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Modelling critical patches of connectivity for invasive Maling bamboo (*Yushania maling*) in Darjeeling Himalayas using graph theoretic approach

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ABSTRACT

Graph theoretic network approach has been used to model the potential connectivity of the natural areas in Darjeeling Himalayas which provide connectivity to the invasive species Maling bamboo (*Yushania maling*). Centrality indices are a tool for quantifying the intuitive notion of relative importance of the elements of a graph. The probability of connectivity (PC) index which takes into account the impact of functional connectivity among the patches like seed dispersal potential was used to identify the natural patches which can act as stepping stone for the spread of the invasive species. The potential niche map of Maling bamboo modelled using species niche model, MaxEnt have been used as the potential areas of its spread from the regions of its current infestations. An open source software (Confer) has been used to model the various graph indices in the spatial domain. Using areas weighted nodes (forest patches) the extent of connectivity among the various patches in the Darjeeling Himalayas have been computed to identify the critical patches responsible for the spread of Maling bamboo. It has been observed that 3 critical forest patches in the Darjeeling Himalaya Singalila NP in the west, Senchal WLS in the central region and Neora Valley NP are the key vertices for the spread of Maling bamboo.

1. Introduction

Invasive species have intrigued ecologists for long. Numerous studies demonstrated the dramatic effect of invaders on recipient ecosystems (Mack et al., 2000). Timely information about the areas of current and future invasion from different sources can help in devising effective control and eradication strategies. One of the ways to identify potential areas of spread of invasive species is through modelling their distribution. Spatial modelling for species distribution is frequently being used for management of natural resources by various stakeholders, as the need for accurate maps of invasive species distributions and abundance is required for its risk analysis (Stohlgren et al., 2010). Species prediction modelling has helped in generating spatial distribution maps of invasive species, area of spread and factors affecting the magnitude and extent of invasion. Current availability of high resolution bio-climatic data on various aspects of environments gives scope for precise distribution modelling.

A network is a mathematical model of a real-world situation, which is amenable to analysis by using graph theory (Diestel, 2005). Applications of networks to describe and understand ecological elements, patterns and processes have had a fairly long history, spanning almost over seven decades. Food-webs were one among the first such examples to be represented as networks (Odum, 1956). Graph theoretic approach to study food-webs defined a paradigm in the study of ecological network, and they continued to be studied as network models (Camacho et al., 2002; Pascual and Dunne, 2006). The ecological network flow models together with the systems theoretic approach to ecology constitute yet another paradigm in application of graph theoretic concepts to ecology, and has subsequently led to the founding of Ecological/Ecosystem Network Analysis (ENA), a method to holistically analyze environmental interactions (Patten, 1978, 1981, 1982, 1985; Fath and Patten, 1999; Ulanowicz, 1980, 1983, 1986, 1997, 2004). Uses of graph theoretic models have gained popularity in metapopulation analysis (Berline et al., 2014; Cavanaugh et al., 2014) and in studying mutualistic interactions (Rezende et al., 2007; Bascompte, 2007).

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Network theory has played a pivotal role in the understanding of systems level analyses of impact of global changes on biodiversity, including problems of species extinction and community fragility (MacArthur, 1955; Dambacher et al., 2003).

With an increasing availability of GIS-based data, detail information of the actual physical geography of a given landscape is now tractable. The present work discusses landscape connectivity for the habitat patches of an invasive species in the Darjeeling Himalayas, and makes use of structural indices in estimating the spread of the species over the area of study, informed by GIS data. Such a GIS-based approach informs graph theoretic modelling of the physical reality of the landscape and allows for a finer-grained approach. In this sense, the present work may be considered complementary to some of the approaches mentioned in the above paragraph.

Graph theory has been recognized as a potent framework for modelling landscape connectivity in scholarship, at least since the last decade of the previous century (Cantwell and Forman, 1993; Dunne et al., 2002; Fall et al., 2007; Gastner and Newman, 2006; Minor and Urban, 2007, 2008; Urban and Keitt, 2001; Taylor et al., 1993; Chetkiewicz et al., 2006).

A graph $\Gamma\left(V(\Gamma), E(\Gamma), \psi_\Gamma\right)$ (henceforth Γ) is an algebraic object comprising a set $V(\Gamma)$ of vertices, a set $E(\Gamma)$ of edges, such that $V \cap E = \phi$, and an incidence function $\psi_\Gamma : E \to [V]^2$ where $[V]^2$ is the set of unordered pair of (not necessarily distinct) vertices of Γ, $\ni e \mapsto \psi_\Gamma(e) = \{v_i, v_j\}, v_i, v_j \in V, \forall e \in E \subseteq [V]^2$. The vertices v_i and v_j are incident with the edge e, and vice versa. In the aforesaid, the edge e joins the vertices v_i, v_j, which, in turn, are the end vertices of e. Also, v_i, v_j connected via the incidence function ψ_Γ, are adjacent to each other. Γ, as defined thus, is an undirected graph. Γ is finite if both V and E are finite sets. Then, $\left|V\right|$ the order and $\left|E\right|$ the size, define the two parameters of Γ, respectively. The degree of a vertex $v_i \in \Gamma$ is the number of edges for which v_i is an end vertex. A path in Γ is a sequence of vertices $v_1, v_2, \ldots, v_n$ and a sequence of distinct edges $e_1, e_2 \ldots, e_{n-1}$ such that each successive pair of vertices v_k, v_{k+1} are adjacent and are the end vertices of e_k. A path that begins and ends at the same vertex is a cycle. Γ is acyclic if it contains no cycle and is connected if there exists a path from any vertex to any other vertex in Γ. For the present work, we shall consider Γ to be undirected and finite graph.

Graph based modeling is a rapid tool in conservation assessment (Urban and Keitt, 2001) and is not data demanding (Saura and Rubio, 2010). Landscape can viewed as a network of habitat patches connected by dispersing individual. Network topology is especially important because it is an emergent property that affects quantities such as spread of information and diseases, vulnerability to disturbance and stability (Albert and Barabási, 2002; Melián and Bascompte, 2002; Gastner and Newman, 2006).

Connectivity can be defined as the degree to which extent the landscape facilitates or impedes movement among resource patches (Taylor et al., 1993). Structural connectivity are measures on the spatial distribution, size and number of fragment of habitat. In the landscape connectivity, habitat patches are directly linked to another habitat patches so that movement of species smooth without having to travel through the intervening habitat or matrix. While functional connectivity does not require physical connections between patches and fragment. The graph theory provides good and powerful tools and algorithms for analyzing network connectivity and assessment of ecosystem vulnerability as a result of combined influence of land use, habitat fragmentation and climate change. Graph theoretic approach to landscape analysis can provide a spatial explicitly representation of complexity of landscape and allow us to assess the importance of individual landscape elements and to guide conservation or restoration efforts (Chetkiewicz et al., 2006; Bodin and Norberg, 2007; Minor and Urban, 2007; Schick and Lindley, 2007; Estrada and Bodin, 2008). The graph theoretic based connectivity in association with other species distribution models can help us in identification of the potential vulnerability of the species to a combination of land use as well as climate change.

Predictive species distribution models (SDM) are extensively used for understanding the role of climate, topography and edaphic factors in the geographic distribution of species and are used in regional biodiversity assessment, wildlife management and conservation planning (Marmonin et al., 2009). Prediction of potential habitat for invasive species is critical for their monitoring and restoration of declining native species populations and conservation of native species and habitat. SDMs like MaxEnt use the extrinsic factors (i.e. climatic regimes, topographic and edaphic factors) to predict the fundamental niche of a species, which in case of invasive species like Maling bamboo also reflects its realized niche as these species have a competitive over the local endemic species.

In this paper we aim to use the graph theoretic approach to identify the connectivity of critical natural areas which provide areas of potential colonization for Maling bamboo, an invasive species in the temperate coniferous and temperate broadleaf forests in Darjeeling Himalayas.

2. Study area

Darjeeling district of West Bengal lies between 26°31′ and 27°13′ north latitude and between 87°59′ and 88°53′ east longitude and its total area is about 3149 sq km. The area is bounded by Nepal on the west, Sikkim on the north, Bhutan on the north-east, Purnea district of Bihar abutting on the south and district Jalpaiguri of West Bengal on the south-east. The southern region of the study area is the foothills and is characterized by discontinuous terrace deposits in a east-west direction. The study area is traversed by a ridge line extending between Darjeeling hills in the west and Kalingpong hills in the east. These two regions are divided by Teesta River which flows from north to south. The region falls under zone IV of earth quake proneness (ranges from I to V) and is in proximity to the convergent boundary of Indian and Eurasian tectonic plates (Britannica Concise Encyclopedia, 2006).

The region is characterized by frequent landslips. This part of Himalaya experience high intensity rainfalls in a short span of time resulting in instability of the slopes (http://darjeeling.gov.in/geography.html). This is backed by the observations that the regions experiencing rainfall between 210 and 410 cm as observed from isohyet maps have the highest concentration on landslides (http://darjeelinginfor.blogspot.com.br/).

The natural forests in the Darjeeling Himalayas are of five types—Tropical semi-evergreen forests; Tropical moist deciduous forest; sub-tropical forests, Eastern Himalayan wet temperate forest and Alpine forest. Apart from the natural forests there are some valuable plantations of *Cryptomeria japonica*, *Pinus patula, and Cupressus* species.

Maling bamboo has a wide elevation range (1800 to 3600 m) and is a generalist. It grows gregariously and competitively excludes the native species by outgrowing the next generation of the native species. The plant grows in clumps and attains a height of around 2.5 to 3 m.

The Darjeeling Hill Areas have a relatively very high population density as a result of it being a tourist spot. With limited scope for extension of agricultural land to cope up with increasing pressure of population the pressure on forested and other restricted areas is gradually increasing. The major land use of Darjeeling hills is tea plantation, rice cultivation, roads and settlements and other miscellaneous construction activities since land use practices play the most important role in determining the stability of the hill slopes, the area is highly prone to landslides. The