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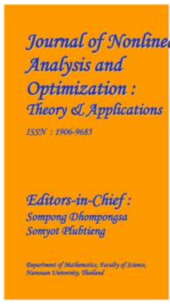

TOPOLOGY IN BIODIVERSITY AND ECOLOGY AS A SUSTAINABLE DEVELOPMENT

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ABSTRACT:

This paper considers applications of topology, i.e. the shape and structure of networks of interacting organisms in ecological systems. Species often form the nodes of such networks, though life stages, age classes or functional groups are sometimes equally applicable. The links between nodes in ecological networks can have a variety of meanings, in particular they can represent transfer of energy or material, they can represent the net effect on fitness or population size (direct and/or indirect) of one species on another, or represent the exchange of information. These differences create at least three types of interaction networks: competition networks, mutualistic networks and food webs (consumption networks), all of which are subsets of the full network of interactions in any community.

Keywords: Eco System, Network Analysis, Degree Distribution, Small World Properties, Climatic Change.

INTRODUCTION:

In nature, species interact in many different ways; no species exists in isolation. Understanding these interactions and how these affect individual organisms, species and whole ecosystems are, therefore, key to a systemic understanding of the natural environment. In the early twentieth century, Lotka and Voltera paved the way for theoretical and mathematical approaches in understanding predator-prey interaction and the resulting dynamics of species populations. In the 1950s, the Odum brothers revolutionized ecology by emphasizing the need for a systemic perspective of the natural environment.

In order to take the field of ecology beyond a mainly descriptive science, and to find solution to challenges facing the natural environment, they argued that better understanding of the large-scale properties of the environment is needed.

Eco systems, although over time defined and/or perceived in many different ways, are basically systems of interacting species limited by constraints arising from the physical environment. The Odum brothers originally modelled ecosystems as sets of components (e.g., species) and flows of energy (the common denominator) cycling through these components. Thus, they essentially laid the foundation for seeing the environment as a networked system consisting of nodes and links. What constitutes a node depends on the question at hand; it could be a species, a group of similar species, an individual organism, groups of organisms, physical objects, etc. The links, i.e., the relations between the system components of interest, also depends on the chosen question; they could e.g., be flows of energy going from prey to predators in food webs, or flows of genes spread through species dispersals among localized populations. Networks can be viewed as maps that outline these local interactions and preserve their importance at the system level. The perspective of networks carries the advantage of simultaneously addressing the members of the systems as well as the patterns of their interactions. This modelling approach, emphasizing localized interaction between separated parts of the system, captures some of the fundamental characteristics of a complex adaptive system

DEFINITION OF THE SUBJECT:

Ecology is, simply speaking, the science of ecosystems, i.e., sets of interacting species constrained by the physical environment. Due to earth's enormous species diversity, species' patterns of interactions quickly become very complex and thus difficult to oversee, although it is clear that the interaction patterns themselves often have profound effects on the behaviors and functioning of the ecosystems. To enable systematic pattern analyses, it is often favorable to represent these patterns of interactions as networks where the nodes are some sort of biological entities and the links represent some sort of interaction between these entities. The entities can e.g., represent species, but they could also represent individuals or groups of organisms. The links could e.g., represent trophic interactions ("who eats whom"). By representing interacting species as a network, analytical focus is set on the actual pattern, or topology, of the interactions themselves.

Topological analysis of ecological systems has a relatively long history in ecology which can be exemplified by the long-lasting scientific debate, spurred by Si Robert May in the 1970s when he, against prevailing interpretation, suggested that an increased number of species interaction would actually lead to decreased eco system stability. More recently, an increased interest among various scientific disciplines on network approaches in complex systems research has re-energized the topological perspective of ecosystem research.

NETWORK ANALYSIS:

A system of interconnected entities, i.e., a network, is mathematically represented as a graph . Graphs consist of nodes and links. Nodes are the terminal points or intersection points of the graph(sometimes called vertices). Links represent connections between nodes and represent the structure of the network over which interaction occurs. There is an entire branch of mathematics called graph theory that deals with the analysis of such graphs. Furthermore, network-oriented analyses are undertaken in several other disciplines; thus methodological, technical and theoretical developments of relevance for networked systems are taking place across disciplines. An example of an interdisciplinary endeavor is the fast-growing organization INSNA (International Network for Social Network Analysis, http://www.insna.org) consisting of sociologists, mathematicians, physicists, computer scientists and others that are mainly occupied with studying patterns of social interactions (i.e., social networks). Thus, the term network analysis will be used here when referring to all kinds of quantitative approaches in analyzing the patterns of interconnections in networked systems.

MODELING A NETWORK SYSTEM:

In conducting topological analyses, the first step would be to represent the system under study as a network, i.e., to define what entities will constitute the nodes, and what kind of relations among the nodes will constitute the links. Modeling a system as a network is in some cases straight forward, because it is more or less obvious what entities will make up the nodes, and what kind of relations would constitute the links.

For example, in studying pattern of friendships among students in a classroom each student would constitute a node, and the reported friendship between any two students would be represented by a link. In other cases, it might be less obvious how to define a node. In studying the dynamic interactions in a ecosystem, should the nodes be represented by individual species, groups of similar species, or even by individual organisms. The method by which one chooses a suitable level of abstraction will depend on the research questions. The problem is, as always in modeling, to choose a level of abstraction that is as simple and aggregated as possible, but still fine-grained enough to capture the essential characteristics of the system in order to help answer the questions at hand.

TOPOLOGICAL CHARACTERISTICS:

In this section, three important characteristics of networks, and some of the associated and commonly used measures defining these characteristics, are briefly reviewed. These are degree distribution, modularity and centrality. How these are of relevance in ecology will be discussed and exemplified in coming sections. Naturally, there are many characteristics that define a network other than those presented here. The applicability of various existing network measures in network-oriented ecological studies is almost a research topic in itself.

DEGREE DISTRIBUTION AND SMALL-WORLD PROPERTIES:

In most real-world networks, links are very unevenly distributed among the nodes (e.g., for a review). If, for example, all links were distributed randomly, the degree distribution would follow a Poisson distribution. There are, however, lots of examples of real networks not following this distribution; thus there must be processes other than chance alone that are in play when networks are formed and shaped over time. Of recent interest are the so-called scale free networks following a power-law degree distribution, meaning that most nodes have few links, but that some rare nodes posses very many links (these nodes are often called hubs). Such networks are quite robust (in terms of the risk for severe network fragmentation) to random node removals (since most of the nodes have very few links), but they would be very vulnerable to a targeted removal of the hubs.

Somewhat related to the degree distribution is the concept of small world networks. A small world network displays a high level of clustering, meaning that two nodes that both possess links to a common third are much more likely to be directly linked to each other as compared to the likelihood that any other arbitrary pair of nodes should be directly linked. In spite of this high degree of clustering, in a small world network the average topological distance between any arbitrary chosen pair of node remains relatively short, thus implying that there are still many links that cross boundaries and therefore link together different clusters. A small world network does not necessarily follow any particular degree distribution, but it has been shown that scale-free networks often display small-world characteristics.

MODULARITY:

Within a network there may be groups (or modules) of nodes that, from a topological perspective, distinguish themselves from the rest. For example, it could be that these groups of nodes are more internally than externally interlinked, i.e., the distinction of groups is based on a high density of interconnecting links among each group's members. In this way, a group would have a relatively high frequency of direct (or indirect) relations within the group compared to outside the group. Examples of such group-assessment methods are LS-sets and lambda sets.

A specific example of another type of group definition is the clique. In a clique every member is connected to every other member; thus this definition of a group does not define members based on their relative cohesion versus non-member – instead it uses an absolute criterion for defining a group. The definition of a clique can be extended to account for directional and weighted links as well.

CENTRALITY:

A fundamental topological characteristic of a node in a network is its level of centrality. The concept of centrality is devoted to analyzing the position of nodes' in the network. The underlying assumption is that some positions are more favorable than others in terms of the influence the nodes occupying them can exert on others (for an introduction and review of the literature). There are, however, numerous ways to exert influence, and accordingly many different measures of centrality have been developed – each focusing on different topological aspects. Here some of these are presented:

1. **Degree centrality:** This is the number of links a node possesses. In a network with directed links, one could distinguish between in-degree and out-degree centrality.
2. **Betweenness centrality:** This measure assesses how much "in-between" a particular node is, based on how many shortest pathways (connecting other nodes) that goes through this particular node.
3. **Closeness centrality:** This measure assesses how close (from a topological perspective) a particular node is to the rest of the nodes in the network.

DEGREE DISTRIBUTION:

In terms of degree distributions, it appears that food webs, like many other types of networks, often experience a skewed link distribution where a few nodes possess many links. This is completely different from what would be expected if the links were distributed randomly. This makes food webs, in accordance with other systems experiencing, a skewed link distribution, quite robust with respect to a random removal of nodes (i.e., species), but quite vulnerable to a targeted removal of the most connected nodes. The distribution of links in food webs is generally different from the previously mentioned scale-free degree distribution in that the tail of the distribution towards very high degree centralities is truncated (see e.g., and references therein). Furthermore, since food webs often tend to experience a relatively high density of links as compared to many other kind of networks, the degree distribution accordingly gets more uniform.

NETWORK CENTRALITY AND KEYSTONE SPECIES:

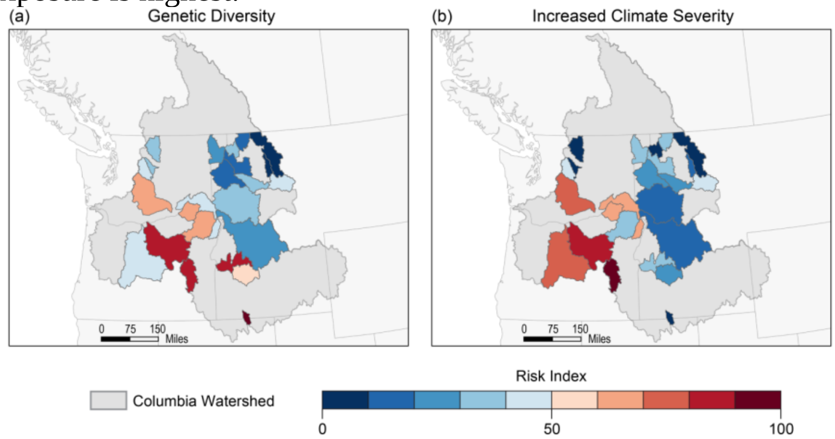
The concept of keystone species in ecology is different, but related to, the concept of dominant species. A dominant species is a species that is high in abundance, and exert a large impact on the ecosystem where they are situated. Keystone species, on the other hand, differ from dominant species in that their effects on the ecosystem are much larger than would be predicted from their abundance alone. It has been suggested that a keystone species is a species with a disproportionably high number of links in the food web. Dunne et al. have also put forward the idea of a structural keystone , i.e., a species that exerts influence on the basis of its structural position within the food web, and not only on the basis of the number of links it has to others.

SPECIES AND POPULATIONS:

There is increasing evidence that climate change is impacting biodiversity, and species and populations are responding in a variety of ways. Individuals may acclimate to new conditions by altering behavioral, physical, or physiological characteristics, or populations may evolve new or altered characteristics that are better suited to their current environment. Additionally, populations may track environmental conditions by moving to new locations. The impacts of climate change on biodiversity have been observed across a range of scales, including at the level of individuals (such as changes in genetics, behavior, physical characteristics, and physiology), populations (such as changes in the timing of life cycle events), and species (such as changes in geographic range).

GENETIC DIVERSITY AND CLIMATE EXPOSURE:

Two maps of the Columbia Watershed in the Pacific Northwest are shown. The left map shows varying levels of genetic diversity of the bull trout species, and the right map shows varying levels of climate severity (a combination of maximum temperature and winter flood risks). Locations where bull trout genetic diversity is lowest, such as portions of Oregon and Washington, correlate to areas where the threat of climate exposure is highest.



FUTURE DIRECTIONS:

Topological analyses alone can provide important insights into complex ecological systems. However, in many cases, it is desirable to also include the strengths of the links in the analyses.

Many network analytical approaches support the inclusion of link strengths, but there are many others that do not. Furthermore, the network perspective has traditionally been rather static, and the analytical focus has been the topological structure currently at hand. But networks evolve and develop dynamically; thus the topology given at one moment in time may be outdated later on. Better understanding of processes that shape network evolution are needed, as are methods capable of longitudinal network analyses applicable in an ecological context. The last statement touches upon the fact that a topological perspective will only be of any significant value when we possess knowledge and/or well-grounded assumptions of important processes. Thus topological approaches need to develop alongside theoretical advances of understanding key ecological processes.

CONCLUSION:

Three topological characteristics, degree distribution, modularity and centrality, all appear to be of relevance in studying different aspects of ecological systems. In food webs, the degree distribution affects the stability in terms of the risk for secondary extinctions following species loss. In addition, the density of links is believed to have effects on the stability of ecosystems, although how, and in what direction, is not entirely clear. Many food webs have a modular structure, i.e., the web is divided into several groups that are only weakly connected to each other. This may effect how far disturbances spread throughout the food web. In a web with many dense but separated groups of species, disturbances may very well be confined within groups. On the other hand, a highly modular structure implies there are fewer opportunities for species to compensate if some of their prey species would decline.

Furthermore, some species may be more influential than others, and that influence may be attributed to their structural position in the food web (structural keystone species). Influence may result from having many links to others, but it could also derive from the possession of structurally important links that for example connects otherwise disconnected groups of species.

In order to analyze the spatial structure of connectivity of fragmented landscapes, a network representation where nodes are patches and links are dispersal possibilities paves the way for topological analyses at the level of landscapes. It appears that simple network characteristics, such as the number of components, can help in assessing how connected different species, with varying dispersal capabilities, actually experience the landscape. Furthermore, network analysis targeted at finding compartments of internally well-connected habitat patches can help in identifying population and met a population boundaries. Finally, by assessing the structural importance of individual habitat patches similar to structural keystone species), land management could be made more efficient by letting different network centrality measures provide guidance in prioritizing conservation efforts. It also met the solution for the Sustainable Consumption on a World Wide Scale.

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