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A network theoretic study of ecological connectivity in Western Himalayas

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ABSTRACT

Network theoretic approach has been used to model and study the flow of ecological information, growth and connectivity on landscape level of anemochory (wind dispersal) of Himalayan moist temperate forest species in the Western Himalaya region. A network is formally defined and derived for seed dispersion model of target floral species where vertices represent habitat patches which are connected by an edge if the distance between the patches is less than a threshold distance. We define centrality of a network and computationally identify the habitat patches that are central to the process of seed dispersion to occur across the network. These central patches are located on map and geographical regions critically important for the flow of ecological information across the network are identified as Gharwal region and eastern Himachal Pradesh of Indian Himalaya. We find that the network of habitat patches is a scale-free network and at the same time it also displays small-world property characterized by high clustering and low average shortest path length. As a result, ecological information propagates rapidly and evenly on a local scale. Hubs in the network are identified as important centres for dissemination of ecological information (seeds) and need to be conserved against a potential attack by malicious agents and also ecological shocks. The network showcase a well-formed community structure. As a consequence of these structural properties of the network, anemochory floral species studied in this work are likely to thrive across the ecological network of forest patches in the Western Himalaya region over time.

1. Introduction

Almost all the natural ecosystems on earth are experiencing degradation and destruction due to human activities. In many of the landscapes, large tracts of contiguous forests no longer exists and remnant natural habitats occur as a mosaic of large and small forest patches. For sustaining the ecosystem processes, a robust movement of energy, information and materials across the network is a prerequisite. In a fragmented landscape, the forest patch connectivity is important for unhindered movement of energy, information and materials. Understanding the functional connectivity of the patches, can provide invaluable information on the conservation policy to be followed as these provide the stepping stones for dispersal and movement of various species across the landscape (Bascompte et al., 2003; Olesen et al., 2011; Jordano et al., 2003; Thebault and Fontaine, 2010).

Landscape connectivity is important in promoting the survival and vitality of species through flow of ecological information in the form of organism movement, seed dispersal and other ecological processes (Taylor et al., 2006). Maintaining connectivity and mitigating the fragmentation of habitat may be critical for landscape process such as gene flow and dispersal (Crooks and Sanjayan, 2006). One of the most formal means to explore, examine and understand the essential structural and functional dynamics of ecological complexity is provided by a complex network-theoretic (and graph-theoretic) approach to ecosystem analysis (Bascompte and Jordano, 2007; Ings, 2009; Olesen et al., 2007; Bascompte, 2009; Pilosof et al., 2016).

Our effort is essentially to realize the western Himalaya forest ecosystem as a complex system. For this we identify the individual habitat patches (entities) of the focal species and try to gain an understanding of the interactions they undergo, thus giving rise to

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various characteristics of the forest system that they are embedded in. Use of graph-theoretic network analysis provides relevant quantitative measures to analyse the landscape and responds directly to the level of isolation of the forest fragments in a changing landscape (Cantwell and Forman, 1993; Fall et al., 2007; Gastner and Newman, 2006; Minor and Urban, 2007; Minor and Urban, 2008; Urban and Keitt, 2001; Chetkiewicz et al., 2006). Advancements in ecological network flow modelling has led to the foundation of Ecological/Ecosystem Network Analysis (ENA), a method to holistically analyse environmental interactions (Patten, 1978; Patten, 1981; Patten, 1982; Patten, 1985; Fath and Patten, 1999; Roy et al., 2016; Ulanowicz, 1983; Ulanowicz, 1986; Ulanowicz, 1997; Fath et al., 2013). Network analysis methods to evaluate consumer – response relations have been developed and studied to find direct and indirect ecological relations between ecological compartments (Ulanowicz, 2004; Scharler and Fath, 2009).

We apply concepts from the theory of complex networks to study the level of connectivity of the major wind pollinated Himalayan moist deciduous forests that prominently include species such as *Abies pindrow (Himalayan Fir), Betula utilis (Bhoj patra/Himalayan birch)* and *Taxus wallichiana (Himalayan yew).* These floral species are wide spread in the Western Himalaya, occupying an elevation range from 1800 to 4500 m and prefer an average temperature variation range of $4^{\circ} - 24^{\circ}$ Celsius.

Since these are endemic species and are also sensitive to climate change, a break in the connectivity of these anemochory species can result in a local extinction in climate change scenario (Stocker et al., 2013). Thus one of our main objective in this work is to identify habitat patches which are critically important in conservation of the ecological network that is responsible for creating connectivity among the populations of these anemochory floral species over the last three decades (1985–2014) in Western Himalayas. One of the ways to identify potential areas of spread of anemochory plant species is through modelling their distribution. Spatial modelling for species distribution is frequently being used for management of natural resources by environmentalists (Stohlgren et al., 2010). The importance of dispersal and movement of species through the landscape have been emphasized 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., 2002; Vos et al., 2001). The restriction of gene flow and dispersal results in isolated populations, which is expected to result in the loss of genetic diversity (Keyghobadi, 2007). The efficacy and advantages of network theoretic approach to landscape analysis to assess the importance of individual landscape elements and to guide conservation and restoration efforts have been discussed in the scholarship (Bodin and Norberg, 2007; Estrada and Bodin, 2008; Bascompte et al., 2006).

Networks are generic representations of complex systems in which the underlying topology is a graph. Networks are generally used to model empirical data from real world problems where the relationship between given components is of importance and may evolve with time. Formally a network N is a four tuple (V_λ, E_λ, ψ_λ, Λ) along with an algorithm A such that for $\Lambda \neq \phi$, $i \in \Lambda$, V_λ is a set of vertices V_i, E_λ is a set of edges E_i, ψ_λ is incidence function $\psi_i : E \rightarrow [V]^2$ where $[V]^2$ is the set of not necessarily distinct unordered pairs of vertices such that $\left(V_i, E_i, \psi_i\right)$ is a graph given by the algorithm *A(i).* The incidence function ψ provides structure to a graph by associating to each edge an unordered pair of vertices in the graph as $\psi(e) = \left\{v_i, v_j\right\} : v_i, v_j \in V, \quad \forall e \in E \subseteq [V]^2$. Here i is the temporal component by virtue of which a network can evolve as per the given algorithm A.

A network is thus an empirical object the underlying graphs for which can be either deterministic as completely determined by an algorithm or stochastic as obtained by modelling real world data. However, a graph is an algebraic object such that an unlabelled graph represents an isomorphism class of otherwise labelled graphs. We call a network as static network if the temporal component Λ consist of a single element i, otherwise the network is a dynamic network. For the purpose of our work in this paper, we define an ecological network as a network N in which V_λ is the set of habitat patches for the target species/population, and E_λ is the set of flows of ecological matter between two distinct habitat patches.

The seed dispersion of representative Himalayan moist temperate anemochorous plants viz. *Abies pindrow, Betula utilis* and *Taxus wallichiana* thus forms a dynamic ecological network $N = (V_\lambda, E_\lambda, \psi_\lambda, \Lambda)$ with Λ consisting of three periods over the years 1985, 1995 and 2005. Here the vertices of underlying graphs represent habitat patches of these species that are connected by edges whenever the distance between two habitat patches is less than three hundred meters. The reason for choosing this distance is because three hundred meters is considered the threshold up to which these wind dispersed (anemochory) species can disperse (Vittoz and Engler, 2007).

2. Study area

The study has been carried out in the Western Himalayan region of India constituting the states of Uttarakhand, Himachal Pradesh and Jammu and Kashmir. 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. The altitude varies from foothills of Himalaya ca. 50 m through 5,500 m. The terrain is diverse and it includes plains, undulating hills and high mountains (Hajra and Rao, 1990). The average annual rainfall is about 1800 mm, 600–800 mm and 1550 mm in Himachal Pradesh, Jammu & Kashmir and Uttarakhand respectively. Temperature varies from sub-zero to 40 °C. The region witnesses alpine and temperate climate except in the plains where the climate is tropical. 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 km2 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. The Himalayan moist temperate forests in these three states stretch across the landscape. The three tree species considered in the study viz. *Abies pindrow, Betula utilis* and *Taxus wallichiana* are some of the indicator species and most responsive to the different stresses of climate and anthropogenic pressure. The information on habitat, distribution and environmental preference of these three tree species is elaborated in Table 1.

These tree species belong to a group of naked seed-producing plants called gymnosperms. The species that belong to this group are usually wind pollinated and wind dispersed with small and light seeds. In general, seed production in gymnosperms is intermittent but a very large quantity of seeds are produced for dispersal by wind. Hence, anemochory is the predominant (possibly exclusive) mechanism of dispersion in the aforementioned target tree species.