Ecosystems Resilience Modeling: Network-Based Simulation of Habitat Loss and Species Extinction

Malavika Venkatesh [*] **Aarohee Vora** [**]

[*] *Indian Institute of Technology Madras, Chennai, 600 036, India (e-mail: bs20b020@smail.iitm.ac.in)*
[**] *Indian Institute of Technology Madras, Chennai, 600 036, India (e-mail: bs20b002@smail.iitm.ac.in)*

Abstract: Our research adopts a network-based methodology to simulate the repercussions of species extinction and habitat loss, aiming to decipher the intricate dynamics of ecological networks. Beginning with meticulous data preparation, cleaning, and contextual analysis tailored to specific ecological frameworks, we delve into constructing and scrutinizing ecological networks to glean insights into species interactions. Through a series of simulations and comprehensive analysis, we not only pinpoint keystone species but also evaluate their pivotal roles in upholding ecosystem stability. Furthermore, we delve into assessing how species loss impacts network structure, biodiversity, and overall ecosystem stability. Utilizing community detection techniques, we uncover the underlying structural organization of species interactions. Concurrently, our simulations focused on patch fragmentation, habitat loss, and migration offer valuable insights into how ecosystems respond to environmental disturbances, thereby guiding the formulation of effective conservation strategies in the face of escalating environmental challenges.

Keywords: Ecological networks, species extinction, habitat loss, network-based methodology, data preparation, keystone species, ecosystem stability, species interactions, community detection, environmental disturbances, conservation strategies

1. INTRODUCTION

Ecosystems worldwide are facing unprecedented challenges due to human activities and the escalating impacts of climate change (1). Understanding the intricate interplay among species and the profound effects of environmental perturbations is crucial for devising effective conservation strategies. Our research adopts a comprehensive network-based approach to simulate and analyze the ramifications of species extinction and habitat loss, delving deep into the complexities of ecological networks (2).

The urgency behind our study arises from the critical need to comprehend the multifaceted consequences of human-induced changes on biodiversity and ecosystem stability (1). As habitats shrink and species face escalating threats, the ability to anticipate and mitigate the cascading effects of species loss on ecosystem dynamics becomes increasingly vital. Through advanced network analysis techniques, we aim to model the intricate web of species interactions and dependencies, shedding light on key facets of ecological resilience and vulnerability.

Our methodology encompasses meticulous data preparation and cleaning processes, followed by data sampling and contextual analysis within specific ecological frameworks. Central to our study is the construction and analysis of ecological networks, allowing us to gain insights into species interdependencies and trophic relationships (2). Employing community detection techniques further unveils the structural organization within these networks, identifying cohesive groups of species and their interconnectivity patterns.

Simulation experiments, including species extinction events and environmental perturbations such as habitat loss, provide a nuanced understanding of network dynamics and ecosystem stability. By identifying and assessing keystone species, our study illuminates critical nodes within ecological networks that are particularly susceptible to disruption, thereby highlighting the vulnerabilities and resilience mechanisms of ecosystems (2) (4).

1.1 Objectives

- Data Preparation and Cleaning: To parse, clean, and organize species interaction data from a reliable database, ensuring data integrity and suitability for subsequent analysis.
- Data Sampling and Contextual Analysis: To sample relevant data subsets for contextual analysis within a specific ecological framework, facilitating a deeper understanding of ecosystem dynamics.
- Network Construction and Analysis: To construct a weighted directed network representing species interactions and trophic relationships, and to analyze network properties using appropriate tools and metrics.
- Community Detection and Structural Analysis: To detect communities within the network and analyze

their structural organization, revealing patterns of species associations and dependencies.

- Species Extinction Simulation and Impact Assessment: To simulate species extinction events and evaluate their impact on network structure, species diversity, and ecosystem stability.
- Simulation of Perturbation Events: To simulate environmental perturbations such as habitat loss and migration, and assess their impact on species distributions and community structures.
- Integration and Interpretation of Simulation Outcomes: To integrate simulation outcomes into species interaction networks and interpret the results to gain insights into ecosystem resilience and vulnerability, with a focus on informing conservation strategies and enhancing biodiversity conservation efforts.

2. METHODOLOGY

(Link to our GitHub Repository)

2.1 Data Preparation

- Data Acquisition and Preprocessing: The initial step involved parsing a large-scale species interaction dataset obtained from the Global Biotic Interactions database (GloBI) stored in a CSV format. Using `python` and `pandas`, specific columns such as species names ('sourceTaxonName' and 'targetTaxonName'), taxonomic ranks ('sourceTaxonRank' and 'targetTaxonRank'), interaction types ('interactionTypeName'), geographic coordinates ('decimalLatitude' and 'decimalLongitude'), and locality identifiers ('localityId' and 'localityName') were selected for extraction, aimed at minimizing computational overhead and preparing the data for cleaning, organizing, and structuring into a format suitable for network analysis. The dataset comprised 13,858,144 rows of interactions.
- Filtering Food Chain Interactions: We filtered the dataset based on interaction type, focusing specifically on 'eats' interactions. This step streamlined the data for our food network analysis, emphasizing interactions crucial to ecosystem food chains.
- Handling Missing Values: We started by visually analyzing missing values using a heatmap, which helped identify patterns in missing data [Fig. 1]. This guided our strategies for data imputation and cleaning. We also standardized the treatment of missing or invalid data by replacing certain entries in the 'targetTaxonName' column with NaN. After filtering out rows with NaN values in critical columns like species names and taxonomic ranks, we obtained a refined dataset free from incomplete or unreliable data points.
- Weighted Network Representation: An 'interaction_pair' column was introduced, identifying unique interaction pairs within the dataset. Interaction weights, represented as 'interaction_pair_fraction,' were computed based on the occurrence fraction for each interaction pair. The weights assess the confidence level of specific interactions, particularly focusing on the predator's preference for certain prey. The dataset size after this stage was 1,903,676 interactions.

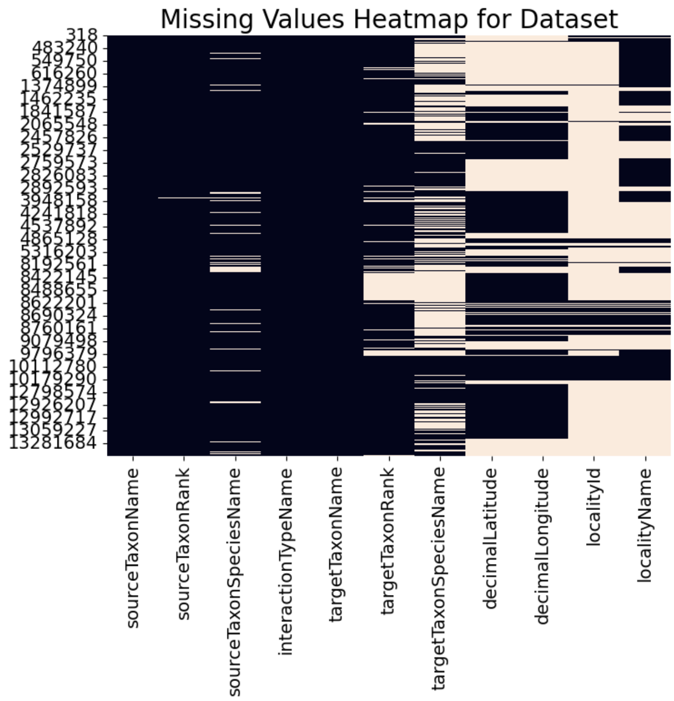


Fig. 1. Heatmap of missing data in species network

- Removing Redundancy and Parallel Edges:Duplicate interactions were identified and removed, streamlining the dataset for network analysis and effectively removing parallel edges between nodes.
- Creating Weighted Directed Network Edge List: The processed data was converted into an edge list format, extracting 'targetTaxonName', 'sourceTaxonName' and 'interaction_pair_fraction'. This was used to make a weighted directed network from prey to predator, to illustrate the transfer of energy and resources through trophic levels. The final dataset for network visualization contained 597,149 interactions.

2.2 Data Sampling

Due to the limitations of global species interaction networks, where geographically distant interactions might not be ecologically relevant, we employed data sampling to focus on the Amazon rainforest ecosystem. This biome boasts exceptional biodiversity, making it an ideal environment for network analysis. We achieved this by strategically selecting entries from the cleaned data where the 'decimalLatitude' and 'decimalLongitude' columns fell within the Amazon rainforest's latitudinal (-5° to 16°) and longitudinal (-72° to -48°) boundaries. This sampling approach ensures the constructed subnetwork reflects the specific ecological context of the Amazon rainforest.

2.3 Network Construction and Analysis

In our study, we utilized network analysis tools to understand species interactions within the Amazon ecosystem. The process of selecting the right tools for analyzing the intricate web of species interactions was crucial. We assessed a variety of tools, including Cytoscape, Gephi, and the Networkx library in Python, to construct and analyze the network both before and after perturbations. After a thorough evaluation, we chose to use Gephi 0.10.1 due to its comprehensive features for network visualization and analysis.

To further enhance our analytical capabilities, we incorporated plugins such as Katz centrality, clustering coefficient, colorEdge, ColorNode, and Force Atlas 3D Layout. These additions allowed us to explore various layouts and network metrics, which were instrumental in evaluating the nodes representing keystone species (4).

We found that the OpenOrd layout [Fig. 2] was the most suitable for constructing and visualizing the weighted network. This was primarily due to its ability to handle the large size of the species interaction network, which was not only directed but also acyclic in nature. This made it an ideal choice for our analysis.

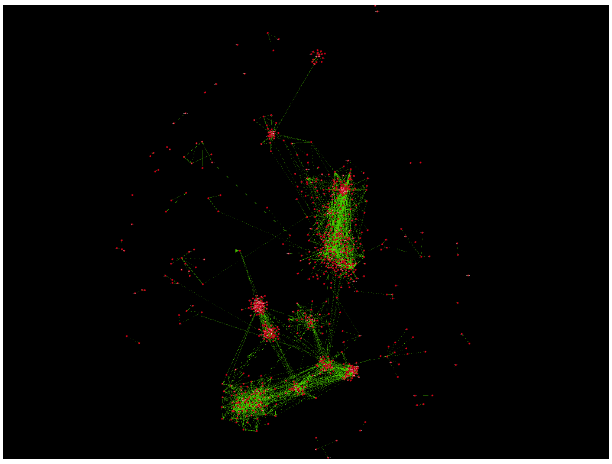


Fig. 2. OpenOrd Layout of the Amazon Rainforest Network

2.4 Simulation of Species Extinction

Our research methodology involved simulating the extinction of species within the Amazon ecosystem and observing the impact on the network structure and ecosystem stability.

We began by identifying the keystone species within the Amazon network (4). This was achieved by leveraging network metrics such as Katz centrality, degree centrality, and betweenness centrality.

- Katz centrality helped us quantify the influence of a species based on its immediate neighbors and their influence. Species with the highest Katz centrality were highlighted as potentially influential in maintaining ecosystem structure and function (7).
- Degree centrality reflected the number of connections a species has within the network. Species with the highest degree centrality were likely playing pivotal roles in information exchange and resource flow.
- Betweenness centrality measured a species' position in controlling the flow of information between other species. Species with high betweenness centrality potentially acted as bridges between different parts of the ecosystem.

We identified the top 5 keystone species [Fig. 3][Fig. 4] using these network metrics. We then conducted simulations to assess the impact of potential environmental perturbations (5). We sequentially deleted each of the top 5 species [Fig. 5], observing the changes in network structure and ecosystem stability. We also simulated the simultaneous deletion of two species from the top 5 [Fig. 5]. Finally, we simulated the extinction of all 5 keystone species [Fig. 5] to understand the potential consequences on network structure and ecosystem stability.

Furthermore, we conducted additional simulations focusing on the extinction of specific endangered species, such as the jaguar (*Panthera onca*) and the black-handed spider monkey (*Ateles paniscus*) [Fig. 5].By assessing the cascading effects of species loss on network dynamics, we gained valuable insights into the vulnerability of the Amazon ecosystem and the potential consequences of species loss on ecosystem dynamics.

2.5 Community Detection

To further elucidate the structural organization of species interactions within the Amazon ecosystem, we employed community detection techniques using Gephi's Girvan Newman Algorithm. By simulating community formation, we aimed to identify groups of species that exhibit higher levels of interaction within themselves compared to interactions with species outside their respective communities. This approach allows for the identification of natural groupings or functional units within the ecosystem, providing insights into the modular organization of species interactions and their implications for ecosystem dynamics and resilience.

The Girvan Newman Algorithm [Fig. 6] is known for its effectiveness in identifying community structures by iteratively removing edges from the network based on edge betweenness centrality, which quantifies the number of shortest paths between pairs of nodes that pass through a particular edge (6). By iteratively removing edges with the highest betweenness centrality, the algorithm partitions the network into distinct communities, revealing underlying patterns of species associations and interactions. Through this process, we gained insights into the modular organization of the ecosystem, elucidating the intricate relationships and dependencies among species within the Amazon network.

2.6 Simulation of Patch Fragmentation, Habitat Loss, and Migration

The simulation of patch fragmentation, habitat loss, and migration represents a fundamental modeling endeavor in our methodology, designed to explain the dynamic responses of species interactions to environmental perturbations within the Amazon rainforest ecosystem.

2.5.1 Motivation and Rationale

The modeling of patch fragmentation, habitat loss, and migration is motivated by the imperative to comprehend how ecological disruptions, such as forest fires and alterations in habitat structure, influence species interactions and ecosystem stability (3). Our model aims to unravel intricate relationships between habitat alteration, species movements, and network dynamics, contributing significantly to the understanding of ecosystem resilience.

2.5.2 Model Scope and Assumptions

Scope of Model: Our modeling framework encompasses three key sets that define the boundaries and assumptions of the ecological system:

- Interactions Within the System: Focuses on interactions solely within the Amazon rainforest, capturing local dynamics and trophic relationships. The assumption is that these interactions are primarily driven by internal ecosystem factors.
- Interactions Beyond Immediate Boundaries: Includes interactions slightly extending beyond the rainforest, influencing regional species dynamics.The assumptn is that these interactions contribute moderately to regional biodiversity patterns.
- Interactions Deliberately Left Out of the System: Encompasses global-scale phenomena or processes, such as intercontinental species migrations or climate-driven range shifts, that extend beyond the regional confines of the Amazon rainforest. The assumption within our model's scope is that while these interactions may indirectly influence rainforest dynamics through broad ecological patterns, their immediate and direct impact on local trophic relationships and species interactions within the rainforest is considered secondary or negligible.

Assumptions and Modeling Considerations:

- Static Model with Respect to Time: Our model assumes a static representation concerning time, meaning we have not explicitly modeled changes in the rate of migration relative to the amount of time elapsed from the perturbation event. This simplification allows us to focus on the immediate effects of habitat fragmentation and migration without introducing additional temporal complexities (3).
- Unavailable Species Count in the Location Patch: The specific count of species in the selected patch is not considered in our model due to data unavailability. While knowing the species count could enhance the precision of our simulations, the lack of this data does not detract significantly from our ability to analyze the broader impacts of habitat loss and migration on species diversity and survival (3).
- Migration Distance Threshold and Migration Probability: We assume a generic migration distance threshold and migration probability for all species rather than species-specific thresholds. This simplification is adopted for analytical clarity and computational efficiency, avoiding the need for complex individual species assessments while still capturing the essence of migration dynamics.
- Non-consideration of New Interactions: We do not consider the formation of new interactions post-migration in our model. This decision is based on practical considerations, as randomly introducing new links after migration could introduce considerable uncertainty and complexity to the network structure, potentially overshadowing the primary effects of habitat fragmentation and migration that we aim to analyze.
- Patch Fragmentation and Habitat Loss Dynamics: Our model assumes that habitat fragmentation, simulated through defined patch boundaries and habitat loss events like forest disturbances, significantly alter species distributions and community structures within affected patches. We incorporate ecological thresholds for fragmentation effects based on empirical data and theoretical understanding of habitat fragmentation ecology (3).
- Press Perturbation Assumption: Our model operates under the assumption of a press perturbation scenario, wherein the affected patch is not recolonized post-disturbance. This simplifying assumption allows us to focus on the immediate effects of habitat loss and migration without incorporating the complexities of post-disturbance recolonization dynamics.

2.5.3 Model Simulation Process

Defining Patch Boundaries: Initially, our model establishes latitude and longitude ranges to demarcate distinct patches within the Amazon rainforest, enabling the simulation of localized environmental changes and subsequent species responses.

Patch Fragmentation and Habitat Loss: The simulation begins with the introduction of habitat loss, emulating scenarios like forest fires. An affected patch is randomly selected, and interactions beyond a specified migration distance threshold are eliminated, reflecting the consequences of habitat fragmentation and loss of ecological connectivity (3).

Species Migration: Migration dynamics are simulated based on defined probabilities, representing species' tendencies to relocate in response to altered habitat conditions (3). The model integrates realistic migration distances and probabilities, enhancing ecological validity.

2.5.4 Model Impact Assessment

Assessing Species Diversity: Post-simulation, our model evaluates the impact on species diversity by comparing the fraction of remaining unique species to the initial species pool. This assessment provides insights into the resilience of species communities to habitat disturbances and migration dynamics (3).

Species Survival and Extinction Analysis: Species unable to survive the simulated environmental changes are identified, shedding light on vulnerable species and potential cascading effects on network structure and functionality.

Monitoring Communities Formation: Community detection methods identify cohesive groups of nodes in a network. Before patch fragmentation in a species interaction network, they reveal distinct ecological niches. After fragmentation, they identify smaller, isolated communities, indicating disrupted ecological dynamics.

2.5.5 Data Integration and Analysis

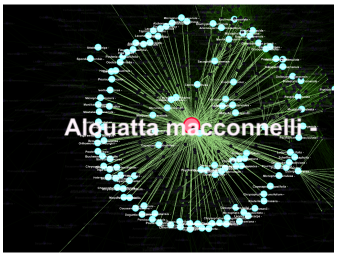
The outcomes of the model simulation are integrated into the broader context of species interaction networks. Surviving interactions, indicative of adaptive responses to environmental challenges, are filtered and analyzed to discern patterns of resilience and vulnerability across trophic levels and interaction types.

3. RESULTS AND INFERENCES

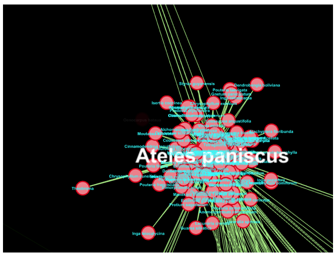
3.1 Identification of Keystone Species

Species	Degree	Betweenness Centrality	Katz Centrality
Alouatta macconnelli	126	0	1.000037538
Ateles paniscus	125	0	1.000037275
Sapajus apella	118	0	1.000037802
Tinamus major	73	72	1.0000189
Thraupis episcopus	49	48	1.000014443

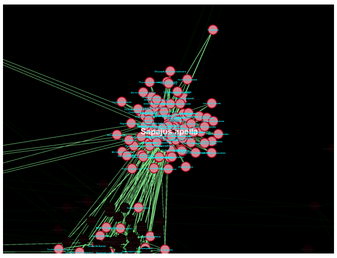
Fig. 3. Top 5 Keystone Species were identified based on the Katz Centrality, Degree and Betweenness Centrality (7)



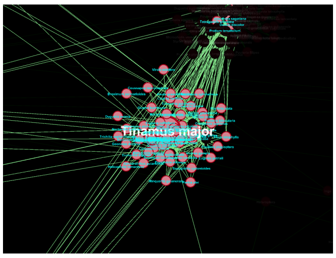
(a) Allouta Macoulli



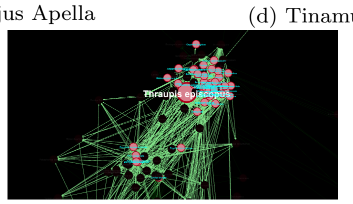
(b) Ateles Paniscus



(c) Sapajus Apella



(d) Tinamus$_{M}ajor$



(e) Thraupis episcopus

Fig. 4. The network visualisation of the identified keystone species

3.2 Impact of Keystone Species Extinction on Species Interaction Network

3.2.1 Decrease in Average Degree

The decrease in average degree, which reflects how many connections each species typically has in the network, highlights the significant impact when key species are removed from the system. Keystone species are crucial because they often sit at the center of the network, interacting with a wide array of other species (4). When these key players are removed, it disrupts the network's structure and connectivity.

For instance, consider the scenario where pollinators like bees or butterflies, essential for pollinating numerous plant species, vanish. This disappearance would lead to a reduction in the average degree as many plants lose their primary pollinators. This decline in connectivity resembles severing critical pathways in a network, disrupting resource flows and weakening trophic interactions. These disruptions can propagate throughout the entire ecosystem, highlighting the intricate dependencies and vulnerabilities within ecological networks (2).

Network	Avg. Degree	Connected Components	Average Path Length
Emperical Network	3.841	28	1.045
Allouatta macconnelli Removal	3.717	29	1.046
Ateles Paniscus Removal	3.716	28	1.046
Sapajus apella Removal	3.724	28	1.046
Tinamus Major Removal	3.77	29	1.027
Thraupis episcopus Removal	3.795	30	1.033
Allouatta macconnelli_Ateles Paniscus Removal	3.592	32	1.048
Tinamus Major_ Thraupis episcopus Removal	3.724	31	1.015
Panthera Onca	3.592	32	1.048
All 5 Removal	3.358	128	1.017

Fig. 5. Network Analysis and Statistical Interpretation

3.2.2 Increase in Number of Components

The increase in the number of components, representing disjointed segments within the network, highlights the fragmentation of the species interaction network following the deletion of keystone species nodes (4). Keystone species often serve as ecological linchpins, maintaining the structural integrity and connectivity of the ecosystem. Their removal can result in the formation of isolated clusters of species with limited interactions between them. For example, the removal of species with high betweenness centrality like Thraupis episcopus leads to increased subnetwork formation, disrupting links for important prey-predator interaction, impeding nutrient and resources flow and reducing overall ecosystem resilience.

We observed another significant pattern in the response of the species interaction network to keystone species node deletions. While the number of components increased gradually for one or two nodes deletions, the difference observed was much higher when five keystone species went extinct in the Amazon ecosystem. Specifically, the number of components changed from 28 to 128, indicating a nonlinear increase in network fragmentation as the number of keystone species lost reached a critical threshold.

This abrupt escalation in the number of components underscores the disproportionate impact of keystone species loss on the structural integrity and connectivity of the ecosystem, further emphasizing the irreplaceable role of these species in maintaining ecosystem stability and resilience. The reduction in graph density from 0.004 to 0.003 also signifies a noticeable decrease in the actual connections compared to the total possible connections within the network, indicating a weakened ability of the ecosystem to efficiently exchange resources and information among species. Additionally, it highlights how anthropogenic activities and natural calamities induced by climate change, leading to the extinction of multiple species beyond a network threshold, could result in ecosystem collapse (1).

3.2.3 Decrease in Average Path Length

The observed decrease in average path length in the species interaction network following the deletion of keystone species nodes indicates a shift towards increased compartmentalization or modularity within the ecosystem. Removal of keystone species disrupts the connectivity between different species, leading to the formation of smaller, more tightly integrated sub-networks or modules. For example, the removal of apex predators like the black caiman can result in the fragmentation of the food web, causing prey species to form smaller, isolated groups with shorter average path lengths between them. This may lead to intensified interactions within these modules but reduced connectivity between them, potentially affecting the efficiency of resource exchange and information flow across the ecosystem.

3.3 Impact of Endangered Species Removal

The removal of endangered species, such as Ateles Paniscus and Panthera Onca, mirrored the general trends observed in network metrics like the decrease in Average Degree and the increase in the number of Connected Components. However, these findings hold significant implications, highlighting the critical role of keystone species in maintaining ecosystem stability and biodiversity (4).

The disruption of essential pathways within the network following the removal of keystone species underscores the vulnerability of ecosystems to biodiversity loss. This emphasizes the urgent need for targeted conservation efforts to preserve these species and their habitats. Conservation strategies must prioritize the protection and restoration of keystone species to safeguard ecosystem functionality, support sustainable development, and ensure the well-being of both ecosystems and communities dependent on them.

3.4 Community Detection Analysis

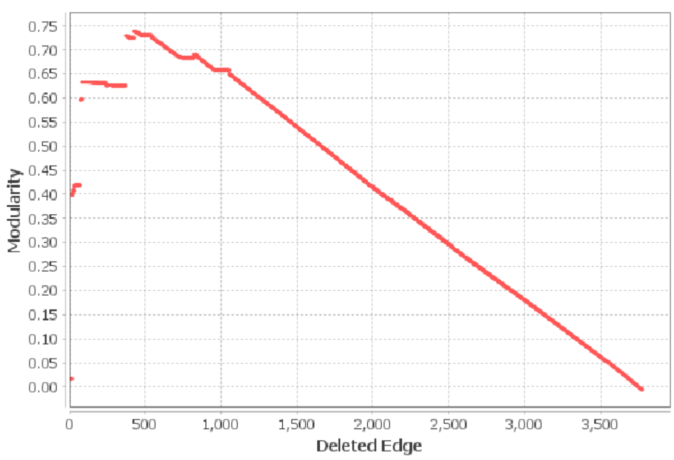


Fig. 6. Graphical Representation of Simulating the Girvan Newman Algorithm

The Girvan Newman Algorithm identified 62 distinct communities within the Amazon species network, achieving a maximum modularity of 0.7412302 [(6)]. Each community represents a cohesive group of species characterized by strong intra-group interactions, indicative of tightly-knit ecological relationships within these clusters. This partitioning of the network unveils the modular organization of species interactions, revealing underlying patterns of species cohesiveness and interconnectivity. Such structured communities suggest specialized ecological niches and functional units within the ecosystem, highlighting the intricate web of predator-prey interactions and the dynamic nature of species relationships. This comprehensive analysis provides valuable insights into the complex dynamics of the Amazon species network, elucidating key ecological patterns and processes that govern ecosystem functioning and resilience.

3.5 Impact of simulation of Patch Fragmentation, Habitat Loss, and Migration

3.5.1 Fraction of Remaining Unique Species and Species Survival:

The printed result, indicating a fraction of remaining unique species after the simulated forest fire and migration, highlights the resilience of the Amazon rainforest ecosystem to environmental perturbations. A fraction close to 1 suggests that the majority of species managed to survive despite the disturbances, maintaining a high level of biodiversity within the affected patch. This resilience could be attributed to various factors such as species adaptability, migration capabilities, and the availability of suitable habitats within or nearby the affected area.

3.5.2 Species Extinction and Vulnerability Analysis:

The list of species that didn't survive in the affected patch provides insights into vulnerable species and potential cascading effects on the network structure and functionality. These species were unable to migrate successfully to suitable habitats, leading to local extinctions. Understanding the reasons behind each species' vulnerability can shed light on specific ecological traits or dependencies that influence survival in the face of environmental changes.

3.5.3 Changes in Network Properties:

The comparison of network properties before and after the simulation reveals significant alterations in the Amazon rainforest species interaction network. The observed trends, such as an increase in characteristic path length and average path length along with a decrease in average degree, signify structural changes in the network's connectivity and complexity.

- Increase in Characteristic Path Length and Average Path Length: Indicates a reduction in the network's overall connectivity. This could be due to habitat fragmentation, which disrupts direct interactions between species and increases the distance or number of steps required for information or resource flow across the network. Longer paths can impede efficient energy transfer and communication, affecting ecosystem functions and resilience.
- Decrease in Average Degree: Reflects a reduction in the average number of connections each species has within the network. This reduction in connectivity

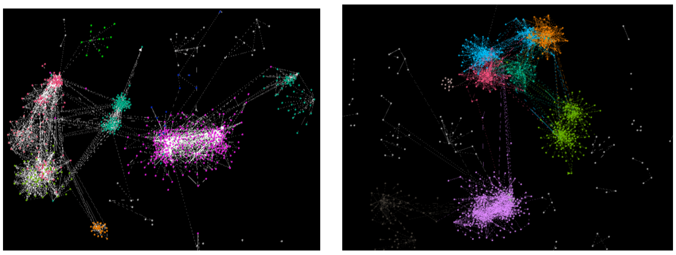
can result from species loss due to extinctions or migration out of the affected patch. As species interactions diminish, the network's robustness and ability to withstand further perturbations may decrease, making it more vulnerable to additional environmental stressors.

3.5.4 Changes in Keystone Species Neighbourhood Connectivity:

There is a decrease in neighbourhood connectivity of keystone species after the simulation, which indicates a potential disruption in their central roles within the network. Keystone species often play critical roles in maintaining ecosystem stability and supporting diverse interactions (4). A decrease in their neighbourhood connectivity suggests a weakening of their influence or the loss of key connections, which can have cascading effects on other species and network dynamics.

3.5.5 Changes in Community Formation

After patch fragmentation in the species interaction network, distinct communities emerged, indicative of habitat loss [Fig. 7]. This fragmentation likely led to isolated pockets of species interactions, reflecting disrupted ecological dynamics and potentially reduced ecosystem resilience. The presence of these discrete communities highlights the impact of habitat fragmentation on network structure and biodiversity distribution.



(a) Before Patch Fragmentation (b) After Patch Fragmentation

Fig. 7. Community Detection in Species Network

4. DISCUSSION

The outcomes of our research reveal several crucial insights into the dynamics of ecological networks, particularly in the context of species extinction, habitat loss, and environmental perturbations. Through rigorous simulations and comprehensive analysis, we were able to unravel the complex interplay of species interactions, ecosystem resilience, and vulnerability.

One of the key findings of our study pertains to the identification and impact of keystone species within ecological networks. Keystone species play pivotal roles in maintaining ecosystem stability and connectivity. Our analysis demonstrated that the removal of keystone species led to significant disruptions in network structure, including decreased average degree, increased components, and decreased average path length. These disruptions underscored the vulnerability of ecosystems to species loss and highlighted the irreplaceable functions of keystone species in sustaining ecological balance.

Furthermore, our simulation of patch fragmentation, habitat loss, and migration provided valuable insights into how environmental perturbations affect species interactions and network dynamics. The fraction of remaining unique species post-simulation highlighted the resilience of the Amazon rainforest ecosystem to disturbances. However, the analysis of species extinction and susceptibility revealed specific species that were unable to survive, shedding light on keystone species and potential cascading effects on network structure and functionality observed when they are perturbed.

Changes in network properties, such as increased characteristic path length and average path length along with decreased average degree, indicated structural alterations in connectivity and complexity following environmental perturbations. These changes emphasize the importance of preserving habitat integrity and mitigating anthropogenic impacts to maintain ecosystem functionality and resilience.

4.1 Limitations

While our study has provided valuable insights into ecological network dynamics, there are certain limitations that warrant consideration. Firstly, our simulations and analyses were based on specific assumptions regarding migration dynamics, species interactions, and habitat responses. These assumptions, although necessary for modeling complexity, may not fully capture the intricacies of real-world ecological systems. Incorporating more nuanced and species-specific parameters in future studies could enhance the accuracy of predictions.

Secondly, our focus on the Amazon rainforest ecosystem, while rich in biodiversity, may limit the generalizability of our findings to other ecosystems with different ecological dynamics. Future research should aim to replicate our methodologies in diverse biomes to validate the robustness and applicability of our conclusions across various environmental contexts.

Additionally, our study primarily addressed short-term responses to environmental perturbations. Long-term effects and feedback mechanisms within ecological networks remain an area for further investigation. Exploring how networks adapt and evolve over extended time scales can provide deeper insights into ecosystem resilience and adaptation strategies.

Despite these limitations, our research serves as a foundational framework for understanding the consequences of species loss and habitat degradation on ecological networks. Addressing these limitations in future studies will contribute to a more comprehensive understanding of ecosystem dynamics and inform targeted conservation efforts worldwide.

5. CONCLUSION AND FUTURE PROSPECTS

In conclusion, our research underscores the critical importance of understanding ecological networks and their responses to species extinction, habitat loss, and environmental disturbances. By adopting a network-based methodology and conducting comprehensive simulations and analysis, we have contributed valuable insights into the dynamics of species interactions, ecosystem stability, and vulnerability.

The identification of keystone species and their impact on network structure highlights the essential roles these species play in sustaining ecological balance. Moreover, our simulations of environmental perturbations emphasize the resilience of ecosystems while also revealing vulnerabilities and potential consequences of species loss.

Looking ahead, our study's assumptions, such as the static model with respect to time and the simplification of migration dynamics, suggest avenues for future research. Incorporating temporal dynamics into our model can enhance the accuracy of predictions regarding species responses to changing environmental conditions. Additionally, refining migration models based on species-specific thresholds can provide nuanced insights into migration patterns and their impacts on network connectivity.

For future directions, we propose exploring the dynamics of species reintroduction to restore network stability and investigating the role of network motifs in ecosystem resilience. Integrating machine learning algorithms to predict species responses to environmental changes and incorporating spatial network analysis techniques can further enhance our understanding of landscape connectivity's influence on species interactions and community dynamics.

By embracing interdisciplinary approaches and leveraging advances in network science, we can advance our knowledge of ecological networks and develop robust conservation strategies to safeguard biodiversity and ecosystem services amidst ongoing environmental challenges.

REFERENCES

[1] Faurby, S., Pedersen, R. S., Svenning, J., & Antonelli, A. (2022). The counteracting effects of anthropogenic speciation and extinction on mammal species richness and phylogenetic diversity. Global Ecology and Biogeography (Print), 31(9), 1810–1823. https://doi.org/10.1111/geb.13560

[2] Delmas, E., Besson, M., Brice, M. H., Burkle, L. A., Riva, G. V. D., Fortin, M., Gravel, D., Guimarães, P. R., Hembry, D. H., Newman, E. A., Olesen, J. M., Pires, M. M., Yeakel, J. D., & Poisot, T. (2018). Analysing ecological networks of species interactions. Biological Reviews, 94(1), 16–36. https://doi.org/10.1111/brv.12433

[3] Haddad NM, Brudvig LA, Clobert J, Davies KF, Gonzalez A, Holt RD, Lovejoy TE, Sexton JO, Austin MP, Collins CD, Cook WM, Damschen EI, Ewers RM, Foster BL, Jenkins CN, King AJ, Laurance WF, Levey DJ, Margules CR, Melbourne BA, Nicholls AO, Orrock JL, Song DX, Townshend JR. Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci Adv. 2015 Mar 20;1(2):e1500052. doi: 10.1126/sciadv.1500052. PMID: 26601154; PMCID: PMC4643828. https://doi.org/10.1126%2Fsciadv.1500052

[4] Wang, Y., Kindong, R., Gao, C., & Wang, J. (2023). Identification of keystone species in ecological communities in the East China Sea. Fishes, 8(5), 224. https://doi.org/10.3390/fishes8050224

[5] Abernethy, G. M. (2022). Perturbation responses in co-evolved model meta-communities. Ecology and Evolution, 12(11). https://doi.org/10.1002/ece3.9534

[6] Lancichinetti, A., Fortunato, S. (2009). Community detection algorithms: A comparative analysis. Physical Review. E, Statistical, Nonlinear and Soft Matter Physics, 80(5) https://doi.org/10.1103/physreve.80.056117

[7] Zhan, J., Gurung, S., Parsa, S. P. K. (2017). Identification of top-K nodes in large networks using Katz centrality. Journal of Big Data, 4(1) https://doi.org/10.1186/s40537-017-0076-5