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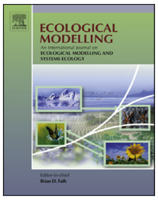

An Ecological Network Perspective in Improving Reserve Design and Connectivity: A Case Study of Wuyishan Nature Reserve in China

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ABSTRACT

To alter the sharply decreasing trend of biodiversity due to human disturbances, much emphasis has been placed on the ecological networks comprised of core areas with high ecological significance and corridors connecting them. The purpose of this paper is to introduce a novel viewpoint and method to identify, analyze and optimize the ecological network of Wuyishan City. The bidirectional least-cost distance model is applied to identify the landscape network in Wuyishan City for the year 1995 and 2005, which can incorportate digraph in ecological network modeling, overcome the limitation of failing to reflect the orientation of the species' dispersal process, and make the process of modeling more convincing by distinguishing flux orientation of “go” and “return” of two random patches. Three new metrics, i.e., network cyclicity, degree of cyclicity, and degree of connectedness, which can quantify the integrity and continuity of network and the relation between network organization and ecological process, are introduced to measure the presence and strength of cyclic pathways in a network and reflect the network's ability to transfer bio-flux. The results show that the ecological network of Wuyishan City in the year 1995 and 2005 have respectively a network size of 18 and 17, degree of connectedness of 1 and 0.7647, network cyclicity of 7.1378 and 8.2570, and degree of cyclicity of 0.3965 and 0.4857, which indicate that the network in Wuyishan City for the year 2005 has strong ability to transfer bio-flux, a high level of eco-process diversity, and a low level of integrity and continuity. It can be concluded that during the past 10 years, different areas of Wuyishan City have gone through landscape degradation and restoration. In the northeast, network components degraded severely and made several patches “isolated islands”, while in the southwest, the network has been developed because of landscape restoration. In particular, the linkages among the patches of natural reserve and its neighborhood increased remarkably, which directly increased the interaction strength and the whole network cyclicity. Then, via scenario analysis, we also identify the patches and linkages that make great contributions to the entire cyclicity and connectedness, such as patches [1,2,3,4,5,6] (Nature reserve and its neighborhood), [12] (bridging the north and west part) and [19] (bridging the south and west part), and linkages among the central patches.

1. Introduction

Beginning from 1956, the construction of nature reserves in China has more than 50 years history. China's world biosphere reserves have made a lot of endeavors in the field of biodiversity conservation and sustainable development. Wuyishan Reserve is an important demonstration project (Gao et al., 2010). Located in the northwestern part of Fujian Province in south-east China, Wuyishan City covers an area of 2813.91 km^2, and is 382 km away from the provincial capital Fuzhou. Tourism is its pillar industry Wuyishan city mainly relies on an export-oriented economy, while tourism is its pillar industry and so by relying on its rich bamboo, timber, rock tea, and granite resources, it has formed a series of sturdy industries to support tourism, including the production of tourist arts and crafts, processing of bamboo and forest products, and making fine rock tea and granite. However, the development of tourism together with the socio-economic activities of local residents transform natural areas to land dominated by human use, resulting in loss, degradation, and fragmentation of species habitat (Wu et al., 2003). Previous surveys indicated that *Macaca thibetana* and *Lophura nycthemera*, which are endangered animals in Wuyishan City, are seldom found within the range of 1 km from roads due to the human activities (Wang and Xiong, 1989; Cheng et al., 2009). Luck et al. (2003) mentioned species diversity defined as the number of species present in persistent populations. Hence, biodiversity loss is an increasing concern in Wuyishan City, which

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calls for solutions in a short time frame. This makes it essential to identify areas that together will protect the species in the nature reserves.

Ecological Network Analysis has long been used in ecological research and provides a description of the trophic links in a community (Memmott et al., 2006; Rathwell and Peterson, 2012). Many ecologists propose the ecological network concept as a suitable basis for sustainable landscape development, which include the spatial cohesion of the ecosystem network (Opdam, 2002; Tress and Tress, 2003), biodiversity conservation (Opdam et al., 2006) and multi-agent decision-making (Buchecker et al., 2003). In addition to their obvious role as descriptions of natural reserve's structure, ecological networks are being used increasingly as the basis for an experimental approach. While food webs may be the most commonly described ecological network. Bodin and Tengő, 2012 propose a novel theoretical framework including two social actors and two ecological resources for addressing this gap that partly builds the rapidly growing interdisciplinary research on complex networks. Ernstson (2013) indicated that at the city-wide level, an ecological network translates how urban 'green' areas, viewed as nodes, are interconnected by ecological flows (water, species movement, etc.) where nodes have different protective and management capacities. Kharrazi et al. (2013) proposed an ecological information-based network to evaluate six economic resource trade flow networks. Toubiana et al. (2013) applied network analysis to study plant metabolism and described the construction an analysis of correlation-based networks from metabolomics data. Food webs and other ecological networks have not been widely applied to the field of conservation biology, but given the practical advances being made in food web construction (for example, ecoinformatics), the theoretical advances (for example, models of extinction dynamics), and the ongoing threat of biodiversity loss, now is a good time to begin to use ecological networks as a conservation tool.

To construct the ecological network and provide a biologically meaningful measure of efficiency of special migration, we implemented a cost-of-path analysis. The spatial arrangement of reserves is another particularly important concern when designing a reserve network, given the potential role in species' long-term persistence by allowing dispersal. In recent years, a broad range of approaches have been proposed to accommodate spatial consideration in reserve selection. These approaches deal with some spatial design criteria as either constraints or objectives, such as performing adjacent rule (Lombard et al., 1997; Zafra-Calvo et al., 2010 Zafra-Calvo et al., 2010), minimizing the boundary length or a linear combination of boundary length and total reserve area (Cabeza et al., 2004), minimizing the maximum intersite distance or the sum of pairwise distances between all planning sites (Onal and Briers, 2002), measuring the total distance between neighboring sites (Onal and Wang, 2008) and the summed distance to mandatory sites (Alagador and Cerdeira, 2007), maximizing the sum of the inverse distances between pairs of sites (Rothley, 1999), enforcing buffers surrounding selected critical sites (Williams and ReVelle, 1998), keeping sites occurring within the stated proximity distance or the dispersal range of species (Cerdeira et al., 2010) and maximizing connectivity (Briers, 2002; Bauer et al., 2010). Recent progress in studies of bidirectional least-cost paths has shown great promise in making realistic applications. These include multi-directional constructing paths with constraints to avoid terrain obstacles by considering directional differences or anisotropy of the terrain surfaces (Xu and Lathrop, 1995), make the process of modeling more convincing by distinguishing flux orientation of "go" and "return" of two random patches (Collischonn and Pilar, 2000).

In this paper, we present a new framework that can be used to select reserve networks for protecting species in nature reserves. This framework is characterized by its two-steps selection manner. First, because of the focus on a nature reserve, the framework selects reserves that are composed of contiguous sites with high and medium species occurrence probabilities to satisfy the representation requirement. Second, the framework designs additional reserves in an attempt to eliminate the human-induced impact imposed on species turnover so as to improve the capacity of the spatial configuration of reserve network to contribute to species' long-term persistence.

2. Methodology

2.1. Ecological network analysis (ENA) of nature reserve

Since Patten and Finn first published their papers on the analysis of flows in ecological networks (Patten et al., 1976; Finn, 1976), there have been many studies of ecological network analysis (Toccolini et al., 2006; Bruinderink et al., 2003; Jones-Walters, 2007). ENA is a systems-oriented methodology to analyze within-system interactions, which is proposed based on input/output models of energy or material flows (e.g., carbon compound flows) through a trophic network (e.g., a food web describing which species eats which other species). Ecological network is a structural model which simulates the flow of material and energy in ecosystem, whose creation begins with its identification of the key compartments that comprise the ecosystem linked via flowpath. New concepts and understandings have been developed based on graph theory.

The entries of the matrix A^2 denote the number of paths of length 2 between nodes in the graph. Similarly, entries of A^n denotes the number of paths of length n. Note that the trace (sum of the diagonal elements) of the matrix A^3 is equal to six times the number of triangles in the graph A^m. A structural connectance matrix, or adjacency matrix, A, is a binary representation of the connections such that $a_{ij}=1$ if there is a connection from j to i, and a 0 otherwise (Eq. [1]):

$$\begin{array}{ccccccc} B & = & I & + & A & + & A^2+A^3+A^4+\ldots\ldots \\ & = & & + & & + & \underbrace{\hspace{8em}}_{} \\ \text{Intergral} & & \text{Initial} & & \text{Direct} & & \text{Indirect} \end{array}$$

(1)

It reflects the total number of pathways (P_k) of different lengths (k) from all nodes to all other nodes. The diversity of ecosystem structure and process is sustained by tracing the path of energy–matter flux through the system. Research results show that indirect pathways play a principal role in influencing the system structure and function.

A structural cycle is the presence of a pathway in the ecological network in which matter–energy passes through biotic or abiotic stores returning for availability to the same or lower trophic levels. Network analysis, specifically the maximum eigenvalue of the connectance matrix, is used to identify both the presence and strength of these structural cycles. The strength of structural cycling or cyclicity is given by the magnitude of the largest eigenvalue (also called the spectral radius), λ_{max} of the structural adjacency matrix. There are three possibilities for the spectral radius: $\lambda_{max}=0$, $\lambda_{max}=1$, and $\lambda_{max} > 1$, respectively (see Fig. 1a and b) (Fath, 1998; Jain and Krishna, 2003). When $\lambda_{max}=0$, then all eigenvalues equal zero and there is no structural cycling and no indirect pathways greater in length than n-1; weak structural cycling occurs when $\lambda_{max}=1$, indicating the presence of cycles, but the number of pathways between nodes does not increase geometrically; lastly, when $\lambda_{max} > 1$, strong structural cycling occurs, in which case the