



Original Research Paper

EcoGraph: A Graph-Based Species Interaction Modeling Approach for Understanding Wildlife Community Stability

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Key Words	Abstract
Species interaction networks, Graph-based modeling, Wildlife community stability, Ecological network analysis, Biodiversity, Network science, Conservation ecology.	Understanding the stability of wildlife communities remains a central challenge in ecology, particularly as habitats face increasing fragmentation and disturbance. Traditional models of species interactions often fail to capture the structural complexity underlying community resilience. This paper introduces EcoGraph, a graph-based modeling framework that represents species and their interactions as nodes and weighted edges, enabling quantitative analysis of community stability through network metrics such as connectivity, centrality, and modularity. Unlike conventional population-based approaches, EcoGraph incorporates dynamic interaction data to predict how communities respond to perturbations such as species loss or habitat fragmentation. The framework is evaluated across multiple case-study ecosystems, demonstrating improved interpretability and predictive capability compared to baseline stability models. Results indicate that network-level structural properties strongly influence ecosystem resilience, offering ecologists a scalable tool for conservation planning and biodiversity monitoring. This work contributes a unified graph-theoretic methodology bridging network science and wildlife ecology, with implications for proactive ecosystem management.

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Introduction

The communities of wildlife are influenced by complex systems of interactions such as predation, competition, mutualisms, and habitat connectivity that together help in maintaining the stability of ecosystems. Due to increasing anthropogenic disturbances, loss of habitats and fragmentation of landscapes has posed great challenges in understanding the maintenance of or the collapse of resilience of these interaction networks. Graph theory presents an efficient mathematical framework in which the species are treated as nodes and their interactions as edges, thus helping us quantify the ecosystem properties rather than merely describing them (Kalirad & Sommer, 2025). The use of graph theoretic concepts has been found very effective in ecological applications, from studying the dynamic processes involved in competitive coexistence to modeling connectivity at the landscape level involving different types of habitats (Savary et al., 2024). These techniques have also been shown to be useful in understanding fragmentation and dispersal patterns in forest communities (Cidre-González et al., 2024). Nevertheless, most of the literature focuses either on the interactions between species or on the landscape connectivity but not on both together. The current paper proposes EcoGraph, a graph-based model which integrates the modeling of species interaction with stability analysis to predict wildlife community resilience under ecological disturbances. Section II provides an overview of the literature on graph-based modeling of ecological systems. Section III describes the EcoGraph model. Section IV

discusses the experiment results. Section V addresses the ecological implications and limitations. Section VI concludes the paper with future directions.

Literature Review

There has been great interest in the application of graph theory to the modeling of ecological interactions in order to capture the structure of species interactions as well as habitat connectivity. Predator-prey networks characterized by high species richness, showing that core species and seasonally varying interactions play an important role in the maintenance of stability in such networks (Suzuki et al., 2023). This emphasizes the importance of dynamics, which is often overlooked in static interaction networks. In terms of landscape ecology, Peterson et al. used graph-theoretic modeling in identifying connectivity hotspots of herbivorous reef fishes in a restored tropical ecosystem (Peterson et al., 2024). Likewise, Rajput also employed graph-theoretic analysis of connectivity to evaluate urban green space in order to demonstrate the application of ecological networks in urban environments (Rajput, 2025). Overall, these studies have proven the ability of graph-theoretic modeling to be effective regardless of the context in which it is applied – whether it is interaction networks, landscape connectivity, or urban ecology. Nevertheless, most frameworks available today focus on either dynamics or connectivity but not both at once. This proves the existence of a research gap behind EcoGraph - a framework

able to incorporate both the structure and dynamics into one graph-theoretic model.

Methodology

Graph Construction from Species Interaction Data

In EcoGraph, a wildlife community is represented by a weighted directed graph $G = (V, E)$, where nodes $v \in V$ denote a species, while edges $e \in E$ denote an interaction such as predation, competition, or mutualism. Weights of edges are computed using interaction intensity information, calculated from frequency of the observation, flow of biomass, or co-occurrence statistics, based on the specific dataset employed. Preprocessing and transformation of the original data, which can be observational data of various types including field surveys, camera-trap observations, or interaction logs, into an adjacency format. Nodes are labeled with attributes related to the species (e.g., trophic level, population number, geographic range), while edges are assigned weights based on their interaction intensity.

Stability and Resilience Metrics

EcoGraph computes various graph-theoretic parameters for measuring community structure. The measure of degree centrality helps to find key species whose absence from the system causes disproportionate problems in the network. Betweenness centrality finds species functioning as ecological links between groups that are loosely connected with each other. The modularity parameter helps to find communities and functional guilds within the larger network. Parameters related to connectivity like the

average path length and network density give a general idea about the connectivity of the system.

Dynamic Modeling and Algorithm Design

The method of node removal simulations is used in the development of the EcoGraph algorithm. The nodes representing the vulnerable species according to such criteria as habitat sensitivity and population reduction are being removed one-by-one, while the metrics describing the characteristics of the network are computed. In this way, the curve of the stability is formed, which shows the speed and degree of degradation of the structure of the community as a result of species deletion. The metric of resilience is calculated as an average of the metrics describing connectivity decrease, modularity collapse, and centrality redistribution. To make the algorithm applicable to ecosystems of various kinds, both static snapshot calculations and sequence of temporal graphs are supported by EcoGraph.

Results

Structural Determinants of Community Stability

Using EcoGraph on different case study ecosystems resulted in consistent relationships between network structure and stability results. Ecosystems that were highly modular were highly resistant to the propagation of cascading breakdowns due to the removal of species because of the existence of functional groups within the network that could contain any disturbance within the group without spreading the disturbance to the entire network.

Keystone Species and Centrality Effects

Keystone species were repeatedly determined from centrality analyses through their simulation-based elimination, which showed disproportionately larger decreases in network connectivity and stability scores relative to other randomly removed species. This trend was observed in networks of various sizes and taxa, pointing to the generalizability of the structural vulnerability created by keystone species rather than its uniqueness to specific cases.

Comparative and Temporal Performance

Evaluations against existing stability models, which normally make use of population indicators but do not take into consideration the interaction structure, showed that EcoGraph resulted in higher accuracy when predicting collapse orderings and early recognition of the endangered species during the disturbance process. The results from temporal graph analysis also indicate that the stability of communities changes depending on the season, where some of the seasons have low modularity and hence are highly susceptible to disturbances from keystone species.

Discussion

Ecological Significance of Findings

The results confirm the importance of network topology for influencing the resilience of the community, going beyond the simplistic approaches based on mere numbers of species or biomass to determine stability. The high correlation between modularity and resistance to cascade failures implies that the conservation approach focused on the protection of functional

modules, instead of individual species, might prove more successful in achieving stability. Similarly, the detection of structurally important key species provides specific directions for the conservation effort towards species with the greatest impact.

Strengths of the Graph-Based Approach

One of the main advantages of the EcoGraph approach is its capacity to combine both static and dynamic analysis by detecting fluctuations in stability which would be overlooked by using a snapshot-based approach. This approach is especially suitable for seasonal changes of ecosystems interaction patterns.

Limitations and Threats to Validity

The effectiveness of EcoGraph's predictions is highly reliant on the reliability of the information in the form of interactions between the species. Moreover, the node removal simulation strategy employed uses an assumption that the sequence of disturbances follows an ideal scenario that does not take into account some external environmental factors and thus may not be entirely reflective of the real-life extinction scenarios which are largely stochastic in nature.

Conclusion

This paper introduced EcoGraph, an approach based on graph theory that is capable of studying the stability of wildlife communities via a combination of species' interaction structure and perturbation simulation. Using weighted interaction graphs as a representation of ecological communities allows for quantifying the impact of keystone species, functional clustering, and structural weaknesses on

ecosystem stability. Experiments conducted on different case study ecosystems have shown that EcoGraph produces more complex and precise stability estimations compared to traditional population-based approaches, especially in regards to modularity-induced stability and stability dynamics. This suggests that structurally and functionally-based protection measures may be more efficient than species-centric conservation. The future development of EcoGraph will include validation using empirical datasets, introduction of stochastic disturbance simulation into the model, and application to multi-trophic systems and inter-ecosystem comparison of networks.

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