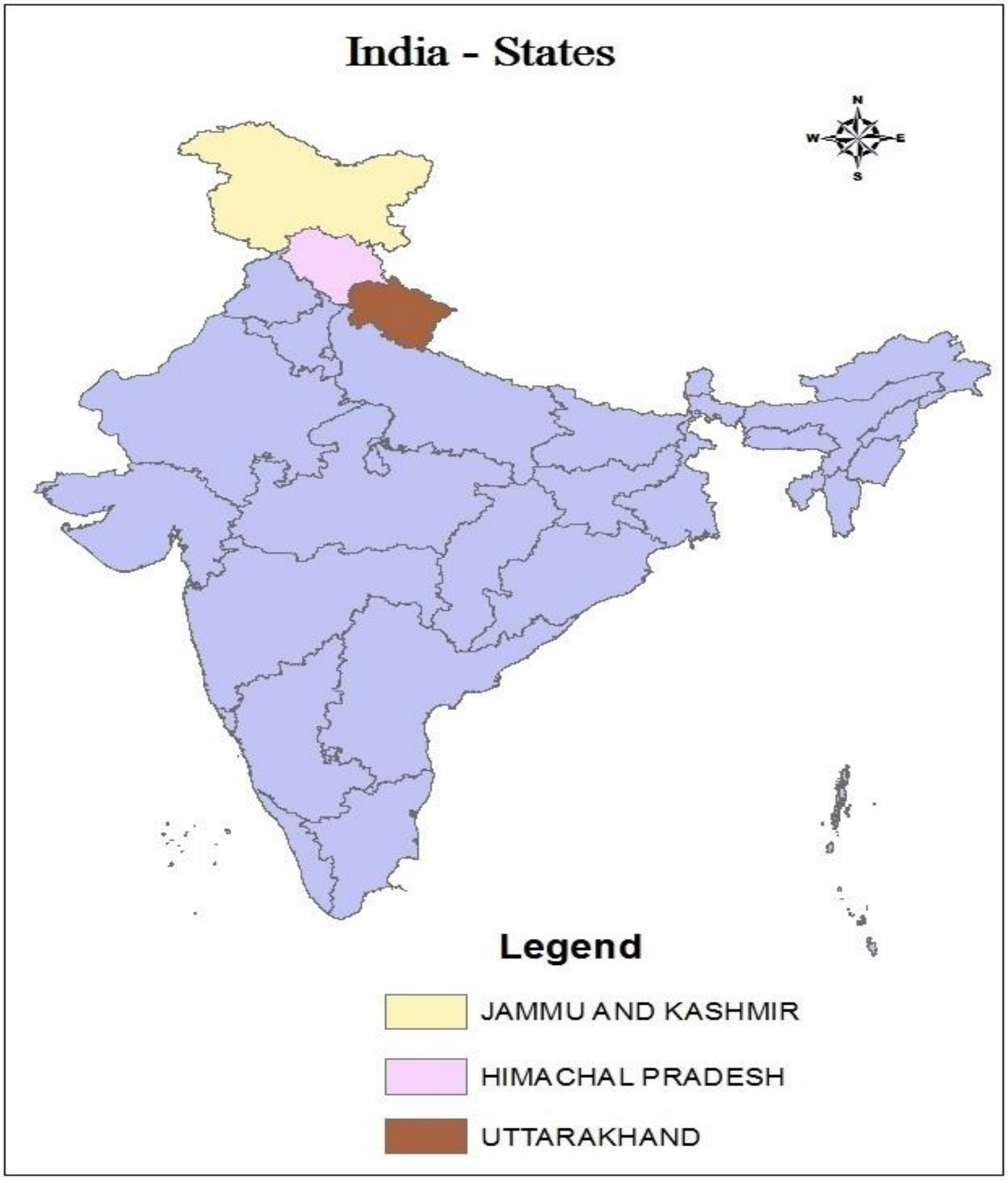


Figure 3.1 Map of study area being highlighted

3.1.1 Geography

The study area lies between 28°43'N to 37°05'N latitude and 72°31'E to 81°03'E longitude. It has a total geographical area of 3,31,382 km^{2}of which Himachal Pradesh, Jammu & Kashmir and Uttarakhand covers 55,673 km^2, 2,22,236 km^2 and 53,483 km^2 respectively. It is bounded by the international boundary of China in the north and east, international boundary of Pakistan in the west and the state boundaries of Punjab, Haryana and Uttar Pradesh in the south. The altitude climbs from flat plains till 5,500 metres. The terrain is so diverse that it includes plains, undulating hills and high mountains.

3.1.2 Topography

Topographically, all the three states can be divided into three distinct zones based on diversity in altitude and flora. Himachal Pradesh has been divided into the Shiwaliks with altitude upto 1,500 m, Middle Himalayan region between 1,500 to 3000 m and the Himadris higher than 3,000 m. Jammu & Kashmir comprises of Kashmir valley, Ladakh and Jammu. Uttarakhand can be divided into the Himalayan region, Shiwaliks and the terrai region.

3.1.3 Climate

The average annual rainfall is about 1,800 mm, 600 to 800 mm and 1,550 mm in Himachal Pradesh, Jammu & Kashmir and Uttarakhand respectively. Temperature varies from sub-zero to 40°C. The region witnesses temperate climate except in the plains area where the climate is tropical.

3.1.4 Demography

The population is 6.86 million, 12.55 million and 10.12 million with a population density of 123 persons/km^2, 56 persons/km^2 and 189 persons/km^2 in Himachal Pradesh, Jammu & Kashmir and Uttarakhand respectively (Census, 2011). The livestock population is 5.23 million, 10.99 million and 5.14 million respectively (livestock census, 2007).

3.1.5 Recorded forest area

As per the State of Forest report (2011), the recorded forest area of Himachal Pradesh is 37,033 km^2 which is 66.52% of its geographical area. Reserve forests constitute 5.13%, Protected forests 89.46%, and unclassed forests 5.41% of the recorded forest area. About two thirds of the state's recorded forest area is under permanent snow, cold deserts or glacier which is not conducive for the growth of trees. The recorded forest area of Jammu & Kashmir is 20,230 km^2 which is 9.1% of the geographical area. Reserve forests constitute 87.21%, protected forests 12.61% and unclassed forests 0.81% of the recorded forest area. The recorded forest area of Uttarakhand is 34.651 km^2 which is 64.79% of its geographical area. Reserve forests constitute 71.11%, protected forests 28.52%, and unclassed forest 0.35% of the recorded forest area.

3.1.6 Forest types

As per Champion and Seth (1968), the study area has following forest types:

- **Group 3 – Tropical moist deciduous forests**

  Present only in a small percent in Uttarakhand. Overwood consists of *Shorea robusta*, *Schima wallichi*, *Michelia champaca* with *Syzygium cumini*, *Mallotus philippensis* as middle storey. This region survives with a Mean Annual Temperature (MAT) of 21-26°C and Mean Annual Rainfall (MAR) of 1000-2000 mm with the number of rainy days varying from 48 to 112.

- **Group 5 – Tropical dry deciduous forests**

  These forests are confined to Himachal Pradesh and Uttarakhand where MAT constitute 24-27°C and MAR 750-1300mm with the number of rainy days varying from 36 to 80. Principle species list includes *Shorea robusta*, *Acacia catechu*, *Adina cordifolia* etc.

- **Group 9 – Subtropical pine forests**

  These forests confine themselves to areas with altitude of 1000 to 1800m, though it descends down to 600m and ascends up to 2300m on southern aspects. Mean Annual Temperature(MAT) comprises about 15-22°C and MAR of 1000-3000mm with the number of rainy days varying from 67 to 122. Species composition includes *Pinus roxburghii*, *Cedrus deodara*, *Quercus semicarpifolia*, *Quercus leucotricophora*, *Rhododendron arboreum* etc.

- **Group 10 – subtropical dry evergreen forests**

  This group occurs on bhabar, the Shiwaliks and the Himalayan foothills not exceeding 1000m altitude. The climate is characterized by long hot, dry season and a cold winter with occasional frost. Rainfall rarely exceeds 1000mm. *Olea cuspidata*, *Acacia modesta* are the most common species of this group.

- **Group 12- Himalayan Moist temperate forests**

  This forest occurs in patches with MAT 13-16°C and MAR 1500-3300mm and is confined at altitudes between 1500-3300m. An important factor that governs these type of forests is the occurrence of good monsoonal rainfall and good snowfall from North West disturbance. This is the ideal condition for Deodar to occur. *Quercus incana*, *Quercus dilatata*, *Cedrus deodara* are the most commonly occurring species.

- **Group 13- Himalayan Dry Temperate forests**

  This is an extremely dry region with MAR 80-800mm (number of rainy days varies from 11 to 62) and MAT 6-17°C. *Pinus gerardiana*, *Pinus wallichiana*, *Quercus ilex*, *Cedrus deodara* are the dominant species of these forests.

- **Group 14- Subalpine forests**

  The Sub alpine forests are the topmost tree forest in Himalayas adjoining alpine scrub which occurs at MAT 2-6°C and MAR 10-55mm. It is found on the altitudinal zone of 2900-3500m. *Abies pindrow, Abies spectabolis, Picea smithiana* are the species of this region.

- **Group 15- Moist alpine scrub**

  This type of scrub normally occurs above 3500m altitude and consists of *Rhododendron arboreum, Betula utilis.*

- **Group 16 – Dry alpine scrub**

  This type usually occurs only at xerophytic conditions in which dwarf scrubs like *Juniperus wallichiana, Juniperus communis, Artimisia* species predominate.

3.2 Materials

3.2.1 Datasets used

- Land Use Land Cover for the year 1985, 1995 and 2005 from IGBP were used for both connectivity and spatial pattern change analysis.
- Land Use Land Cover generated for 2014 with the help of Awifs datasets
- Environmental variables from World Bioclim were used as inputs for Maxent model.
- ASTER DEM datasets for the whole western Himalayan region with 30 meters interval was also used as inputs for Maxent model.

3.2.2 Software's used

- Erdas Imagine 2014 – was used for image processing
- ArcGIS 10.1 – was used for database creation and GIS analysis
- Maximum Entropy Species Distribution modeling, Version 3.3.3k - for Maxent modeling.
- MS Office 2013 – for graph creation and report writing
- Conefor 2.6 – used for connectivity analysis based on graph theory
- Patch analyst 5.1 – used for spatial pattern analysis
- Graphab – to create the topology of the graph network

Chapter – 4 Methods

4.1 Data Preparation for Habitat Connectivity Analysis

LULC of the whole Western Himalayas generated for 1985, 1995 and 2005 that includes the three states of Himachal Pradesh, Jammu Kashmir and Uttarakhand was verified for accuracy with the help of MSS, LISS I, LISS III datasets respectively and Google Earth for all the three time periods. AWIFS datasets for 2014 was used to generate 2014 LULC. Then, Forest patches were extracted from the LULC. Forest habitats with less than 5 hectare area were removed.

A new field for node ID and Area of the habitat patch was created and inputted into the extension tool ID within distance. After this process, two ASCII files named Node file and distance file were generated. These two ASCII files are the inputs for the graph network analysis.

4.2 Graph theory model

A model for graph theory analysis with different connectivity indices called Conefor 2.6 (Saura and Torne, 2009) was used to perform the connectivity study. It is an open source software package using R libraries quantifies the importance of habitat nodes and links for the maintenance or improvement of connectivity. It is used as a tool for decision making in landscape planning and habitat conservation through identification of critical areas for ecological connectivity. It was developed by Santiago Saura and Josep Torne at the polytechnic University of Madrid and the University of Lleida with the help of C++. It was designed to run as a graphical user interface in windows and mac systems and in linux through commands. It can also be run from R programming.

4.3 Graph Network Analysis

Threshold distance is an important parameter that has to be fed into the graph theory model based on which the analysis will run. For this current study, threshold distances ranging from 100 to 25000 meters were analysed. The threshold used for performing graph theory analysis were 100, 200, 300, 500, 750, 1000, 2000, 3000, 4000, 5000, 7500, 10000, 15000, 20000 and 25000 meters respectively.

4.3.1 Individual Node Importance

A graph network of the forested patches was created using the edges of the polygons as nodes. The edge-to-edge distance was calculated through the shortest path algorithm. With the nodes and its distance between nodes information, graph theoretical indices calculated the degree of node importance for each and every node. For calculating the importance of each particular node, comparisons need to be made with the delta values for each index (dI):

$$dI = 100.\frac{I-I'}{I} \qquad (1)$$

Where I is the index value before the change and I’ the value of the same index after the change (after a certain patch loss). There are two models based on which the following landscape connectivity indices will work. They are:

4.3.2 Binary Connection Model – graph with unweighted links

The binary connection model considers each two nodes (habitat patches) as either connected or not, with no intermediate modulation of the connection strength or direct feasibility among them. The existence of a link between a pair of nodes implies the potential ability of an organism to directly disperse between these two nodes, which are considered, connected.

4.3.3 Probabilistic Connection Model – graph with weighted links

The probabilistic connection model characterises the connections through a probability of direct dispersal between each two nodes (habitat patches) as an estimation of strength, frequency or feasibility of that direct movement by any organism.

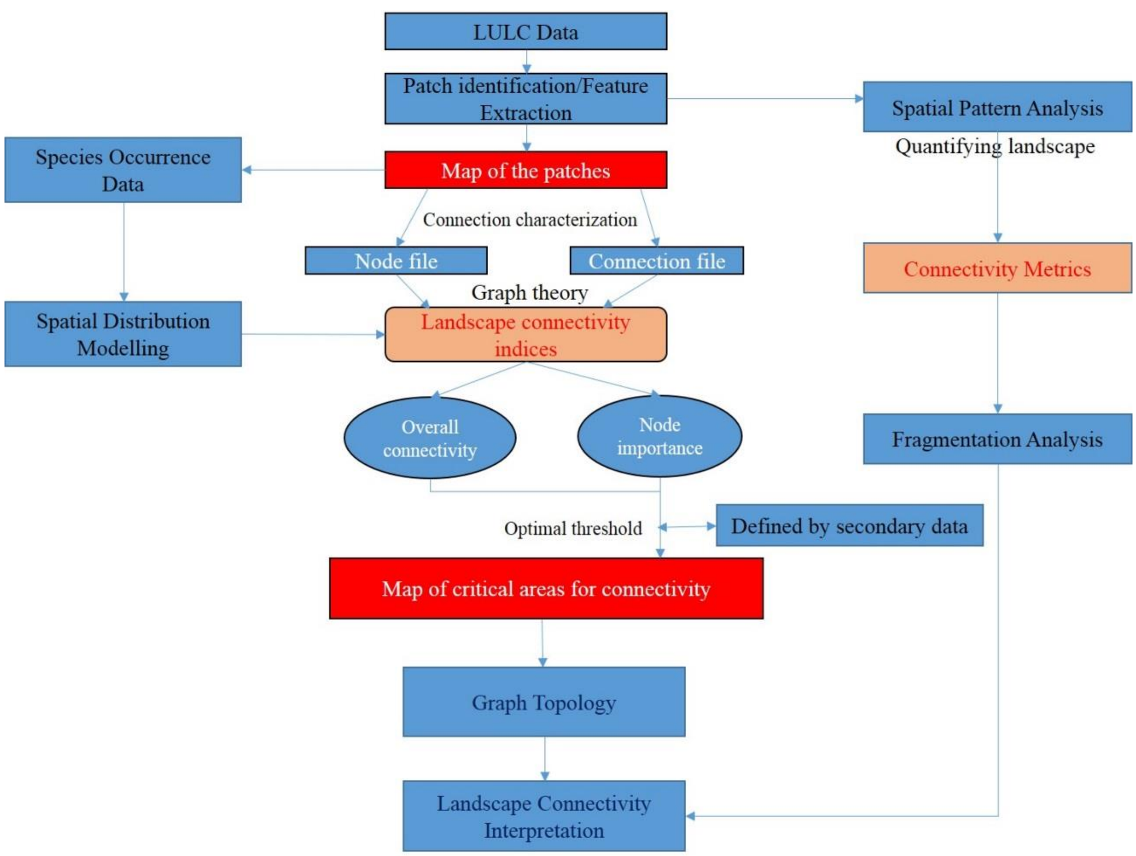


Figure 4.1 Methodological flowchart of the study

4.4 Landscape Connectivity Indices

4.4.1 IIC- Integral Index of Connectivity

The integral index connectivity (IIC) described in Pascual-hortal and Saura (2006) is based on binary connection model and given by

$$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i.a_j}{1+nl_{ij}}}{{A_L}^2} \quad (2)$$

Where n is the total number of nodes in the landscape; a_i and a_j are the attributes of nodes I and J. nl_{ij} is the number of links in the shortest path between nodes I and J; A_L is the maximum landscape attributed. If the value of A_L is not specified, the IICnum values can be instead of IIC.

The IIC includes the intra, flux and connector as describe by Saura and Rubio (2010) these fraction will be automatically calculated if IIC is selected. dIICflux will estimate the amount of dispersal fluxes between a particular patch and the rest of the patches in the landscape, while dIICconnector fraction measuring the contribution of the analyzed patch to the connectivity between other patches as a connecting elements or stepping stone between them and the dIICintra is the contribution of patch involved in the intrapatch connectivity within components.

4.4.2 H- Harary index

Harary index as described in Ricotta et al. (2000) and Jordan et al. (2003) is based on binary connection model and given by

$$H = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1, i\neq j}^{n}\frac{1}{nl_{ij}} \quad (3)$$

Where n is the total number of node in the landscape and nlij is the number of links in the shortest path between patches I and J. For patches which are not connected nlij=∞.

4.4.3 LCP- Landscape Coincidence Probability

The Landscape Coincidence Probability (LCP) as described in Pascaul-hortal and Saura (2006) and Saura (2010) is based on binary connection model. LCP ranges from 0 to 1 and it increases with improved connectivity as computed by

$$LCP = \sum_{i=1}^{NC}\left(\frac{c_i}{A_L}\right)^2 \quad (4)$$

Where NC is the number of components in the landscape, ci is the total component attribute, and AL is the maximum landscape attribute.

4.4.4 F – Flux

The Flux (F) as described in Saura and Pascal-hortal (2007) is based on probability connection model and given by

$$F = \sum_{i=1}^{n} \sum_{j=1, i \neq j}^{n} p_{ij} \qquad (5)$$

Where *n* is the total number of nodes in the landscape and p_{ij} is the probability of direct dispersal between nodes i and j.

4.4.5 AWF - Area-weighted flux

The Area-Weighted Flux (AWF) as described in Bunn et al.(2000), Urban and Keitt (2001) and Saura and Pascual-Hortal (2007) is based on probability connection model.

$$AWF = \sum_{i=1}^{n} \sum_{j=1, i \neq j}^{n} p_{ij} \cdot a_i \cdot a_j \qquad (6)$$

Where *n* is the total number of nodes in the landscape, p_{ij} is the probability of direct dispersal between nodes *I* and *j* and a_i and a_j are the attributes of the nodes *i* and *j*.

4.4.6 PC - Probability of connectivity

This index is recommended as the best index for the type of connectivity analysis presenting several relevant improved characteristics compared to other existing indices (Saura and Pascual-Hortal 2007). It also considers a richer connection model than IIC and it is not affected by the presence of adjacent habitat patches or cells in the analysed datasets (Saura and Pascual-Hortal 2007).PC ranges from 0 to 1 and increases with improved connectivity. It is given by:

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i \cdot a_j \cdot p_{ij}^*}{{A_L}^2} \qquad (7)$$

Where *n* is the total number of habitat nodes in the landscape, a_i and a_j are the attributes of nodes *I* and *j*, A_L is the maximum landscape attribute, and p^*_{ij} is the maximum product probability of all paths between patches *I* and *j*.

The PC includes the intra, flux and connector as describe by Saura and Rubio (2010) these fraction will be automatically calculated if PC is selected. dPCflux will estimate the amount of dispersal fluxes between a particular patch and the rest of the patches in the landscape, while dPCconnector fraction measuring the contribution of the analyzed patch to the connectivity between other patches as a connecting elements or stepping stone between them and the dPCintra is the contribution of patch involved in the intrapatch connectivity within components.

The ecological significance of these indices are described in table 4.1

Table 4.1 Ecological significance of the connectivity indices

Index	Ecological Significance
Harary Index	Dispersal distances can be directly related to the landscape between every pair of nodes

Integral Index of Connectivity	Area of the patches (intra-patch connectivity) included for computation along with the number of links
Landscape Coincidence Probability	Probability that two randomly chosen points fall in the same habitat patch
Flux	Sum of all the probabilities of direct dispersal between two patches
Area Weighted Flux	It is the inclusion of area of the patches with the sum of all the probabilities of direct dispersal
Probability of Connectivity	Area of the patches along with the maximum product probabilities of all possible paths

4.5 Data preparation for Maxent modelling

4.5.1 Environmental Variables

Nineteen bioclimatic variables with 30 seconds (approximately 1 km) spatial resolution (Nix, 1986), biologically more meaningful to define eco-physiological tolerances of a species (Graham and Hijmans 2006; Murienne et al., 2009), were obtained from WorldClim dataset (Hijmans et al., 2005; http://www.worldclim.org/bioclim.htm). The variables are resampled to 90m spatial resolution using nearest neighbour resampling technique. The bioclimatic variables are listed in the table 4.2.

Table 4.2 Bioclimatic variables

BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp – min temp))
BIO3	Isothermality (BIO2/BIO7) (*100)
BIO4	Temperature Seasonality (standard deviation *100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter

BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

Elevation (Digital Elevation Model; DEM) data was obtained from ASTER GDEM. The GDEM covers the planet from 83 degrees North to 83 degrees South (surpassing SRTM's coverage of 56 °S to 60 °N), becoming the first earth mapping system that provides comprehensive coverage of the Polar Regions. It was created by compiling 1.3million VNIR images taken by ASTER using single-pass stereoscopic correlation techniques, with terrain elevation measurements taken globally at 30 meter (98 ft) intervals (Nikolakopoulos, K. G et al, 2006).

4.5.2 Presence data

Occurrence data of *Quercus leucotricophora, Quercus semicarpifolia, Taxus baccata, Rhododendron arboreum, Betula utilis* and *Abies pindrow* were used from secondary source. These presence datasets are to be converted into CSV file and inputted into maxent.

4.6 Maxent

Maxent model is a maximum entropy-based machine learning program that estimates the probability distribution for a species‟ occurrence based on the environmental constraints (http://www.cs.princeton.edu/~schapire/maxent/). The principle of maximum entropy approach is to ensure that approximation satisfies any constraints on the unknown sites, meaning that the estimated probability of unknown distribution involves less number of constraints but more choices (Jaynes, 1957).

4.7 Model Development

For running Maxent model, all the raster datasets were converted into ASCII format (.ASC) and is saved in a single folder. The presence points were saved in a comma separated value (.csv) format then inputted in the model. Maximum Entropy Species Distribution Modeling, Version 3.3.3k build was used in modelling. The maximum number of background points were 10,000. Auto features were used in feature selection. 80% data for training and the rest 20% for testing was selected and used. A total of 500 runs were set for model building. Total replications were set as 10. The replicated run type was set as "cross validate". The average of the 10 replications was taken as the final output. Other values were kept as default.

4.8 Species distribution

The Jackknife procedure was used to assess the importance of the variables. The final potential species distribution map had a range of values from 0 to 1 which were regrouped in to four classes of potential habitats viz., highly suitable (>0.6), suitable (0.4 – 0.6), moderately suitable (0.2 – 0.4) and least suitable (<0.2).

4.9 Graph analysis based on species distribution

The forest patches with high potential distribution (<0.6) were masked out from the LULC and the above mentioned methodology for graph analysis was performed only for those patches which have the potential distribution of a particular species.

4.10 Level of Connectivity

The level of connectivity of the habitat patches used for analysis were clubbed into different classes such as very low level of connectivity (if degree of connectivity <0.5), low level of connectivity (if degree of connectivity 0.5-1), medium level of connectivity (if degree of connectivity 1-8), high level of connectivity (if degree of connectivity 8-20) and very high level of connectivity (if degree of connectivity >20).

4.11 Spatial Pattern Analysis

Spatial pattern analysis for this study was done with the help of Patch Analyst 5.1 (Rempel et al., 2012). Patch Analyst is an extension for ArcGIS software that can work with both Raster and Vector formats. This program was developed by Rob Rempel under the Spatia Ecology Program, Centre for Northern forest Ecosystem Research. Land Use Land Cover datasets were used as inputs for the spatial statistical analysis.

4.12 Spatial Pattern Metrics

4.12.1 Class Area

Class Area is defined as the sum of areas of all patches belonging to a particular class.

4.12.2 Number of Patches

Under ‘Analyse by class’, Number of patches belonging to an individual class.

4.12.3 Total Edge

Total Edge calculates the sum of perimeter of all the patches belonging to a particular class or the landscape as a whole.

4.12.4 Edge Density

Edge Density is defined as the amount of edge relative to the landscape area.

$$Edge\ Density = \frac{Total\ Edge}{Total\ Landscape\ Area}$$

4.12.5 Mean Shape Index

This metric calculates the Shape Complexity. MSI will be equal to 1 if all patches are circular. With increasing irregularity the vale increase from 1. Based on the deviation from this circularity and based on its irregularity, it calculates its value.

$$Mean\ Shape\ Index = \frac{\frac{Sum\ of\ each\ patch's\ perimeter}{\sqrt{Square\ root\ of\ patch\ area}}}{Number\ pf\ patches}$$

Chapter – 5 Results

An attempt has been made to apply Remote Sensing and GIS in the field of Landscape Connectivity through this study. It has enabled us to get a number of desired outputs as per well-defined objectives and methodology within the given time period. The resultant outputs have been suitably described and discussed later in the report. Figure 5.1 shows the forest – non forest map of Western Himalayan region for the years 1985, 1995, 2005 and 2014. These forest features are extracted to assess the level of connectivity between the habitat patches.

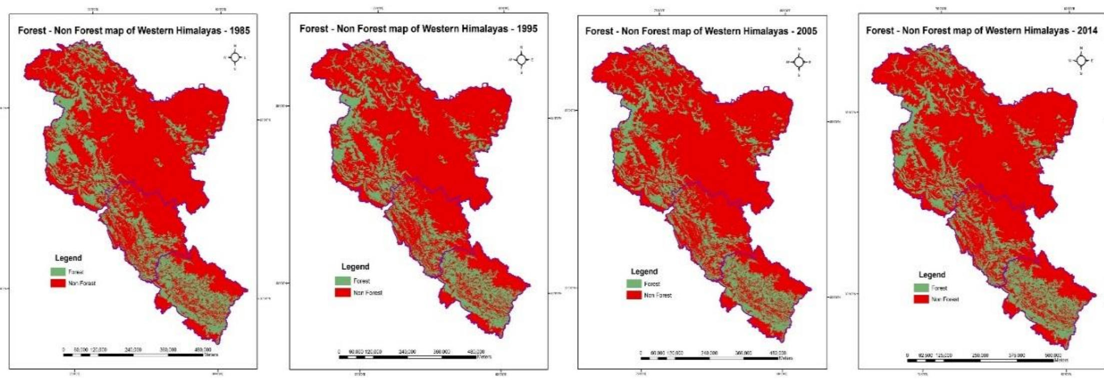
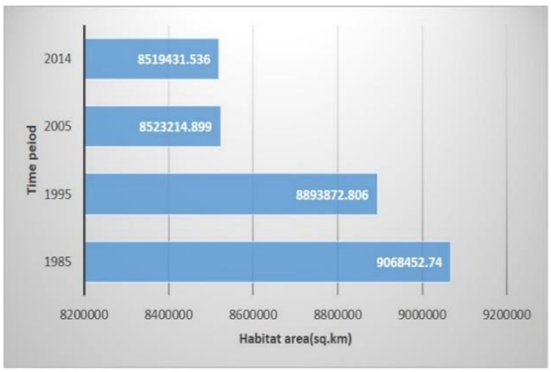


Figure 5.1 Forest – Non Forest map of Western Himalayas

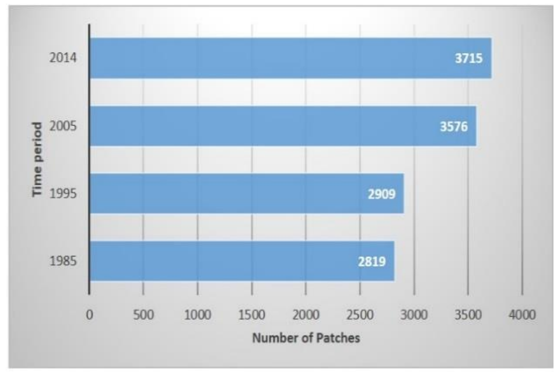
5.1 Dynamics of forest patterns

Forestland as habitat patches occupied 27.30%, 26.78%, 25.67% and 25.28% of the total landscape in 1985, 1995, 2005 and 2014 respectively. So, 2.02% of landscape was converted from natural habitat into other land uses as a whole, thus decreasing the area of forest from 9.07km^2 to 8.49km^2 and becoming more fragmented during this period. The characteristics of the landscape changed with land cover dynamics. The forests in the central part almost vanished and existing habitat patches got shrink. Approximately, 0.42% and 0.49% of the habitats lost from 1985 to 2014 were converted into croplands and shrub lands respectively, which in any case cannot be considered as a habitat to permeate connectivity. Assessing this period large patches of contiguous forest cover has fragmented into several medium sized patches.

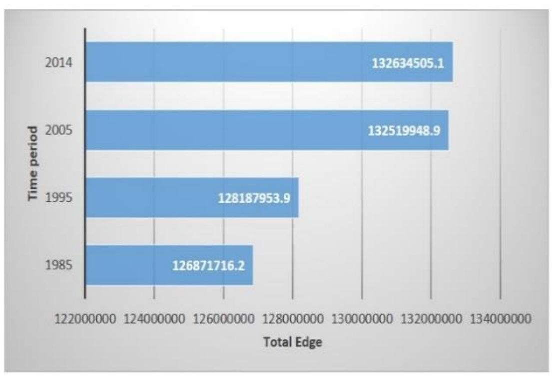
The areas and numbers of forest patches already changed significantly from 1985 to 2014, and the fragmentation of habitat patches is becoming more serious. The forest patch area reflects the forest protection to a large extent. The changes of different pattern metrics are shown in figure 5.2. The decrease in forest area from 1985 to 2014 as witnessed in figure 5.2(a) has proved the decline in the total forest cover from 90, 68,452.74 km^2 to 8519431.536 km^2. While the rise in fragmentation can be understood with the increase in number of forest patches from 2819 to 3715 (figure 5.2[b]) in that particular time frame. This gradual increase in habitat patches with the decrease in habitat area proves the high level of fragmentation and habitat loss. As the patches got fragmented giving birth to plenty of new patches, the perimeter of the patches showed gradual increase as observed through the metrics Total Edge (figure 5.2[c]) and Edge Density (figure 5.2[d]. A Shape index was used to check the irregularities in the shape of the patches which witnessed 2014 as more irregular period than the previous three time periods (figure 5.2[e]). The results showed that large forest patches occupied maximum of the habitat patches but still the rise in the number of patches with decrease in area proved that the forest patches have been constantly subjected to fragmentation. Also, there exists a high linear correlation between area and perimeter (R^2 = 0.9935) as shown in figure 5.2(f). These indicate the better performance of fragmentation indices in the study area.



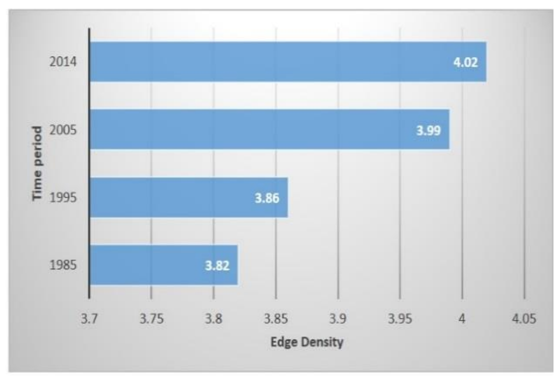
Habitat area (a)



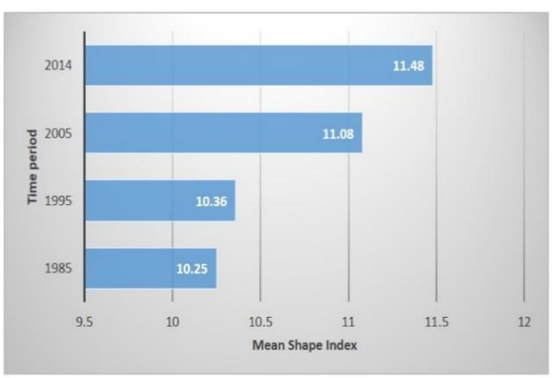
Number of Patches (b)



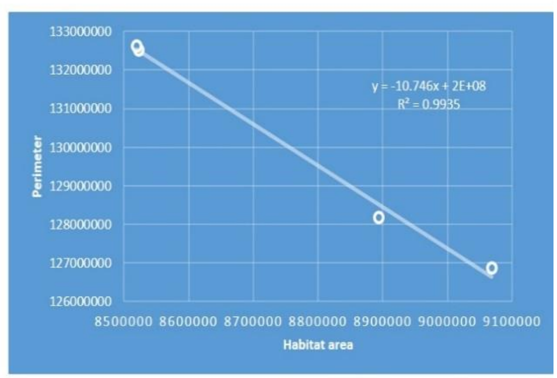
Total Edge (c)



Edge Density (d)



Mean Shape Index (e)



Perimeter vs Area (f)

Figure 5.2 Spatial pattern analysis outputs for fragmentation study

5.2 Analysis for optimal threshold distance based on NL and NC

It is expected that, at shorter threshold distance Number of Links (NL) increases linearly and becomes saturated as the threshold distance increases. But in the present study, threshold distance did not reach the saturation point (figure 5.3[a][c][e][g]) because of the heavily fragmented habitat patches. Number of components (NC) was found to decrease with increasing threshold distance (figure 5.3[b][d][f][h]). Summarizing all these graphs comes to a conclusion that NL and NC are inversely proportional. At low threshold, if NL is relatively less and NC is relatively more then, the functional connectivity is not proper. With increase in NC, connectivity among them should increase within the components. Owing to the impenetrability of the landscape, as a result of Land Use (Habitation, Agriculture etc.,), the increase in functional connectivity reduces. Hence threshold distance based on highest NC should be used for the current fragmentation status. Most of the tree species dispersed through wind has a maximum dispersal distance of 300 m (Tamme et al., 2014). Taking our results as well as other literature into consideration, a threshold distance of 300 meters was adapted for this study as the species we have taken are wind dispersed.

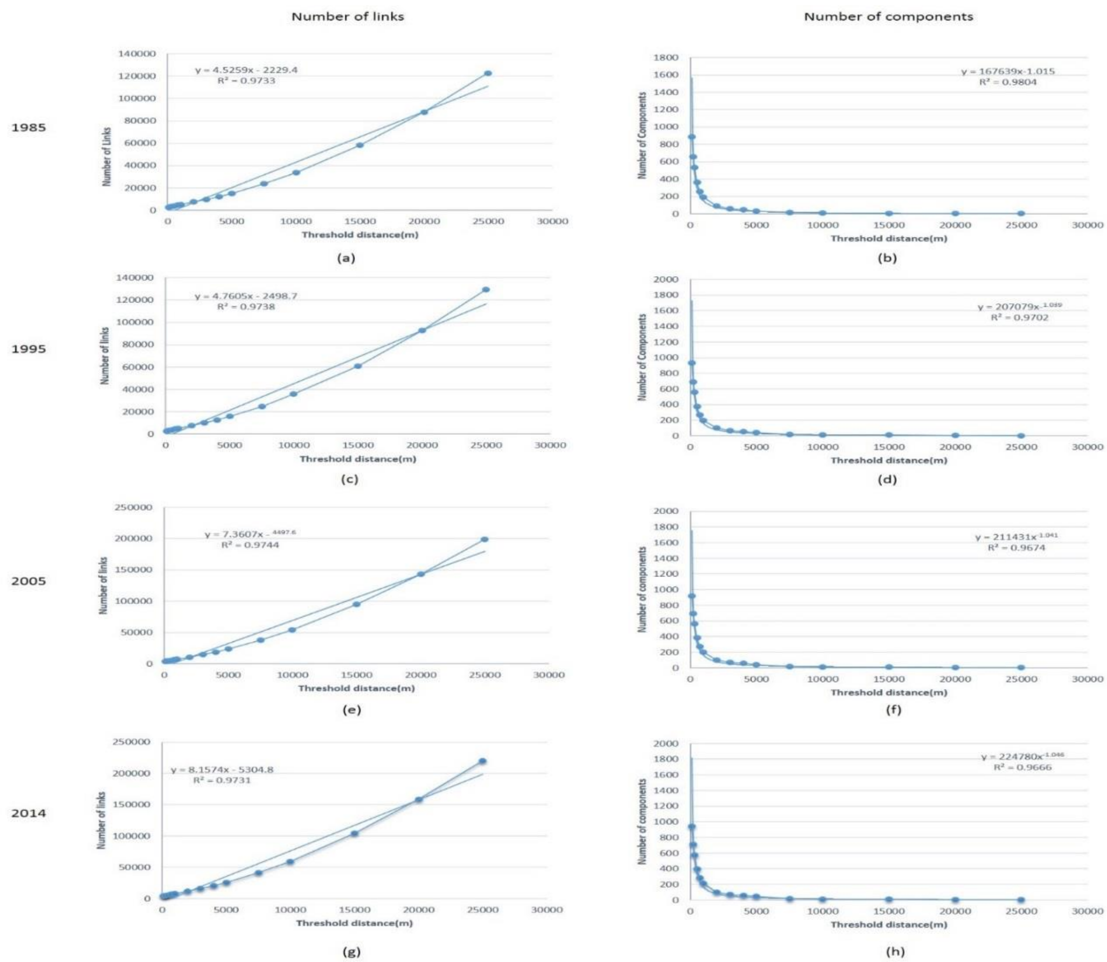


Figure 5.3 Overall connectivity analysis based on Number of links and Number of components versus threshold distance

5.3 Prioritization of patches according to their importance value

An importance value for all the patches taken into analysis can be derived from graph theory. The higher dI (level or degree of connectivity), the more important that node is for landscape connectivity, either for maintaining it or improving it. As the threshold distance chosen was 300 meters, connectivity assessment output resulted in more isolated patches and components from 1985 to 2014 because of the fragmentation that has been done far beyond the tree dispersal distance. Figures 5.4, 5.5 and 5.6 shows the importance value of the nodes categorized into five different ranges distributed throughout the study area based on its level of connectivity with its neighbouring patches for different indices at four different time periods used in this study.

5.3.1 Prioritization according to Harary index

The performance of Harary index is based solely on the number of links between a patch with its neighbours. As witnessed in the figure 5.4 (a) (b) (c) (d), Harary index has given a very low level of connectivity for all the patches in the Jammu and Kashmir region but for Uttarakhand and Himachal forests, the decrease of connectivity can be observed along the border of Himachal Pradesh and Uttarakhand region during 1985-2014 (figure 5.4 (a) to figure 5.4 (d)) from very high (dH ranges >20) to high (8<dH range>20). But on the other hand, Himachal Pradesh forests have witnessed an improvement in the level of connectivity on the basis of Harary index. Figure 5.7 (a) (b) (c) (d) shows the logarithmic graph of dH ranges to the number of patches in western Himalayas. With the low threshold distance of 300 meters, the performance of an index like Harary based only on the number of links tend to show more number of patches in very low category. As mentioned above, the obtained number of patches in the very low category (dH ranges<0.5) are 2724, 2809, 3442 and 3633 in 1985, 1995, 2005 and 2014 respectively. As the number of patches in very low category is more, the area and number of links for these patches tend to appear more for this category (figure 5.7 (e) to (h) and (i) to (l)).

5.3.2 Prioritization according to Landscape Coincidence Probability

This index works on the principle that two randomly chosen points in the habitat belong to the same component or not. If yes, then, how much will be the probability of connectivity among them? The performance of the patches in the western Himalayan region based on LCP index is based on the central position and the size of the patches which can be observed in the figure 5.4 (e) (f) (g) (h). Along the borders of Uttarakhand and Himachal Pradesh, the period 1985 showed very high connectivity (figure 5.4 (e). In 1985 and 2005, the same area ranked quite low belonging to high connectivity (figure 5.4 (f)(g)) while in 2014, the same patch got reduced in size and got separated as two patches belonging to medium and high connectivity. Even though number of patches (figure 5.8[a] to [d]) in the very low category is more, but the area percent (figure 5.8[e] to [h]) in this category is less compared to other categories performing well with very little number of patches in hand. Number of links proves to be directly proportional to the number of patches. More the number of patches, more is the number of links and vice versa (figure 5.8 [i] to [l]).

5.3.3 Prioritization according to Integral Index of Connectivity

A habitat availability index which calculates the level of connectivity based on the number of links between the patches and the area of the respective patches. Figure 5.5 (a) to (d) have shown the level of connectivity of habitat patches based on IIC from 1985 to 2014. Unlike other indices, high levels of connectivity can be seen in the periphery of the study region. Fragmentation in western Jammu and Kashmir can be witnessed in the figure 5.5 (d) comparing it with figure 5.5 (a). Habitat patches in that region were well connected in the past than the present. Quite an equal distribution of area percent and number of links are witnessed in the figures 5.9 (e) to (l) only with a few number of patches (figure (5.9[a] to [d]). These can be attributed to the statement, more the size of the patch more is the level of connectivity.

5.3.4 Prioritization according to Flux

One more index which works based only on the number of links is Flux. Figure 5.5 (e) to (h) gives an outline about the level of connectivity of Flux index in the study area. Most of the patches are ranked very low and not even the biggest patch with its central position can rank high for this index which shows its poor performance. Number of patches (figure 5.10 [a] to [d]) in very low (dF<0.5) is very high with a few numbers in low (0.5<dF>1) and medium (1<dF>8). With respect to the number of patches, percentage of area (figure 5.10 [e] to [h]) and number of links (figure 5.10 [i] to [l]) are high only in this category.

5.3.5 Prioritization according to Area Weighted Flux

Area weighted flux as the name suggests includes the weightage of area along with the flux index. Figure 5.6 (a) to (d) shows the patches connected based on this index. Patches with large area had ranked high while even the patches which are linked but with less area had ranked low for this index. Not much difference was found in the performance as the number of patches in the very low (dAWF<0.5) tend to appear far more than the other categories (figure 5.11[a] to [d]). With respect to figure 5.11 [a] to [d], the area and number of links in each category is plotted against the dAWF ranges and found to be more in very low category with a slight increase in the medium (1<dAWF>8) category (figure 5.11 [e] to [l]).

5.3.6 Prioritization according to Probability of Connectivity

The performance of the habitat patches based on probability of connectivity is shown in the figure 5.6 (e) to (h). In western Jammu and Kashmir, the area of the blue patch (high connectivity) seems to reduce from 1985 (figure 5.6(e)) to 2014 (figure 5.6(h)). More or less, the outputs of this index compared to the area weighted flux is equal as seen in the figure 5.6 (a) to (d) compared to figure 5.6 (e) to (h). But the topographical position of the patches plays a major role in this index which is not witnessed in any other index. The patches in the central position tends to ranks high than the patches at the periphery. And the patches which help in linking other patches termed scientifically as stepping stones are given more importance in this index. Figure 5.12 (a) to (d) describes the more number of patches in very low (dPC<0.5) but quite a large number in medium (1<dPC>8) category. As the allocation of large number of patches is at Medium category, its area

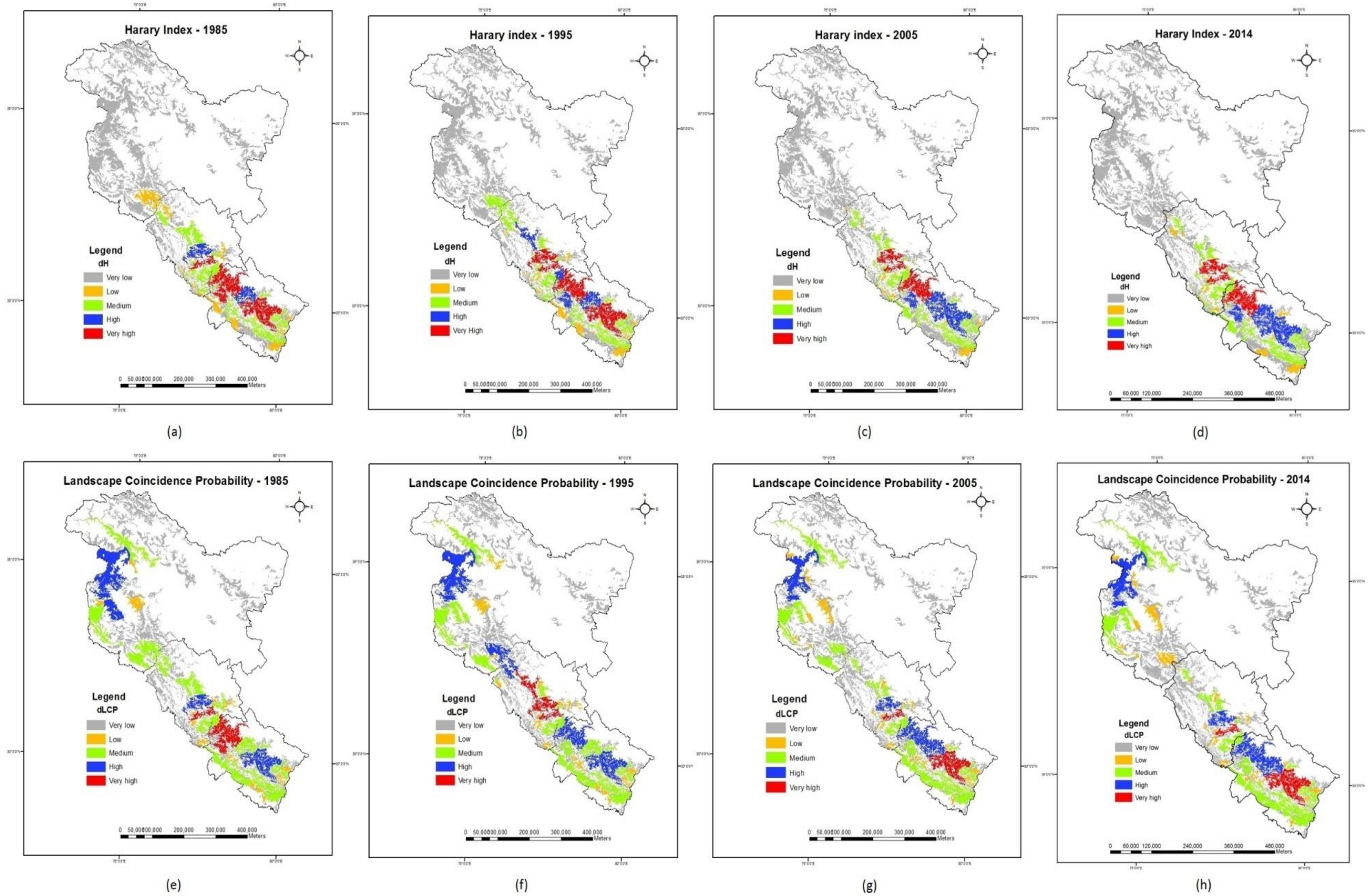


Figure 5.4 Maps indicating the critical patches for connectivity on the basis of H (Harary index) and LCP (Landscape Coincidence Probability)

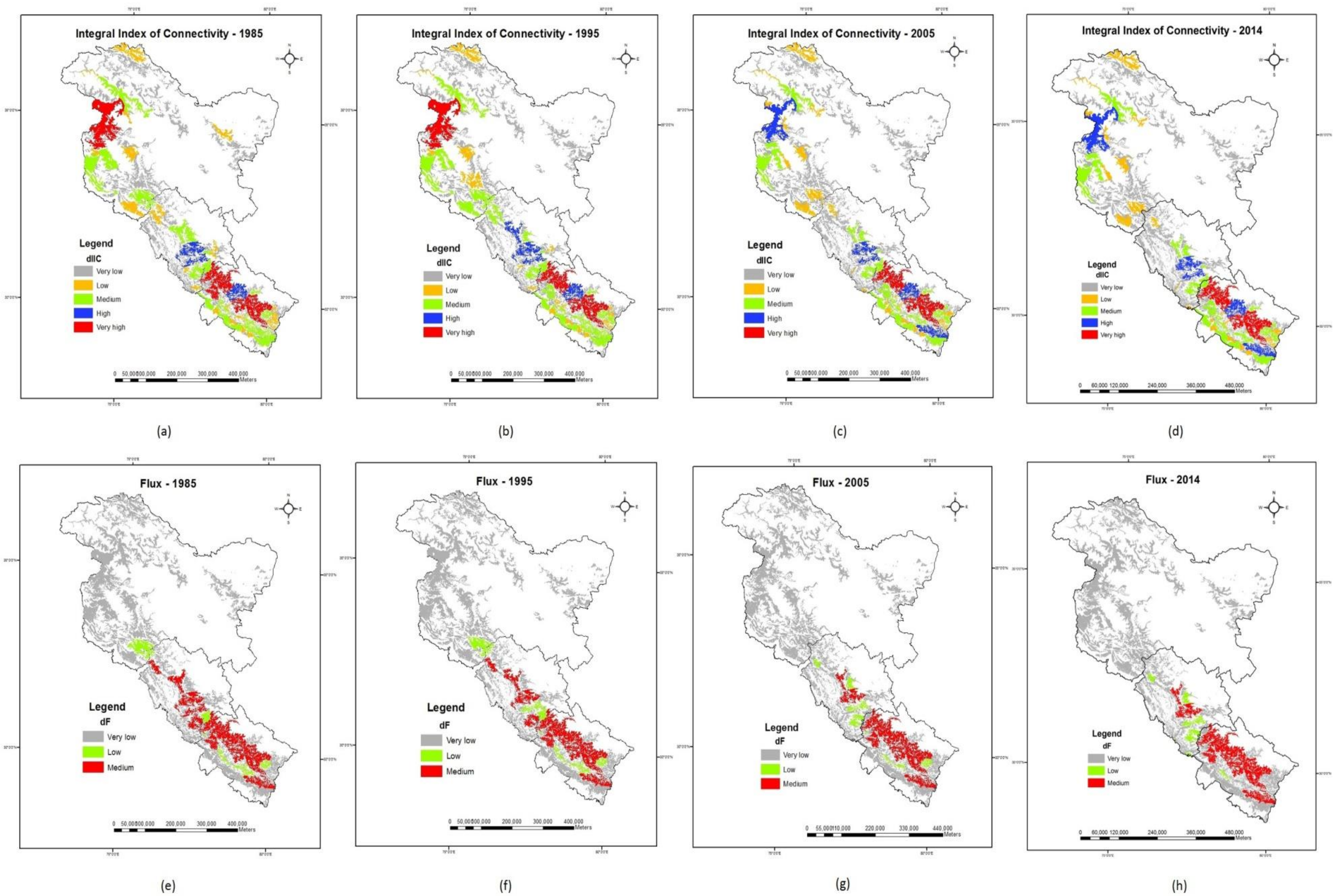


Figure 5.5 Maps indicating the critical patches for connectivity on the basis of IIC (Integral Index of Connectivity) and F (Flux)

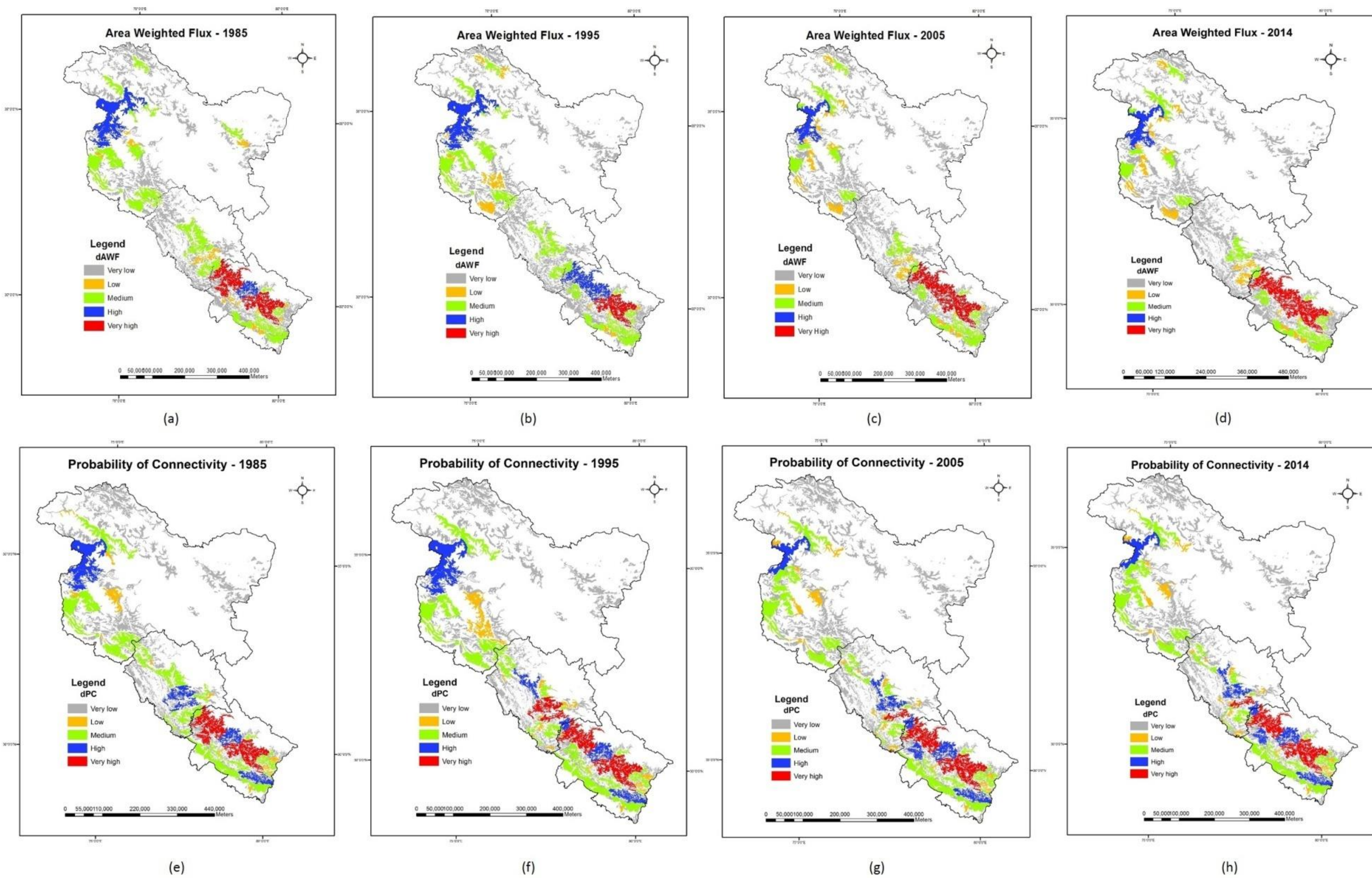


Figure 5.6 Maps indicating the critical patches for connectivity on the basis of AWF (Area Weighted Flux) and PC (Probability of Connectivity)

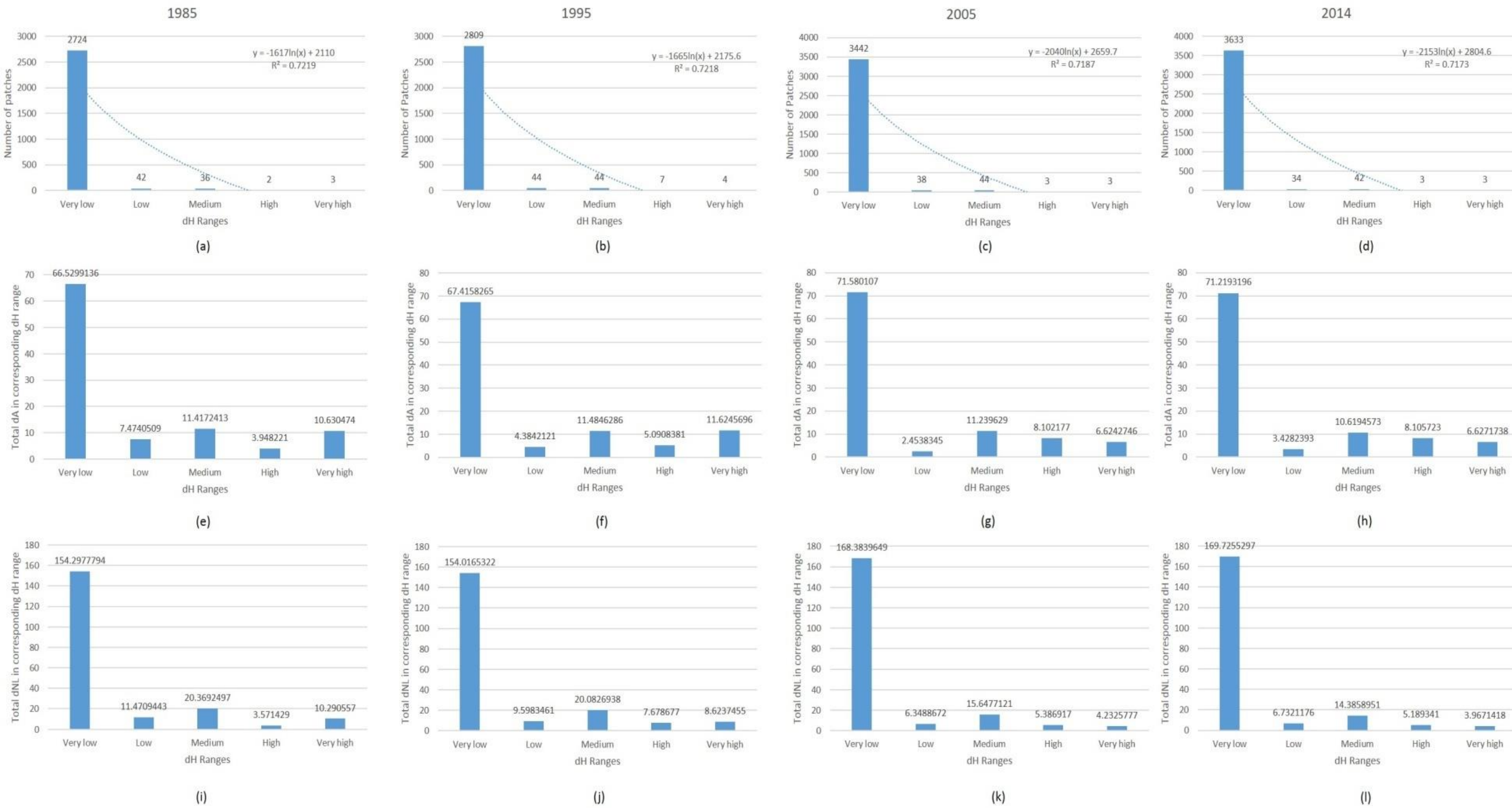


Figure 5.7 Graphs of dH (Harary index) ranges versus Number of Patches, total dA (Percentage of Area) in corresponding dH range and total dNL (Number of links) in corresponding dH range at different time periods

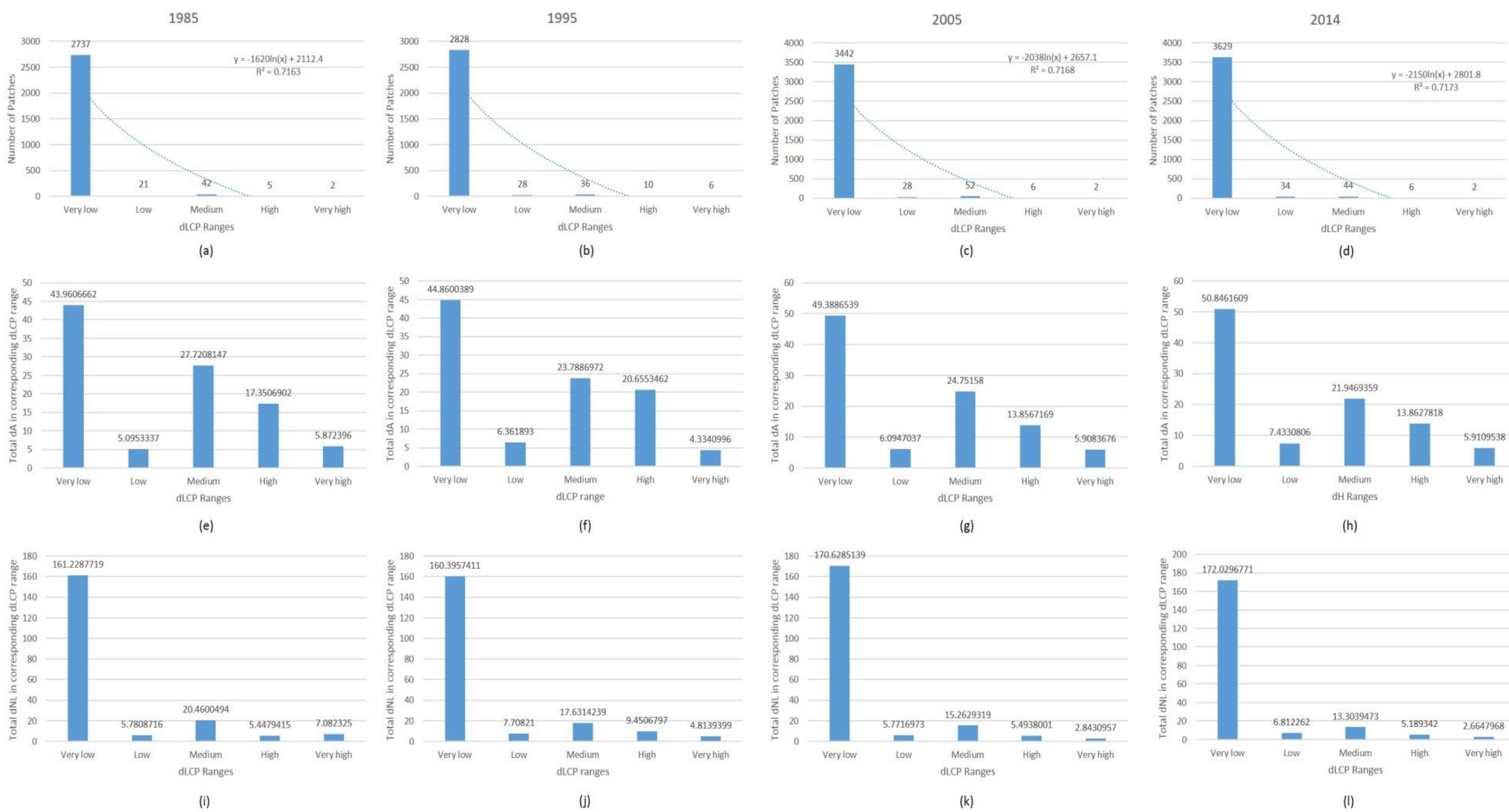


Figure 5.8 Graphs of dLCP (Landscape Coincidence Probability) ranges versus Number of Patches, total dA (Percentage of Area) in corresponding dLCP range and total dNL (Number of links) in corresponding dLCP range at different time periods

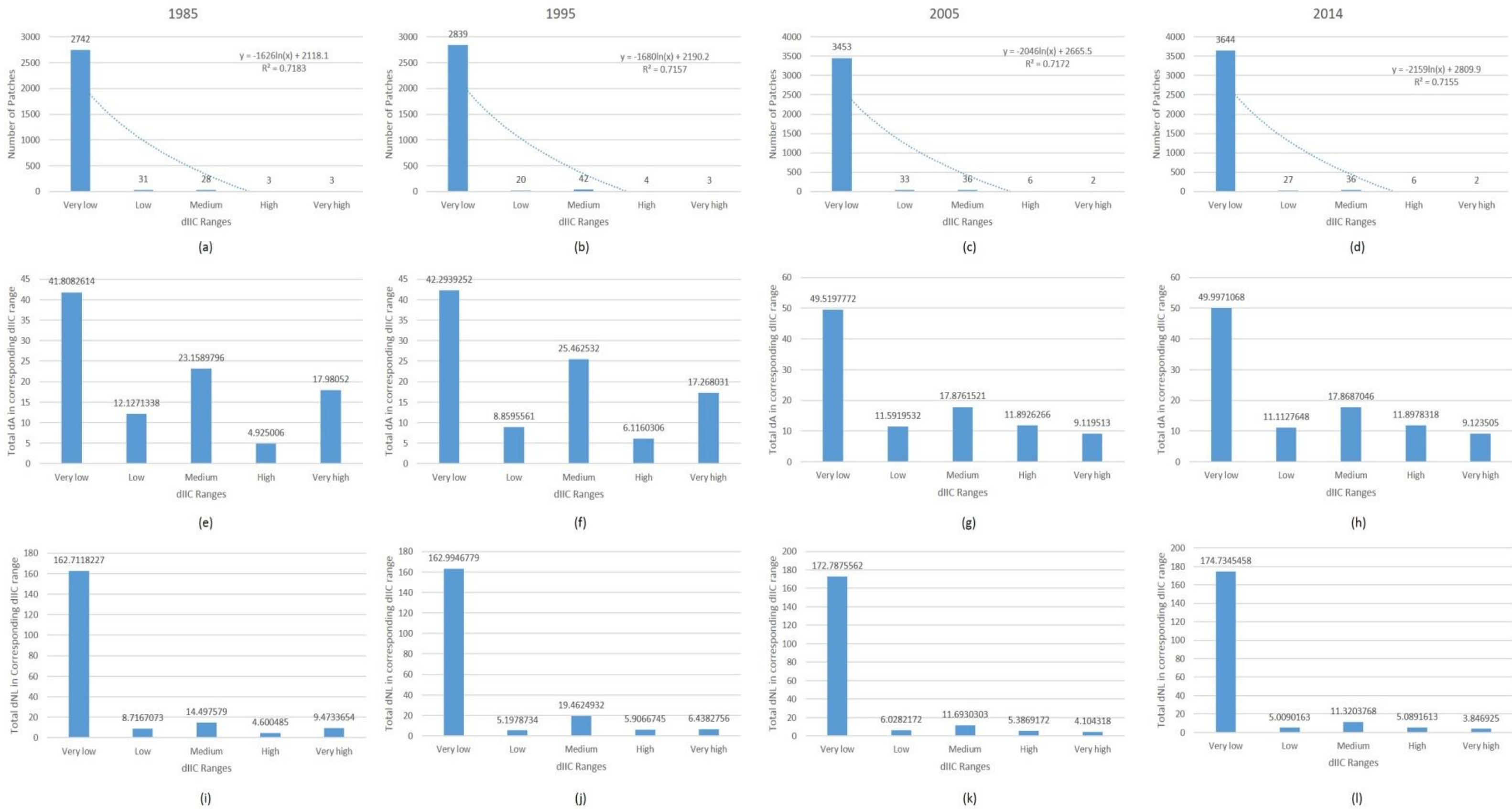


Figure 5.9 Graphs of dIIC (Integral Index of Connectivity) ranges versus Number of Patches, total dA (Percentage of Area) in corresponding dIIC range and total dNL (Number of links) in corresponding dIIC range at different time periods

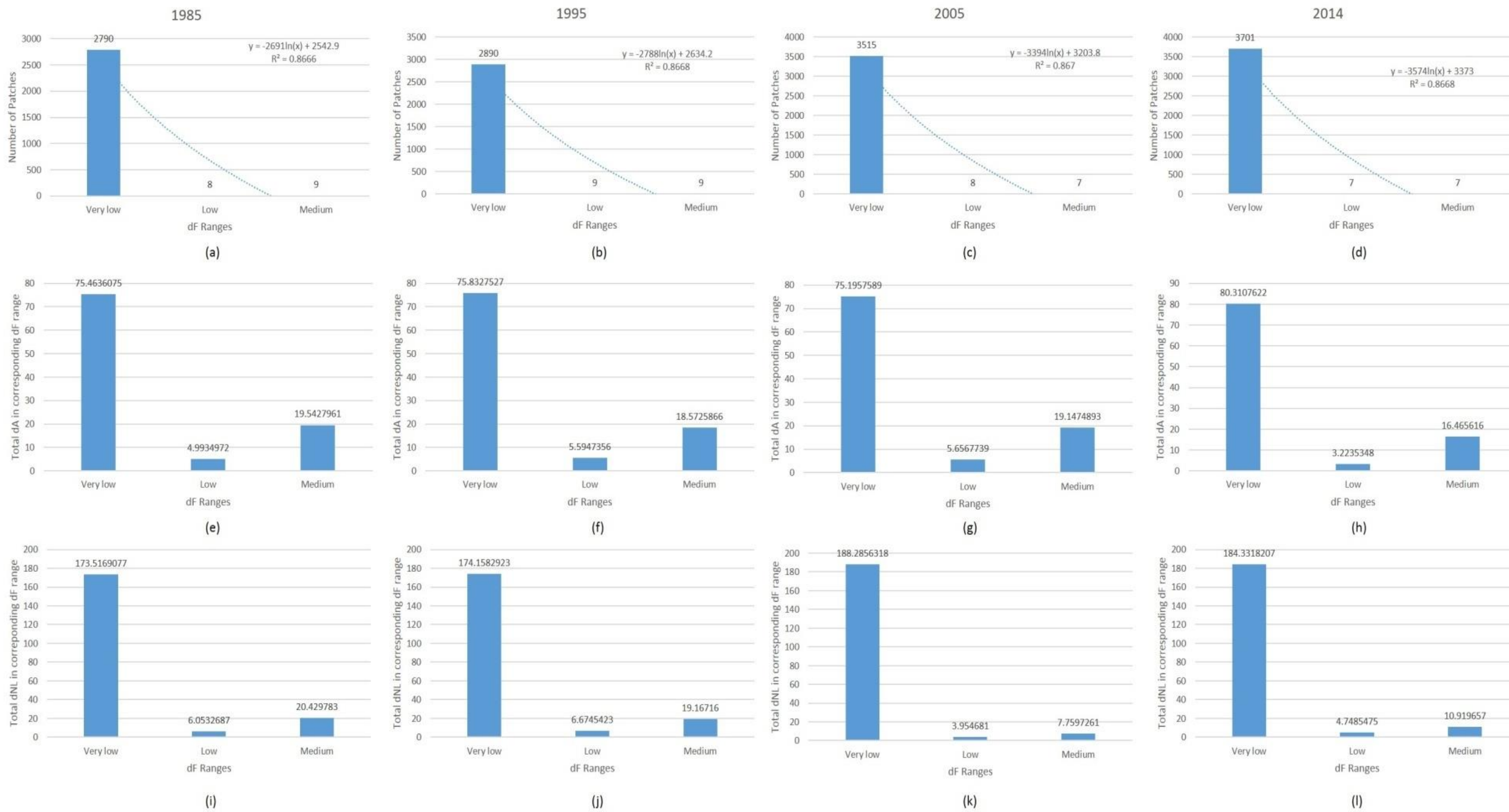


Figure 5.10 Graphs of dF (Flux) ranges versus Number of Patches, total dA (Percentage of Area) in corresponding dF range and total dNL (Number of links) in corresponding dF range at different time periods

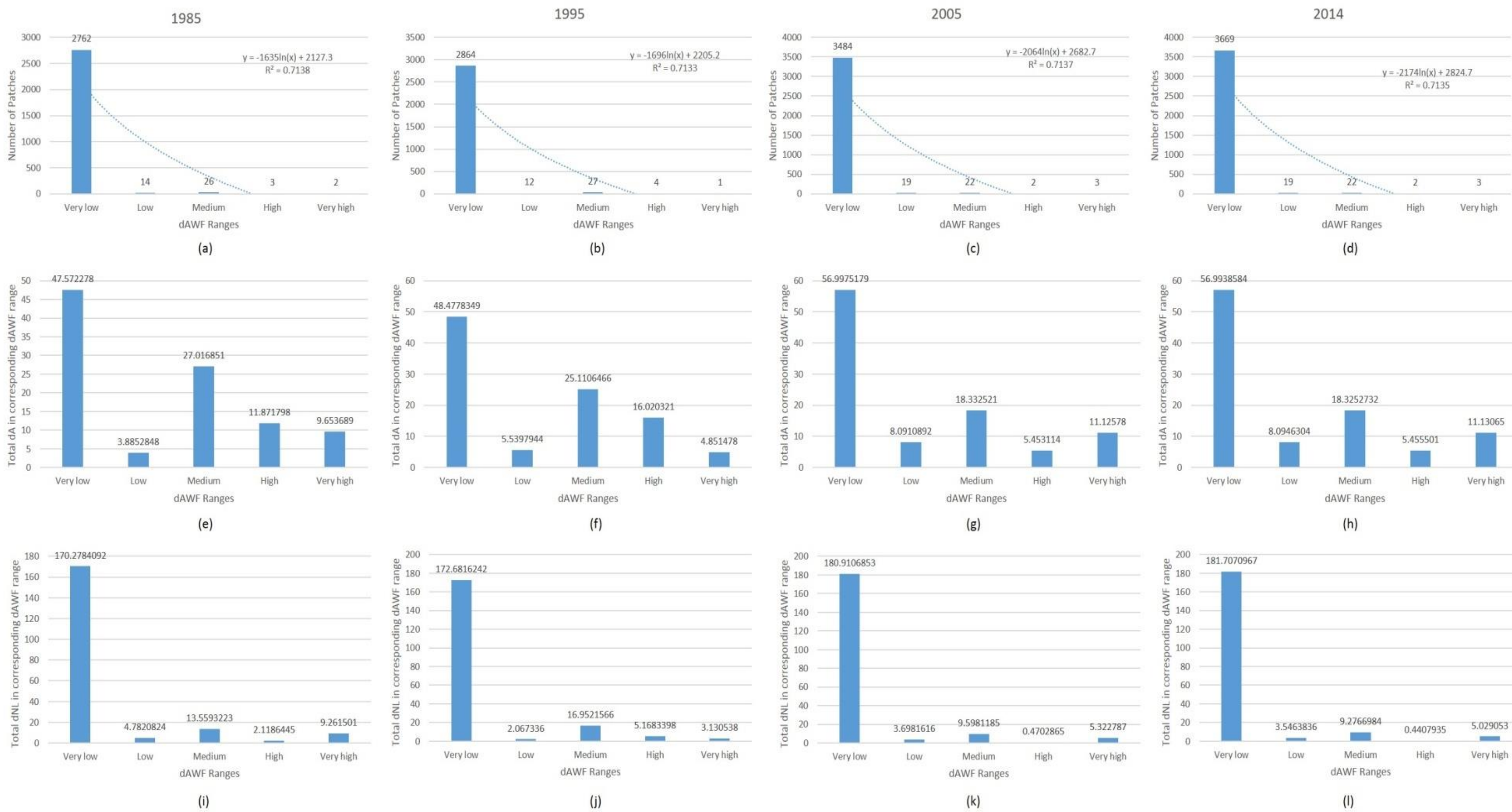


Figure 5.11 Graphs of dAWF (Area Weighted Flux) ranges versus Number of Patches, total dA (Percentage of Area) in corresponding dAWF range and total dNL (Number of links) in corresponding dAWF range at different time periods

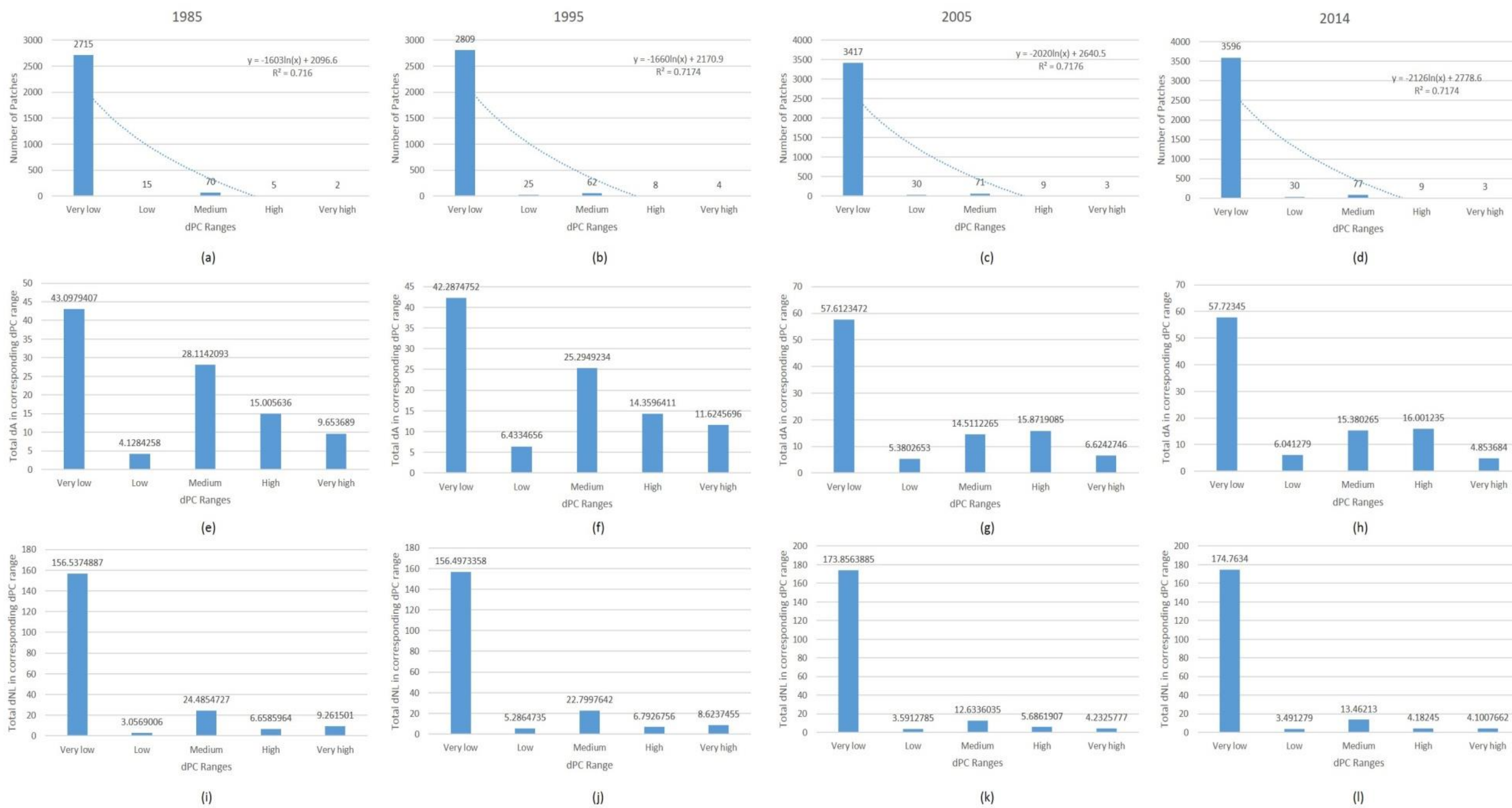


Figure 5.12 Graphs of dPC (Probability of Connectivity) ranges versus Number of Patches, total dA (Percentage of Area) in corresponding dPC range and total dNL (Number of links) in corresponding dPC range at different time periods

percent (figure 5.12 [e] to [h]) and number of links (figure 5.12 [i] to [l]) ranks second to the very low category. This is a good sign as this index has given high values for patches with large size and the patches which act as linkages in the landscape as medium values.

5.4 Potential distribution modelling

5.4.1 Model Behavior

The percent contribution was determined by adding the increase in regularized gain in each iteration. The model is re-evaluated on the permuted data, and the resulting drop in training AUC (Area under Curve) is mentioned in the table 5.1 for the respective species, normalized to percentage.

5.4.1.1 *Abies pindrow*

The Jackknife evaluation results indicated Temperature Annual Range (BIO7) as major factor influencing potential distribution of *Abies pindrow*, followed by Precipitation of Wettest Quarter (BIO16) and Mean Diurnal Range (BIO2) (Figure5.13). Table 5.1 gives the percent contribution of the heuristically defined environmental variables which were consistent with the Jackknife evaluation.

Table 5.1 Environmental variables used and their contribution in Maxent modeling for *Abies pindrow, Betula utilis* and *Taxus wallichiana*

Abies pindrow		*Betula utilis*		*Taxus wallichiana*	
Variable	Percent Contribution	Variable	Percent Contribution	Variable	Percent Contribution
Bio7	48.8	DEM	33.8	Bio7	51.8
Bio16	15	Bio2	33.4	Bio14	15.2
Bio2	11.3	Bio19	5.4	Bio2	12.7
DEM	5.3	Bio4	5.3	Bio11	8.1
Bio4	4.6	Bio8	5	Bio4	3.8
Bio19	3.6	Bio14	4.6	Bio17	3.6
Bio12	3.4	Bio18	4.3	Bio19	2.9
Bio14	2.6	Bio16	2.6	Bio15	1.4
Bio17	2.4	Bio17	1.9	DEM	0.4
Bio18	1	Bio1	1.1	Bio18	0.2

Bio11	0.9	Bio15	1.1	Bio9	0
Bio15	0.8	Bio7	0.5	Bio16	0
Bio13	0.1	Bio13	0.3	Bio6	0
Bio3	0.1	Bio3	0.3	Bio8	0
Bio8	0	Bio5	0.2	Bio13	0
Bio6	0	Bio11	0.1	Bio12	0
Bio1	0	Bio10	0.1	Bio3	0
Bio9	0	Bio6	0	Bio5	0
Bio10	0	Bio12	0	Bio10	0
Bio5	0	Bio9	0	Bio1	0

5.4.1.2 *Betula utilis*

The Jackknife evaluation results indicated Digital Elevation Model (DEM1) And Mean Diurnal Range (BIO2) as major factors influencing potential distribution of *Betula utilis*, followed by Precipitation of Coldest Quarter (BIO19) and Temperature Seasonality (BIO4) (Figure 5.14). Table 5.2 shows the percent contribution of the heuristically defined environmental variables which were consistent with the Jackknife evaluation.

5.4.1.3 *Taxus wallichiana*

The Jackknife evaluation results indicated Temperature annual range (BIO7) as a major factor influencing potential distribution of *Taxus wallichiana*, followed by Precipitation of driest month (BIO14), Mean Diurnal Range (BIO2) and Mean temperature of coldest quarter (BIO11) (Figure 5.15). Table 5.3 shows the percent contribution of the heuristically defined environmental variables which were consistent with the Jackknife evaluation.

5.4.2 Species distribution

The potential distribution of *Abies pindrow, Betula utilis* and *Taxus wallichiana* were modelled with the help of Maximum entropy species distribution model and their potential distribution maps were displayed in figure 5.14. Spatial extent of these distributions are mentioned in table 5.2. Of the total area of 85, 500 km^2, *Abies pindrow* has a potential area of 6,153 km^2. While *Betula utilis* and *Taxus wallichiana* has 6392.01 km^2 and 7967.05 km^2 area for high potential distribution respectively.

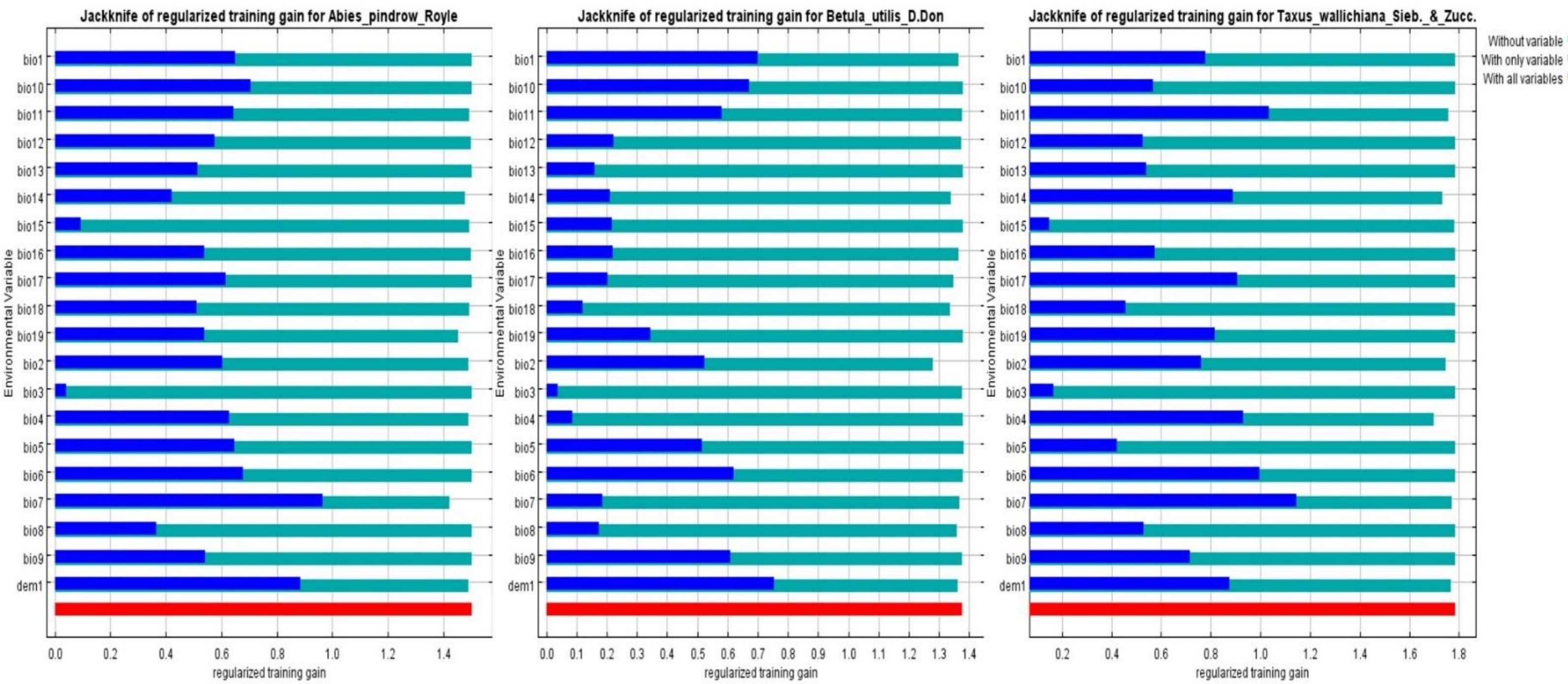


Figure 5.13 Jackknife test for evaluating the relative importance of environmental variables of *Abies pindrow, Betula utilis* and *Taxus wallichiana*

Table 5.2 Spatial distribution of different distribution classes.

Category	*Abies pindrow* (in km^2)	*Betula utilis* (in km^2)	*Taxus wallichiana* (in km^2)
Least suitable <0.2	24898.59	21729.7	35878.23
Moderately suitable 0.2-0.4	36642.56	38117.89	26250.44
Suitable 0.4-0.6	17838.73	18892.98	15621.4
Highly suitable >0.6	6153.95	6392.01	7967.05

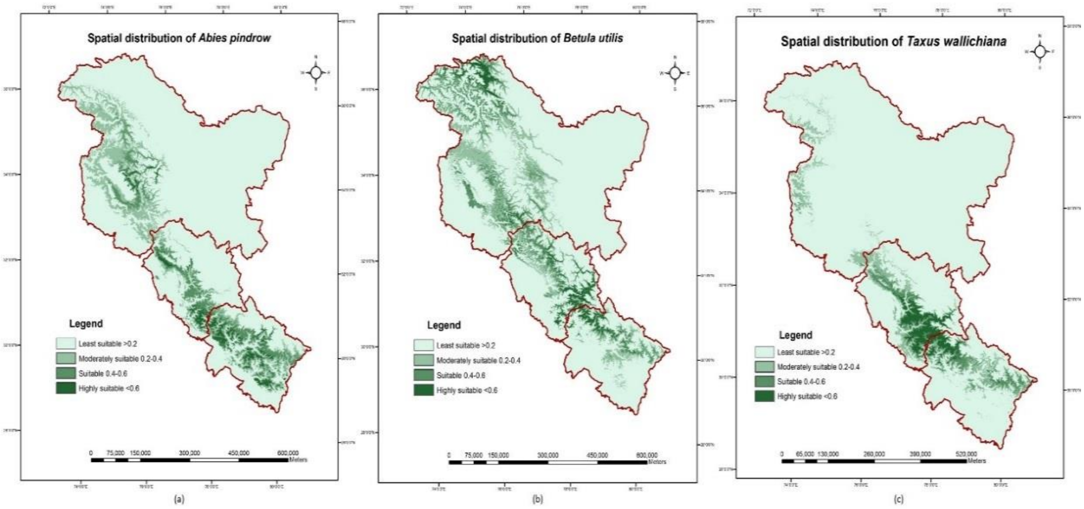


Figure 5.14 Potential distributions of *Abies pindrow, Betula utilis* and *Taxus wallichiana* in Western Himalayan region

5.5 Integration of species distribution modelling with graph theory

Patches with high potential distribution (>0.5) were taken as inputs for graph theory model to estimate the level of connectivity for the selected climate sensitive and endangered species. Also, the connectivity indices used has been analyzed well in this study for defects or redundancy. Probability of Connectivity was found to have an upper hand than its counterpart Integral Index of Connectivity in finding the critical patches as well as stepping stones. Even though Harary index uses only the number of links for analysis, it cannot be neglected for its capability to find the level of connectivity of the patches. Thus, these two indices were chosen to be the best connectivity indices to study the connectivity of these species (*Abies pindrow, Betula utilis and Taxus wallichiana*).

5.6 Level of connectivity of *Abies pindrow, Betula utilis* and *Taxus wallichiana*

Level of connectivity for *Abies pindrow, Betula utilis* and *Taxus wallichiana* based on Harary index and Probability of Connectivity were calculated and the importance values of these patches where sorted as very low, low, medium, and high and very high are shown in the figures 5.15, 5.16 and 5.17. *Abies pindrow* is found to be present in Himachal and Uttarakhand more abundantly than Jammu and Kashmir (figure 5.15). The degree of connectivity in the Kashmir region is very low because of relatively low number of patches but still PC index ranks high for the center most patch because of the patch's large area and its central position surrounded by patches which can allow the free movement of genes. Patches in the Himachal and Uttarakhand are closely spaced and hence the level of connectivity is high. All the central patches in this region has ranked very high in Harary index and most of the corner patches have ranked low to very low. This is a major defect of this index. Probability of Connectivity index has performed much better than the previous one in terms of assigning the value to these patches and we are not able to find any discrepancies or inconsistency in its performance. *Betula utilis* as the figure 5.16 witnesses has been well distributed spatially in the Western Himalayan region. The probability of inbreeding in *Betula utilis* is much more far from *Abies pindrow* as it has been distributed spatially and more than that connected between among them. The major problem here as seen by the performance of PC index has shown that the connectivity of these species between the lower region and upper region of the study area has been hanging in a few stepping stone patches which has to be given more importance and these patches has to be improved or more patches has to be reforested. *Taxus wallichiana* as shown in figure 5.17 has been found to be very sparsely populated in the Kashmir region and other than that it is a common species in the Garhwal region and the Himachal forests. They are found to be well connected among them in our present study area.

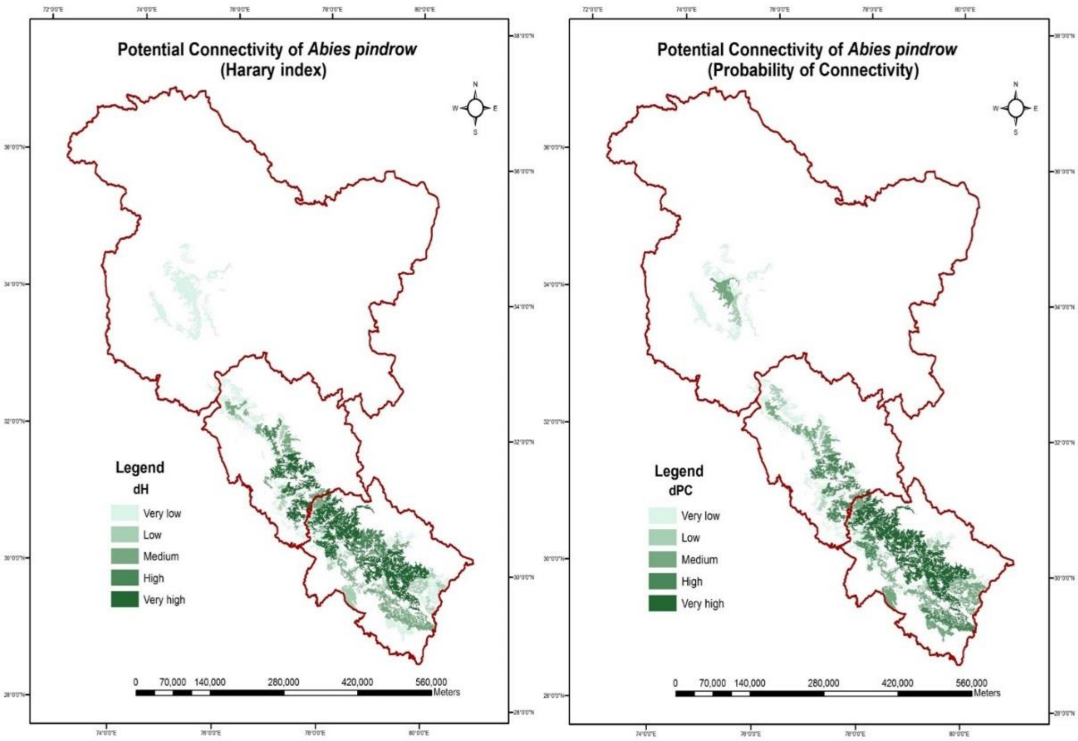


Figure 5.15 Level of connectivity of *Abies pindrow* based on Harary and Probability of Connectivity index

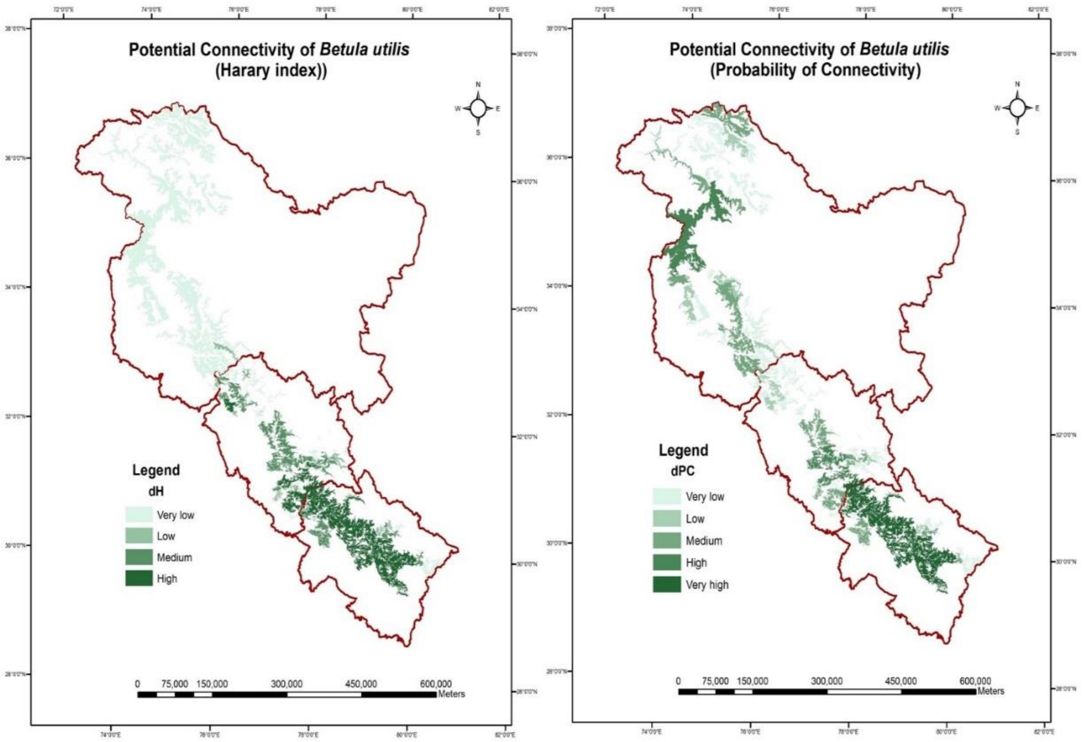


Figure 5.16 Level of connectivity of *Betula utilis* based on Harary and Probability of Connectivity index

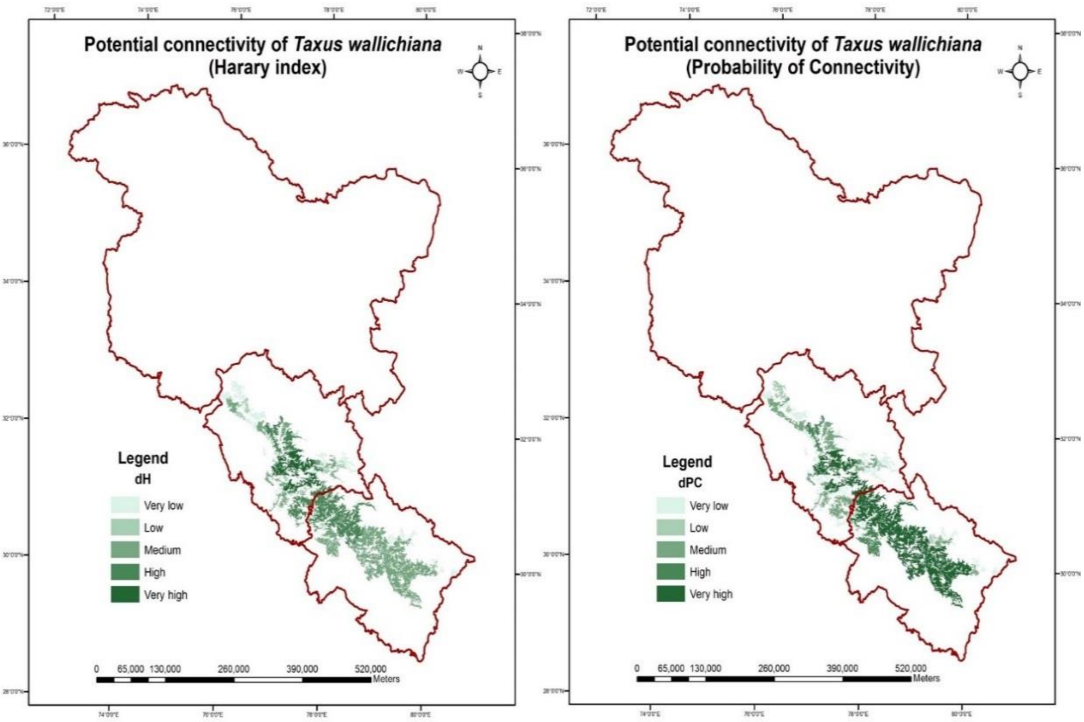


Figure 5.17 Level of connectivity of *Taxus wallichiana* based on Harary and Probability of Connectivity index

5.7 Generation of Graph Topology

Network topology was created for the three species considered for this study (figure 5.18, 5.19 and 5.20). These networks were created with the help of all pairs shortest path algorithm. A threshold of 300 meters were used for creating link sets. Based on this algorithm, with the specified threshold, minimal planar graph was constructed to find the important hubs for connectivity.

5.7.1 Graph Topology of *Abies pindrow*

A total of 926 forest patches were observed to have high potential distribution of *Abies pindrow* in Western Himalayas. A minimal planar graph based on 300 meter threshold was created. 55 edges were observed in the study with *Abies pindrow* distribution (Table 5.3). A major hub along with 7 supporting hubs were observed in our study site. Figure 5.18 (a) and (b) observes the level, extent and amount of connectivity for *Abies Pindrow.* The output had mentioned that the species present in Jammu and Kashmir is totally isolated from the mountain ranges of Himachal Pradesh and Uttarakhand. Well even in Himachal Pradesh, the patches are scattered and are way beyond the dispersal capability of the species. But still, these patches are connected with some of its neighbours to sustain the gene flow. A major hub in Uttarakhand acts as a connecting node for most of the patches surrounding it. This single large patch should be given high priority for conservation corresponding to this species.

Table 5.3 Information about the Graph construction

	Abies pindrow	*Betula utilis*	*Taxus wallichiana*
Number of patches	926	609	30
Edges	55	36	300
Threshold	300	300	594
Major Hubs	1	2	1
Minor Hubs	7	10	5

5.7.2 Graph Topology of *Betula utilis*

With a threshold of 300 meters, 609 patches which are found to be highly suitable for *Betula utilis* has been used to construct the thresholded planar graph. 36 edges were found to be present (Table 5.3). Like *Abies pindrow,* this species was found to be well connected in Uttarakhand and Himachal Pradesh forests with a major hub. This major hub is to be given more importance for conservation but one more major hub supported by three minor hubs surrounding it in Jammu and Kashmir region has to be tried for creating linkages within the landscape. So, a gene flow can be made possible in this region (Figure 5.19).

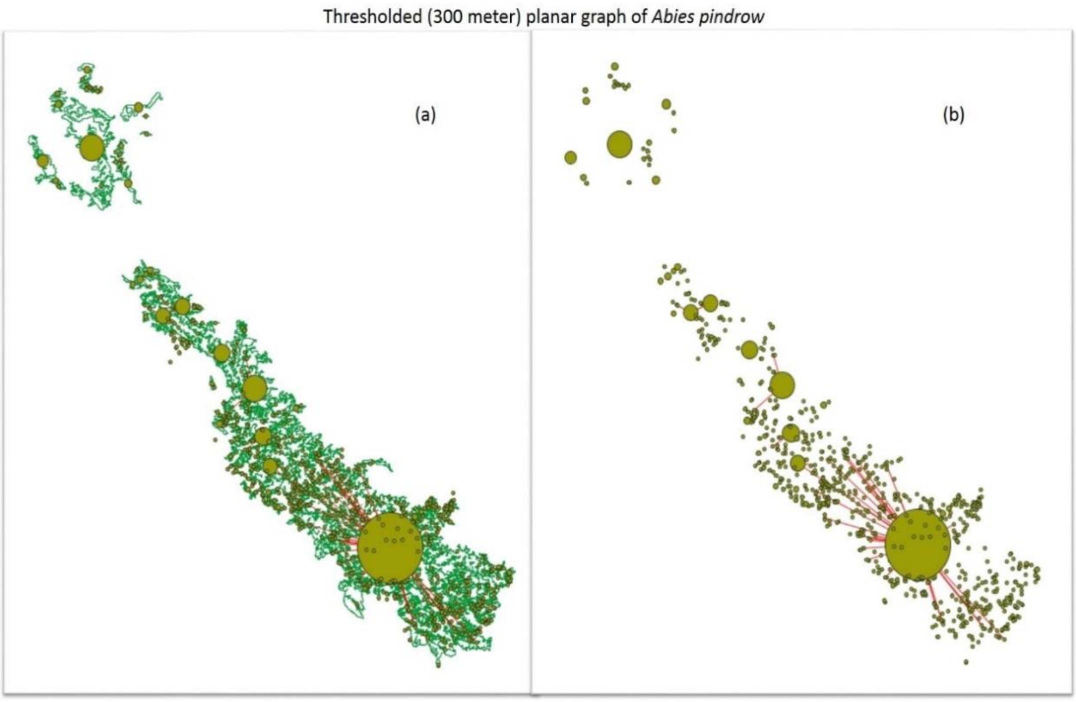


Figure 5.18 Thresholded planar graph of *Abies pindrow* for Western Himalayas a) Topology created based on the patch capacity b) Graph topology showing the connectivity of *Abies pindrow*

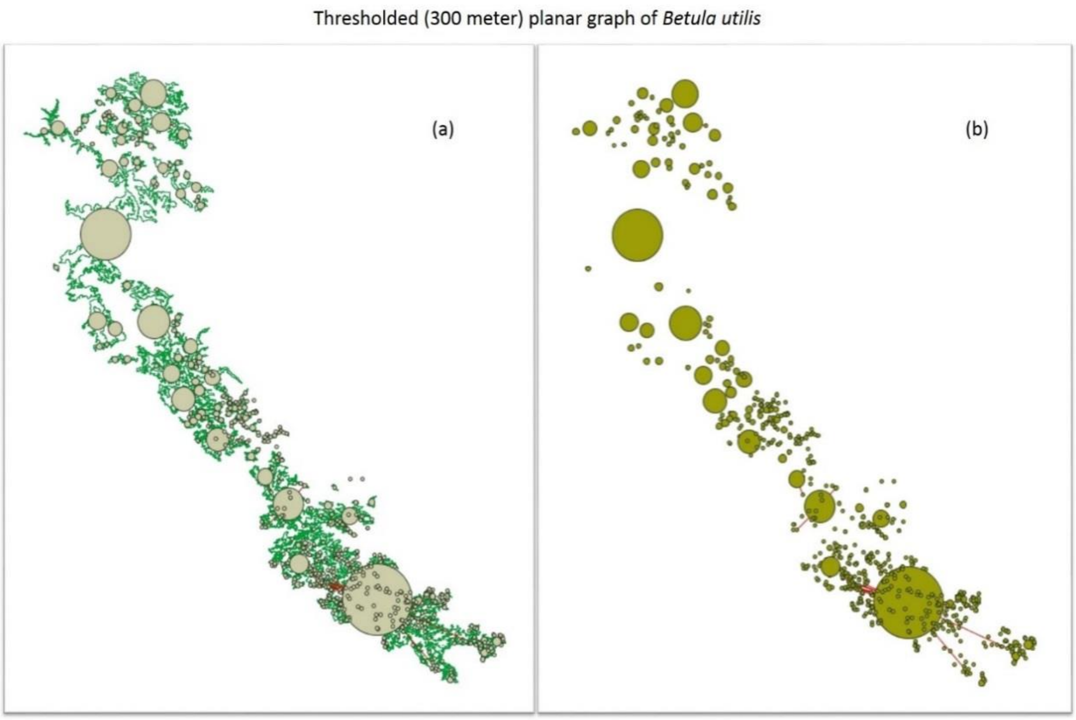


Figure 5.19 Thresholded planar graph of *Betula utilis* for Western Himalayas a) Topology created based on the patch capacity b) Graph topology showing the connectivity of *Betula utilis*

5.7.3 Topology of *Taxus wallichiana*

30 edges were created with a threshold distance of 300 meters for 594 patches which were found to be highly distributed for *Taxus wallichiana* (Table 5.3). One major hub was found in the Uttarakhand region which is so powerful that it connects with most of the patches in Uttarakhand and Himachal Pradesh (Figure 5.20).

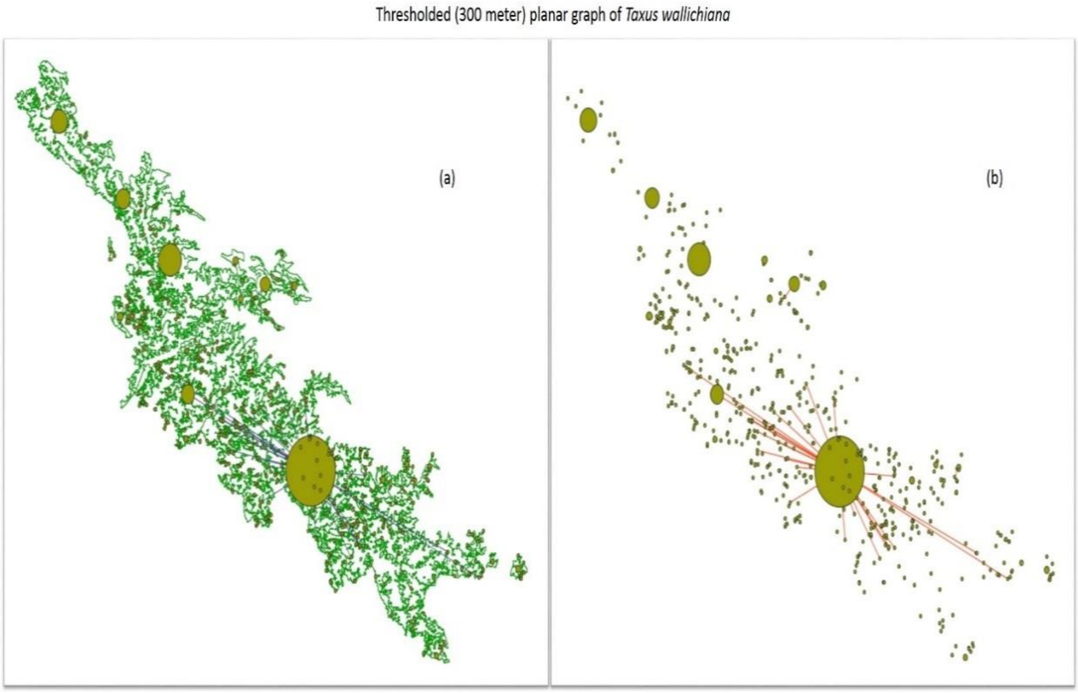


Figure 5.20 Thresholded planar graph of *Taxus wallichiana* for Western Himalayas a) Topology created based on the patch capacity b) Graph topology showing the connectivity of *Taxus wallichiana*

5.8 Discussion

The primary aim of this study was to analyse the level of forest connectivity and to find the extent of fragmentation with datasets for four decades viz., 1985, 1995, 2005 and 2014. It has become mandatory to study changes in spatial pattern along with connectivity assessment, because the amount of habitat and species configuration in a landscape is influenced by habitat loss and fragmentation which are considered as two separate components (Laita et al., 2011). Proofs obtained experimentally frequently found that habitat loss and fragmentation continue to result in the loss of both species and genetic diversity (Bailey, 2007). But all these changes due to habitat loss affect connectivity in many ways depending upon the geographical location of the habitat patch while fragmentation either alters or erases the traits of forest ecosystems. To prevent these losses, Taylor et al. (1993) had considered landscape connectivity as an important consideration and he defined it as “the degree to which the landscape impedes the dispersal movement of populations across habitat patches”.

5.8.1 Landscape pattern analysis with GIS methods

For assessing the harmful effects of forest fragmentation, a comparison of landscape pattern metrics on temporal LULC data is useful for describing the changes in landscape. In our study, we compared the changes in the landscape fragmentation through fragmentation indices and shape indices (Rempel et al., 2012). The decline in the forest cover from 1985 to 2014 in Western Himalayas can be largely explained from our spatial pattern analysis outputs. Habitat area decreased constantly with the increase in number of habitat patches (figure 5.2 (a)(b)) which can be attributed to the severity of fragmentation on the extent of connectivity. With fragmentation increase, the perimeter or edge of the patches tend to increase increasing the vulnerability of these patches. Landscape patterns can be estimated using landscape pattern metrics. Mcgarigal et al. (2002) had specified that the composition and configuration of ecosystems across a large landscape can be quantified through these metrics. Also the need to integrate dispersal capabilities of focal species with spatial landscape pattern analysis was specified by Saura et al. (2011).

5.8.2 Overall connectivity analysis for optimization of threshold distance

Before approaching the habitat patches for graph construction, threshold distance should be decided first and based on this distance the graphs are created. Number of links (NL) and Number of Components (NC) were plotted against the different threshold distance used for graph construction to estimate the saturation point in the graph. Since the landscape is extensively fragmented in the study area which is also large, the saturation point didn't arrive for the threshold distance between 100 to 25000 meters. But it is of no use to find a saturation point beyond 25 km as it is highly unlikely for species considered in the study to disperse beyond this distance (Tamme et al., 2014). The ecological effects of the changes in forest connectivity are the influence of the ecological process (dispersal activities) among habitat patches. Dispersal distances play a significant role in evaluation of landscape connectivity (Suzuki and Suzuki, 2011). Also, Laita et al. (2010) had specified that the effectiveness of connectivity analysis had always depended on the dispersal abilities of focal species. Thus, selection of effective threshold distance based on dispersal abilities is essential. While documenting dispersal range requires habitat suitability, mark-recapture, or experimental removal-recolonization studies which can be so data intensive. Hence, few studies related to species dispersion are taken into account. Most of the scientists studied the dispersal behaviour of the focal species with respect to particular parameters. Thompson et al. (2011) studied the dispersal distance of the seeds with respect to the plant height, seed mass. Stephenson et al. (2007) analysed the mechanistic models of seed dispersal for *Rhododendron ponticum*. But only, Tamme et al. (2014) came to a general conclusion after analysing all the plant and tree traits that how far a species can disperse under specific conditions. He observed that the tree species can disperse under normal windy conditions for a distance approximating 300 meters. This distance can increase or decrease depending upon the mass of the seed and speed of the wind.

Remnant forest patches needs to be linked to maintain the flow of genes and materials for ecological persistence. The probability of maintaining diversity for any organism depends on complex interactions that involve population sizes, its silvics and their dispersal ability. Also, different species has different dispersal range based on their nature of dispersal agents, size and weight of the seeds etc., Seeds which can disperse through winds (anemochory) can reach maximum distance when they are light-weighted. Species which get dispersed through vertebrate animals such as birds and mammals through ingestion (endozoochory) get dispersed based on the dispersal or migration range of that animal. These facts has prevented creation of a common ecological profile across species for connectivity analysis. Thus, based on a study about dispersal distance (Tamme et al., 2014) as well as our own study, it was decided to go with 300 metres which is the average dispersal distance of a wind dispersed tree species. Three species (*Abies pindrow, Betula utilis* and *Taxus wallichiana*) which disperse through wind was taken for connectivity study in the present Western Himalayan landscape. These species are more climate sensitive and are endangered in the IUCN red list. Taking all this into consideration, a threshold distance of 300 meters was used for this study.

5.8.3 Forest connectivity – graph theory

A major drawback of these pattern metrics are that they are not linked explicitly with ecological processes. With the natural habitats being lost and fragmented due to developmental activities and anthropogenic pressure, ecological processes like species movement has been studied through landscape connectivity (Foltete et al., 2012). And the most important change that happens with the change in forest connectivity is the reduction of biodiversity and alteration in species composition (Liu et al., 2014b) which can disrupt the functioning of the whole ecosystem. The importance of habitat patches in terms of connectivity can be quantified by CS2.6 program (Saura et al., 2011).

5.8.4 Performance of connectivity metrics

The performance of the indices was tested based on the resultant outputs of the respective indices used in this study. Harary index analyses the level of connectivity based on the number of links between two patches. This can lead to contradictory results either by giving high importance values to patches which are very small but connected with all the neighbouring patches or by giving low importance value for a single large patch not connected with any patches. Because connectivity does not cover inter-patch alone, it takes into account the intra-patch connectivity also. While landscape coincidence probability index gives better results than Harary index by drastically reducing the percentage of area belonging to very low connected patches. Integral Index of Connectivity, Landscape coincidence probability, Area weighted flux and Probability of Connectivity results in somewhat accurate level of connectivity for the patches comparing the connectivity maps. Flux was found to be very low for most of the patches in this current study. Probability of Connectivity was found to be best index to use in our study because of its ability to depict the stepping stones, topographical position of the patches which no other index can analyse. Landscape Coincidence Probability was found to be unique for revealing the habitat features and network patterns in the measurement process of landscape connectivity (Liu et al., 2014b).IIC was found to achieve all the properties of an ideal index (PascualHortal and Saura, 2006). PC exhibits favourable calculation properties and satisfies the need to simultaneously calculate functional connectivity and identify important habitat patches in a landscape (Saura and PascualHortal, 2007; Saura et al., 2011). Other than these better performing indices, low performance of the few landscape indices can be attributed to their inherent limitation through which they give unpredictable responses to few basic changes in the landscape (Li and Wu, 2004). Based on the preferred PC index of functional connectivity, habitat patches of high importance values could provide references for the improvement of landscape management practises in a better and scientific way.

5.8.5 Behaviour of Maximum Entropy species distribution modelling

Potential distribution of these species was modelled with the help of Maximum entropy species distribution modelling. Maxent is a maximum entropy-based machine learning program that estimates the probability distribution for a species' occurrence based on the environmental constraints and field presence data. A common statement about Maxent model states that the predicted potential distribution areas through Maxent modelling often appear as over-estimated compared to the habitat. This is because, it predicts the species fundamental niche rather than realized niche (Kumar and Stohlgren, 2009 and Pearson, 2007). This negative effect of the model is accepted for this study because these areas predicted which may not be currently occupied by the species can be considered as candidate areas for prioritisation, propagation and conservation of the species. In reality, the species might have failed to disperse due to geographic barriers or any other disturbances but these areas can be considered for reintroduction in case of any extinction prevention of the species.

5.8.6 Connectivity of focal species

As previously discussed, collection of detailed information about species dispersal is more difficult. Thus few climate sensitive, endemic to Himalayas was taken for study. The species (*Abies pindrow, Betula utilis and Taxus wallichiana*) used in this study have a common dispersal agent i.e wind. Thus average wind dispersal range was taken into account. Level of connectivity based on Harary and Probability of Connectivity was analysed as many of the indices were found to be either redundant or inferior to these indices. However, quantitatively evaluating the amount of disturbance on the flow of species between patches is still a great challenge in ecology. In this study, although few features of the species can be identified but still the dynamic changes regarding those species behaviour are difficult or complicated to predict in detail.

5.8.7 Topology of the graph

Network topology of the patches showed that the graphs were quite different from each other based on the distribution the focal species. This proves that a single landscape can have different characteristics for different organisms. More interestingly, all three topology created for *Abies pindrow, Betula utilis* and *Taxus wallichiana* are scale-free networks. A scale-free network is characterised by a few hubs (high-degree nodes) with a majority of low-degree nodes (Barabasi and Bonabeau, 2003). The peculiar feature of these networks is that the node degree distribution follows a continuously decreasing function. Scale-free networks are highly resistant to random disturbances but vulnerable to deliberate attacks on the hubs (Barabasi and Bonabeau, 2003).In simple words, network connectivity would show little change if most of the smaller patches were removed but would quickly break apart if hubs were disturbed or removed. It was also found that a network of bat-roosting trees was shown to have scale-free topology (Rhodes et al., 2006).Thus, conservation and monitoring should be best spent on hub patches. Analysing landscapes within this framework allows assessment of multiple aspects of connectivity and subsequently can lead to more informed conservation plans.

Chapter – 6 Conclusions and Recommendations

6.1 Conclusions

Habitat patches have different roles within a landscape network. Apart from serving for shelter, forage and breeding, they also serve as dispersal fluxes to other habitat patches and may even behave like a stepping stone. Changes in landscape patterns and networks may influence the ecological process of seed dispersal activities in the landscape. Graphs can merge landscape configuration and focal species biology like metapopulation theory to obtain the measures of connection (Urban and Keitt, 2000). The potential of graph theory is far from realized still with very little data, a graph of habitat patches can be constructed then ecological information collected can be infused into them by considering a range of threshold distances to define edges or links. This doesn't mean that it should replace other approaches but it is a computationally powerful approach than others with its simplicity and flexibility to deal with landscape connectivity.

This study was done with four different time periods (1985, 1995, 2005 and 2014) to access habitat (forest patch) connectivity. The most important preliminary step to study connectivity includes habitat pattern analysis by analysing the changes in the pattern of the landscape over time. The results of the spatial pattern analysis prove the increasing rate of forest fragmentation leading to the loss of connectivity as well as habitat loss. The most important requirement for connectivity is the identification of threshold distance based on which the Number of Links (NL) and Number of Components (NC) are derived. This depends on the number, size and spatial distribution of the forest patches. These NL and NC indices give an overall opinion about the connectivity of the landscape. The level of connectivity of the landscape with respect to forest patches decreased gradually with the increase in forest fragmentation from 1985 to 2014 as witnessed in the results of connectivity study based on six connectivity indices. Patches which are very small has been fragmented much in the past decades and few of them are left isolated. Thus, connectivity will decrease along with the Number of Links leading to the more cost involvement in establishment of a link or connection. On the other hand, patches which are large has the possibility to link themselves with more adjacent forest patches and also organisms can move freely within them owing to the large area availability. It is necessary to establish networks of habitats connected by protected linkages to maintain the survival of critical elements of the landscape.

A systematic analysis of the complexity of landscape and prioritisation of patches using these connectivity indices on the basis of graph theory provided a much needed understanding of the efficiency of patches for conservation and protection. Patches having high degree of connectivity indices should be protected from any further degradation while medium degree of connectivity should be improved and maintained from external invasion. Low connectivity patches need to be improved in the area so that links can be established with other patches. Overall, graph theory is a robust tool for identifying potential forest patches for connectivity. This study will be helpful for forest monitoring, biodiversity conservation and connectivity in Western Himalayan region.

There are a few limitations in this study that needs to be highlighted for future reference. The processing is so slow that choosing necessary patches for analysis will serve the purpose quickly else parallel computing need to be used. Dispersal ranges of many species have not been studied till date. Proper analysis of the dispersal traits should be undertaken as a preliminary study to estimate the exact level of connectivity of the focal species. Also this study revealed the need for a hierarchical analysis of patch size, number, inter-distance and relative importance of patches to arrive at optimal level of connectivity.

6.2 Recommendations

The work can be extended to consider the following recommendations for reference in terms of result as well as applicability in other studies.

- Importance and potential ecological impacts of ongoing landscape pattern changes need to be assessed with suitable and effective methods
- This graph based habitat availability approach can be studied in other forest ecosystem types with the selection of potential target species (with more biological information)
- The degree of connectivity (dI) values of habitat patches under different dispersal abilities can be mapped and quantitatively classified into different important value classes for biodiversity conservation
- Landscape connectivity relevant to key species as large scale assessment can be further integrated with other detailed small-scale observations.
- This study can be extended for conservation of many species and analysis can be of source-sink dynamics (directed graphs) with more information about topography, wind-driven connectivity etc.,
- Future studies can focus on multiple scale inputs of Land cover changes to analyze the change in connectivity at different scales
- Reforestation works can be undertaken based on these outputs for more scientific management of forests, and their results analyzed through the graph
- Present and Future simulations can be done for metapopulation and even metacommunity dynamics

The study can be regarded as stepping stone in habitat connectivity with spatial data in India and can be modified accordingly for future studies.

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