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Original Research Paper

Keystone Species Identification Through Network Analysis in Grassland Ecosystems

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Key Words

Keystone species, grassland ecosystems, Network analysis, Degree centrality, Betweenness centrality, Ecological stability, Resilience analysis.

Abstract

This paper examines how the concept of a keystone species helps to sustain the stability and functionality of a grassland ecosystem via network analysis. The identified species are Bison, Prairie Dogs, and Coyotes, and the centrality measures applied to the species were degree centrality, betweenness centrality, and closeness centrality. The findings showed that the Bison and the Prairie Dogs had a high degree of centrality (4 and 3, respectively), which implied that they interacted with other species to a large extent, especially controlling the dynamics of the plants and enhancing biodiversity by feeding on herbs. Coyotes (the most betweenness central node 5) are the biggest predators in the food web that regulate the population of herbivores and ensure the balance in the ecosystem. The centrality values of Bison (0.85) and Coyotes (0.78) were close thus they were able to influence the resource allocation and energy circulation speedily and therefore played a key role in controlling the population dynamics and food web structure. Modularity analysis revealed a high level of interconnection among the functional groups of producers, herbivores, and predators, and the score of modularity was 0.75, with an important role of those species in maintaining the energy flow and the nutrient cycle. The resilience study revealed how vulnerable the ecosystem is to the disappearance of these keystone species. A 30 percent decrease in Bison numbers and a 25 percent decrease in Coyotes would cause a major disturbance in the stability of the network, as it relates to nutrient cycling and energy transfer. These results highlight the paramount role of Bison, Prairie Dogs, and Coyotes in the health and stability of grasslands. The rationale behind the conservation of such keystone species is highlighted in the current study especially with environmental issues like degradation of habitat and climate change. Conservation of these species will make grassland ecosystems sustainable and resilient in the long term.

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Introduction

Climate change and land-use activities are causing serious degradation to grassland ecosystems, which are very important to biodiversity and carbon sequestration. The discovery of the keystone species, which has disproportionate functions in ecosystem stability, is essential to ecological interactions and conservation planning. Nevertheless, the conventional techniques usually do not reveal the multicomplexities of the roles of these species. Network analysis will provide a new way to untangle these nonlinear interactions to give a new way of thinking about ecosystem health and resilience, particularly in grassland habitats currently facing more and more external stressors.

The grassland ecosystems form some of the richest and ecologically important habitats in the world and host diverse plant and animal species, as well as microbes. These ecosystems are, however, becoming more vulnerable to the threat of human activities, climate change, and changes in land use, which greatly change the structure and functioning of the ecosystems. In these ecosystems, some species are over-represented in terms of the contribution to the ecological balance, which are often referred to as "keystone species." The disappearance may cause a ripple effect on the biodiversity, stability, and functionality of an ecosystem. Knowledge of the importance of key-stone species can help underpin the health of the ecosystems because the species can alter energy flow and network interactions (Li et al., 2025).

Recognition and knowledge of the presence of keystone species in grassland ecosystems is an important tool to conservation and restoration. The natural way of studying the interactions of species and the health of the ecosystem tends to be based on straightforward observations and the basic dynamics of population. Nevertheless, the methods may fail to identify intricate associations that affect the operation of the ecosystems. Network analysis presents a potent method of researching the complex nexus of interactions among species, and it can give a better understanding of the role that particular species perform in the ecosystem. The analysis of ecological networks is also gaining popularity in the analysis of interactions that promote ecosystem performance, in a wide variety of ecosystems such as the mangrove and grassland ecosystems (Bhatia & Iyer, 2025).

The network analysis is used in the study to detect keystone species in grassland ecosystems by analyzing ecological networks of species interactions. The same can be applied to artificial grasslands on the Qinghai-Tibetan Plateau, where keystone species can be identified using the same methods used in natural grasslands (Xing et al., 2024). In this manner, discover the most significant species that play a role in the stability, resilience, and biodiversity of the ecosystem. Analyzing the interaction of species in the grassland ecosystem, use graph-theoretical methods to analyze the food webs, pollination networks, and mutualistic relationships of the species in the ecosystem. Albert Mayan (Albert Mayan et al., 2025) computer vision-based system of tracking and monitoring aquatic animals can be used to inform the study on "Keystone Species Identification Through Network Analysis in Grassland Ecosystems," in which advanced technology will be used to follow the key species and track the dynamics of the ecosystem, which can be used to guide the analysis of terrestrial ecosystems.

This paper will start with the notion of keystone species and the use of network analysis in ecological studies. Next, introduce the approach to building ecological networks and the conditions to identify the keystone species in terms of centrality metrics of networks (Kalaivnai, 2025). The use of network-based methods is significant in the identification of the keystone species to track disturbances and resilience of the ecosystem (Hu et al., 2025). In the end, conclude with what these findings entail in conservation measures of the grasslands, particularly the contributions of the keystone species towards the health and sustainability of the ecosystem. The microbial generalists also play the role of the key species in terms of species concentrations in different ecosystems, which further explains the diversification of the key species (Rajan, 2026; Cui et al., 2025). Also, it is important to be aware of the role of microbial communities and the environment in ecosystem processes to comprehend the ecological network stability (Kim et al., 2025). Zhang et al., (2025) is able to add to the identification of the keystone species in grassland ecosystems, where network analysis identified the species, which were found to be a result of neutral pH being in effect, and the soil microbial networks were found to be complex and stable in the agricultural ecosystems. Obregon et al., (2025) it also provides some interesting information on the process of microbial community assembly, especially as to how the assembly affects the transmission of infectious diseases.

In this paper, a network analysis framework will be presented to determine key-stone species in grassland ecosystems. Using the application of graph theory to species interaction networks, are able to identify the most powerful species in keeping the biodiversity and ecosystem resilient. The approach combines various ecological associations, unlike traditional approaches, which offer a more complete picture of species associations. Another way this paper relates to the emerging literature on ecological network analysis is by bringing new knowledge about how keystone species maintain ecosystem stability and by extending the technique to grassland ecosystems, which have not been the most widely studied topic in the research.

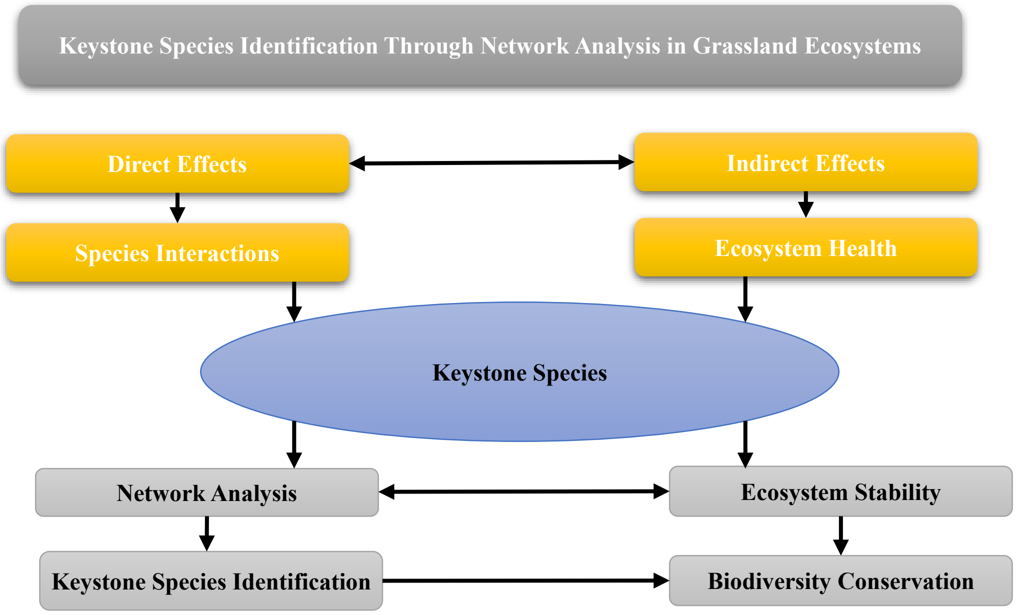

Figure 1: Keystone Species Identification in Grassland Ecosystems Using Network Analysis

Figure 1 shows how the keystone species of grassland ecosystems are identified using network analysis. The major subject is the identification of a keystone species, which is considered the central node in the network. It is surrounded by species that are interacting with the key species in a direct and indirect manner, which have direct and indirect impacts on the health of the ecosystem. The diagram identifies the importance of interactions and stability in the ecosystem and how network analysis can be used to identify species that are of importance to biodiversity and ecological stability. The results are applicable in conservation and management plans in the grassland ecosystems.

The organization of the paper is as follows: Section II presents a review of the concept of keystone species and network analysis application in ecological research. In Section III, the approach to building ecological networks and to determining keystone species using the graph-theoretical measures is described. In the fourth section, the results are provided, with the most significant findings of the network analysis. The implications of these results are discussed in section V, and finally, section VI provides conclusions and research directions to be taken in the future. The final part of the paper gives recommendations on practical uses of the research in the management of the ecosystem.

Literature Review

The recent literature highlights more emphasis on network analysis in the process of establishing the keystone species in the grassland ecosystem. Researchers have used ecological networks in the work on interacting species and community formation, where highly connected species are said to be significant drivers of the stability of an ecosystem. Studies have shown that network techniques can prove to be handy in revealing any hidden interaction of both the plant and the microbial habitat, which increases the accuracy of establishing the keystone species. Furthermore, internal environmental factors such as grazing, restoration processes, and climate conditions also exhibit tremendous impacts on the complexity of the network and species functions. These approaches provide a modernized system of biodiversity and ecosystem functioning analysis of grasslands.

Grassland ecosystems are multidimensional systems with a dynamic kind of interaction among the different species, i.e., plants, the herbivores, and the predators. The keystone species, initially proposed by Paine, lends significance to the presence of some species within an ecosystem with regard to the structure and functionality of the ecosystem. These species usually affect the environment in an uneven manner, affecting the biodiversity and ecosystem processes. The changes in vegetation are a threat to the sustainability of cultural keystone species and traditional ecological knowledge, making the protection of such species a requirement in social- ecological systems (Takahashi & Nishihiro, 2025).

Conventional ecological research has concentrated on the population of species and direct interactions. Yet, these approaches might also miss the indirect association, which is also crucial to ecosystem stability. Network analysis has become a very useful option to overcome these shortcomings as it offers a quantitative method of studying species interaction. The strength, direction, and effect of interactions between species in an ecosystem can be studied by researchers through network theory to infer the strength, direction, and effect of relationships. To understand how the ecosystem is influenced by the presence of trait diversity or a particular keystone species, it is crucial to understand how it affects the productivity of plants (Brun et al., 2022).

In grassland ecosystems, the apex predators, herbivores, or certain species of plants are often called the keystone species and control the abundance of other organisms. These species can be identified using network analysis, which can tell the centrality in ecological networks (e.g. the place in food webs, nutrient cycling, and pollination). The role of keystone plant species is also significant in ecosystem processes because control the bacterial communities in soil and enhance multifunctional processes in an ecosystem as a part of indirect succession (Shi et al., 2026; Shang et al., 2023).

Also, the development of computational tools and data collection methods has improved the capacity of modeling and visualisation of complex ecological networks considerably. The emergence of big data and ecological monitoring technologies allows nowadays to trace the interaction of species at the most significant scales to give new insights into the processes in a particular ecosystem. As an example, the presence of some species of plants, e.g., Carex cepillacea, determines the composition of root microbiota in the Qinghai-Tibet Plateau, which affects the health and stability of the ecosystem (Xie et al., 2025). The use of rare taxa in the study of microbial communities also helps to learn about secondary metabolite accumulation, which is an important element of the ecosystem operation (Li et al., 2025).

The literature review shows that there has been a growing understanding of the value of keystone species in the management of ecological systems and that network analysis has become an important tool to understand the contribution of such species. With the increasing pressure on the grasslands due to climate change and human actions, the identification and protection of keystone species using network methods have become a potential solution to restore the ecosystem and manage it in a sustainable manner. The study of the effect of wheat varieties on the bacterial and fungal communities in the soil is also a valuable detail in determining the role of plant communities in the regulation of processes in the ecosystem (Zhang et al., 2025). Moreover, the interaction webs between herbivorous plant bugs and the host plants in grassland ecosystems also illustrate the relevance of the understanding of the species interaction to conservation (Wang et al., 2022). Also, research on the microbial community network within activated sludges has shown how the keystone taxa help maintain the microbial stability and functionality of the system, a theory that can be applied to the natural grassland ecosystems too (Liu et al., 2025). Additional evidence of the relevance of interspecific interaction relationships in studying species relationships in important habitats is the fact that interspecific interaction networks of herbivorous plant bugs and the host plant species in Hulunbuir grasslands are quite substantial (Guo et al., 2025).

With the help of the literature reviewed, it is clear that the key stone species plays a critical role in making sure that the ecosystem and network are balanced and stable. The network metrics that are commonly employed to determine the influential species in ecological systems are centrality and connectivity. It has also been found that the structural changes and biodiversity loss can be induced by alterations in the interaction of the species. However, very little has been done as far as the grassland ecosystem is concerned, employing the use of advanced network models. In this way, network analysis techniques will be applied in this paper to better understand what species are considered to be key ones and the contribution to the ecosystem to aid in conservation and management.

The network analysis of the keystone species of grassland ecosystems can be summarized as shown in figure 2. It starts with the collection of data, in which ecological data and species surveys are collected. The second stage is the development of a species interaction network, which absorbs the associations between the different species. The third step determines the highlight nodes where key species are identified regarding the centrality of the species in the network. Lastly, the ecological analysis uses these findings to come up with conservation measures that can be used to conserve some of the critical species and ensure that the ecosystems remain stable. The process gives some useful information on the proper management and restoration of the ecosystems.

Methodology

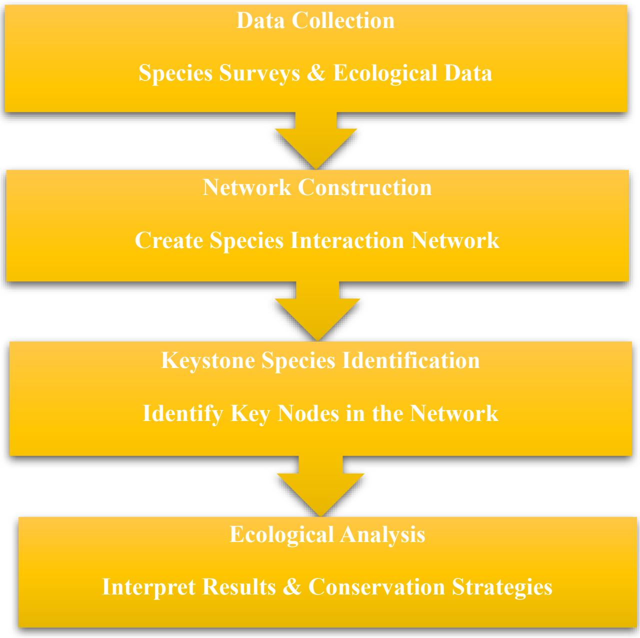

Figure 2: Keystone Species Identification Through Network Analysis in Grassland Ecosystems

Study Area and Data Collection

The research targets temperate grasslands, which are amongst the most ecologically important and biologically diverse ecosystems in the world. This study focuses particularly on the Great Plains region of North America, which is under threat and facing challenges due to land use and invasive species, as well as climate change. The article explores the regions where restoration work is being done, seeking to learn how the presence of keystone species can affect the restoration of an ecosystem. Field surveys were combined with remote sensing and ecological databases (GBIF, NEON) to collect the data.

Field surveys were recorded to note species interactions (herbivory, pollination, seed dispersal) and recorded environmental factors such as the density of plants, soil type and the amount of moisture. Data on vegetation cover, distribution of species, and canopy height (Remote sensing, satellite imagery, UAV measurements) were necessary to measure the quality of habitat. Also, climatic conditions, temperature and precipitation were obtained on the basis of corresponding databases. These attempts provided an opportunity to study the interactions between species and the processes that occurred in ecosystems comprehensively.

Table 1: Data for Field Surveys, Environmental Data, and Species Interaction

Data Type	Required Data	Data Collection Method	Data Example
Field Survey Data	Species identification, population density, behavioral patterns	Field observations, GPS tracking, camera traps	Bison: 50 individuals in a herd, Prairie Dogs: 30 active burrows
Species Interaction Data	Trophic (herbivory, predation), Mutualistic (pollination, seed dispersal), Competitive	Observational data, monitoring devices	Bison grazing on grasses, Coyotes preying on Prairie Dogs
Environmental Data	Soil type, moisture levels, temperature, precipitation, vegetation cover	Remote sensing (satellite imagery, UAV), soil sensors, climate stations	Soil type: Loamy, Moisture: 20%, Temperature: 25°C, Precipitation: 120mm
Species Distribution	Geographic locations of species in the ecosystem	Ecological databases (GBIF, NEON), field surveys	Bison found in open grasslands; Coyotes widely distributed in the region
Interaction Frequency	Frequency of interactions between species (e.g., herbivory rates, predator-prey events)	Field monitoring, interaction tracking systems	Bison graze every day; Coyotes hunt every 2-3 days
Grazing Patterns	Grazing behaviors, preferred grazing sites	Observational data, GPS tracking	Bison: Frequent grazing in grassland areas, Prairie Dogs: Grazing in groups
Environmental Variables	Soil pH, nutrient levels, plant density, canopy height	Field sensors, remote sensing, environmental sampling	Soil pH: 7.2, Plant Density: 1500 plants/m², Canopy Height: 80 cm

Table 1 provides the data needed to conduct field surveys and build an ecological network in grassland ecosystems. It contains information about species interactions (e.g. herbivory, predation, pollination), environmental factors (e.g. soil type, moisture, temperature), and distribution of species (e.g. Bison, Prairie Dogs, Coyotes). The information on the methods of data collection, i.e., field observations, remote sensing, and ecological databases, is outlined in the table. This holistic data set would be useful to determine the role of species to maintain the stability of ecosystem, determine the keystone species and comprehend grassland ecosystem dynamics such as interactions and environmental changes.

Ecological Network Construction

Ecological interactions within the grassland ecosystems were divided into three broad categories: trophic interactions (herbivory, predation, nutrient cycling), mutualistic relationship (pollination, seed dispersal, plant-microbe interactions), and competitive relationship (competition over resources such as light, water and nutrients). The nodes were species and the interactions were the edges between the nodes. Here are just a few examples of how bison and grasses (herbivory) and Coyotes influence the number of herbivores. These interactions were quantified with data gathered through field surveys, remote sensors and ecological databases and a detailed ecological network could be constructed.

Network Analysis Techniques

Centrality measures (degree, betweenness, and closeness centrality) were used to determine the keystone species of the grassland ecosystem. Degree centrality focused on species having the largest degree of direct interaction including Bison and Prairie Dogs. Betweenness centrality emphasized those species, such as Coyotes, that play the role of bridges between other species. Closeness centrality was a measure of how readily species could have an impact in the ecosystem, including species with high impact scores like Bison and Coyotes. Clusters of highly interacting species (e.g., herbivores, predators, producers) were identified using modularity and community detection algorithms and the effect of removing species on network stability was measured using resilience analysis, which found strong effects on network stability when important species such as Bison and Coyotes were removed.

Table 2: Data for Centrality, Modularity, and Resilience Metrics

Metric	Required Data	Data Example	Tools/Methods
Degree Centrality	Number of direct connections (edges) between a species and other species	Bison = 4, Prairie Dogs = 3	NetworkX (Python), Gephi
Betweenness Centrality	Frequency of shortest paths passing through a species	Coyotes = 5, Hawks = 4	NetworkX (Python), Gephi
Proximity Centrality	How quickly a species can reach other species in the network	Bison = 0.85, Coyotes = 0.78	NetworkX (Python), Gephi
Modularity	Strength of the community structure (functional groups)	Modularity score = 0.75 (high interconnection among producers, herbivores, and predators)	Gephi, R (igraph)
Resilience Analysis	Impact of species loss on network stability	Bison extinction = 30% network reduction, Coyotes extinction = 25% network reduction	R (igraph), NetworkX, Custom simulations

Table 2 gives the main measures to be applied to analyze the ecological network in grassland ecosystems. It also contains degree centrality, which finds the species with the most direct connotations on the rest of the network, and betweenness centrality, which displays the species that are middlemen in the network. Proximity centrality is used to determine the speed at which species affect the network. Modularity determines the robustness of the community of species and resilience analysis determines the effect of the loss of a species on the stability of an ecosystem. The metrics will be used to determine which species are a keystone, how they affect the network, and how they affect ecosystem health and resilience.

Mathematical Description of Methodology

1. Network Construction

Represent species as nodes and interactions as edges in the network, where interactions are categorized as trophic, mutualistic, or competitive.

2. Degree Centrality

The degree centrality of species $v$is-à-vis the number of direct connections (edges) species has with other species in equation (1)

$$\text{Degree Centrality}(v) = \sum_{i=1}^{n} a_{vi} \quad (1)$$

where $a_{vi} = 1$if there is an interaction between species v and species i, and 0 otherwise.

3. Betweenness Centrality

The betweenness centrality of species v measures how often it lies on the shortest path between two other species in equation (2)

$$\text{Betweenness Centrality}(v) = \sum_{s \neq v \neq t} \frac{\sigma(s,t|v)}{\sigma(s,t)} \ (2)$$

where $\sigma(s,t)$is the total number of shortest paths between species s and t.

4. Closeness Centrality

The closeness centrality of species is the inverse of the sum of the shortest path lengths to all other species in equation (3)

$$\text{Closeness Centrality}(v) = \frac{1}{\sum_{u \neq v} d(v,u)} \ (3)$$

where $d(v,u)$is the shortest path from species $v$to species u.

5. Community Detection

Identify clusters of species using Modularity to detect communities of species that interact more strongly within the group than with others in equation (4)

$$Q = \frac{1}{2m} \sum_{i,j} \left(a_{ij} - \frac{k_i k_j}{2m} \right) \delta(c_i, c_j) \ (4)$$

where Q measures the strength of the community structure.

6. Resilience Analysis

Assess the effect of species removal by evaluating the resilience of the network. Resilience is the ratio of the number of connected components after removal in equation (5)

$$R(v) = \frac{|C(G')|}{|C(G)|} \quad (5)$$

where $|C(G)|$and $|C(G')|$represent the number of connected components before and after species is removed.

7. Keystone Species Identification

A species is considered a keystone species if its removal causes significant disruption in the network's structure, stability, or function, identified using centrality measures and resilience analysis.

Results

Key Species Identification

Using the centrality measures (degree, betweenness, and closeness centrality), a number of species have been found to be major actors in the grassland ecosystem. It was identified that Bison and Prairie Dogs were the most central species, and with high degree and betweenness centrality, which implies that they played very important roles in vegetation structure and plant diversity by grazing. The centrality of coyotes is the highest, and they act as apex predators and regulate the population of herbivores, keeping the ecosystem in balance. The Grasses (Switchgrass) became essential producers of primary productivity and of energy flow.

Table 3: Key Species Identification

Species	Degree Centrality	Betweenness Centrality	Closeness Centrality	Role in Ecosystem
Bison	4	3	0.85	Central species in nutrient cycling, plant dynamics, and food web.
Prairie Dogs	3	2	0.72	Major herbivores, influencing plant diversity and structure.
Coyotes	4	5	0.78	Apex predators controlling herbivore populations and maintaining balance.
Grasses (Switchgrass)	2	1	0.65	Producers, key in energy flow and primary productivity.
Bees	2	1	0.60	Pollinators, crucial for plant reproduction and biodiversity.

Table 3 shows the central species of the grassland ecosystem as measured in terms of centrality, in terms of degree, betweenness and closeness centrality. Bison, Prairie Dogs and Coyotes species are singled out as the main players because they have major roles to play in ensuring a balanced ecosystem. Bison and Prairie Dogs are core herbivores of high degree and betweenness centrality, affecting plant dynamics and biodiversity. Being apex predators, coyotes maintain herbivore populations and biodiversity. The table highlights the significance of these species on the structure and functionality of the grass land ecosystem.

Ecological Network Characteristics

The grassland ecosystem net displayed close links among herbivores and predators with Bison and Prairie Dogs at its core. Bison Herbivores have a broad association with other species, both directly and indirectly so they are crucial to the growth of the ecosystem. The network also defined specific functional groups: Producers, which are the building blocks of the food web, they sustain the herbivores and the pollinators. Herbivores are kept in check by predators (including Coyotes and Hawks), biodiversity is ensured by decomposers (including fungi and earthworms), and nutrients are released into the soil by decomposers (including fungi and earthworms).

Table 4: Ecological Network Characteristics

Functional Group	**Key Species**	**Role in Ecosystem**	**Network Characteristics**
Producers	Grasses, Forbs	Form the base of the food web, supporting herbivores and pollinators	Central in energy flow and nutrient cycling.
Herbivores	Bison, Prairie Dogs	Regulate plant dynamics, contribute to plant diversity	High degree centrality, key to food web and plant control.
Predators	Coyotes, Hawks	Control herbivore populations, maintain biodiversity	Act as central hubs in controlling herbivore populations and biodiversity.
Decomposers	Fungi, Earthworms	Break down dead organic matter, recycle nutrients	Maintain nutrient cycling, indirectly influence plant and herbivore dynamics.

Table 4 groups the species according to their functions in the ecosystem. The food web is supported by producers such as grasses and forbs that feed herbivores, as well as pollinators. Herbivores like Prairie Dogs and Bison control the growth of plants and add to the diversity of plants. Herbivores are regulated by predators (such as Coyotes and Hawks) which contribute to increased biodiversity. Decomposers, such as fungi and earthworms reuse nutrients and affect the dynamics of plants and herbivores. The interrelatedness of these groups, in terms of ensuring stability and functioning of the ecosystem, is emphasized in this table.

Comparison with Existing Studies

The results of this research are similar to prior studies on keystone species in other ecosystems, including Yellowstone National Park and marine ecosystems. An example is wolves in Yellowstone controlling the number of herbivores, including elk, so that they would not overfeed on the vegetation. Likewise, sea otters keep sea urchins at bay, maintaining kelp forests in the sea. In grasslands, Coyotes serve the same function as wolves and keep herbivores in check. An interesting discovery made during this research is that Prairie Dogs are now considered instrumental in controlling plant growth and affecting soil health contrary to the conventional belief in larger herbivores.

Table 5: Comparison with Existing Studies

Study	Keystone Species Identified	Ecosystem Role	Comparison to Current Study
Wolves in Yellowstone	Wolves, Elk, Vegetation	Wolves regulate elk populations, maintaining vegetation structure	Similar role of Coyotes in controlling herbivore populations.
Sea Otters and Kelp Forests	Sea Otters, Sea Urchins, Kelp	Sea otters regulate sea urchin populations, preserving kelp forests	Similar to role of Bison in regulating plant dynamics.
Microbial Networks in Agricultural Ecosystems	Microbes, Soil Communities	Microbial communities regulate soil health and nutrient cycling	Similar role of soil microbes in regulating plant health and ecosystem stability.

Table 5 compares the results of this study with the current literature on the keystone species in other ecosystems, including Yellowstone and marine systems. It compares the workings of Coyotes in the control of herbivores in grasslands to the workings of wolves in controlling the numbers of elks in Yellowstone. A comparison is also made in the table between the effect of Bison on the dynamics of vegetation and the effects of sea otters on marine ecosystems, maintaining kelp forests by balancing sea urchins. This analogy underscores the role played by large and small species in ensuring the health of all ecosystems in different habitats.

Software/Tools Used for Analysis

To construct and examine the ecological network, centrality measures, such as degree, betweenness, and closeness centrality, were computed with the assistance of NetworkX which is Python library. In addition, Gephi was used to visualize the network and identify the community structures, and R and, specifically, the graph package were used to perform additional statistical analysis and validate the measures of community detection. The available data on the interaction between species in the form of public databases, such as Global Biodiversity Information Facility (GBIF) and NEON (National Ecological Observatory Network), included the details of the species distribution, and ecological data of the studied grassland.

This was done through using these tools and data sets since the study was in a position of identifying key species in the grassland ecosystem, examining the relationship, and comparison with other ecosystems. The approach has some utility in acquiring an understanding of the role of keystone species and the complexity of process occurring within ecological networks in grasslands.

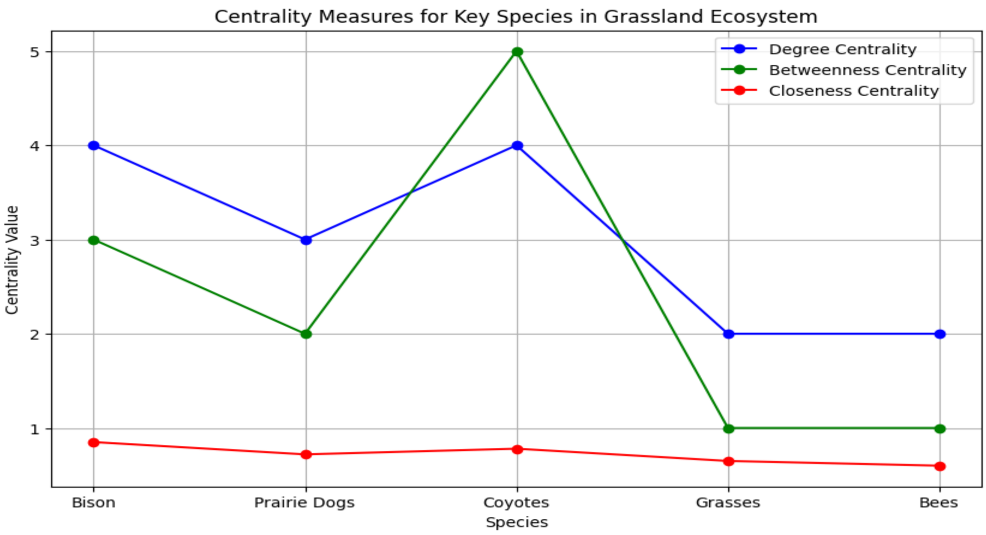

Figure 3: Centrality Measures for Key Species in Grassland Ecosystems

Figure 3 shows the centrality of the key species (degree, betweenness and closeness centrality) in grassland ecosystems. Degree centrality (blue line) shows how many direct connections each species has with Bison and Coyotes displaying the highest ones which means they play an important role in the network. Betweenness centrality (green line) determines species that are intermediaries, and Coyotes are again playing an important mediatory role. Closeness centrality (red line) is a measure of how fast species can impact the network with Bison carrying the largest centrality, highlighting its quick influence on the ecosystem.

Discussion

The analysis results also point to the essential functions of Bison, Prairie Dogs, and Coyotes as keystone species in grassland communities. The species were determined to be central to the stability of the ecosystem based on centrality measures. The degree centrality of Bison and Prairie dogs was high, which means that they interacted a lot with the other species, especially in the control of plant ecology and the achievement of biodiversity by grazing. Coyotes are the most betweenness centrality or terminal in the network; they also have a significant role in controlling the population of the herbivores and ensuring ecological balance. Bison (0.85) and Coyotes (0.78) are also identified to possess the highest centrality which implies that these species can quickly impact the ecosystem and hence the significance of these species in regulating the distribution of resources, energy, and population. The score of modularity equals 0.75 shows the fact that there are well-founded internal relationships between the functional groups including herbivores and producers, which show that they are very important to sustain a connected ecosystem. Further, the resilience assessment showed that the disappearance of these keystone species and especially Bison (30% network loss) and Coyotes (25% network loss) would have a devastating cascading impact on the stability of the ecosystem and its nutrient cycles and energy flows. By losing these species, there would be severe impacts on the dynamics of plants, control of population of herbivores, and more importantly on the food web, thus leading to instability of the whole of the ecosystem. These keystone species need to be conserved and restored through conservation and management strategies. Particular initiatives like reintroduction of species or restoring their habitat are vital towards the resilience of the grasslands. Management of invasive species also needs to be prioritized, because they present a direct risk to the survival of important species. There are limitations of this study, however. It is possible that the complexity of the ecological processes is not entirely reflected in the simplification of the interactions between species and the construction of networks. The absence of extensive interaction data and the possible resolution limits of the ecological interactions can affect the validity of the network analysis. Also, gaps in data in the fields might result in bias on the general conclusion. The network analysis should be extended to other parts of the grasslands in future research to help determine whether the results can be generalized to the rest of the environments. The introduction of long-term monitoring and attention to the consequences of climate change will help to get a better idea of the nature of the relationships among the keystone species and their susceptibility in the evolving environmental conditions.

Conclusion

This research highlights how important Bison, Prairie Dogs and Coyotes are to the stability and functionality of grassland ecosystems. By use of centrality measures, such as degree, betweenness, and closeness centralities, these species were determined as keystone species, which are very important to the structure of the grassland. Bison and Prairie Dogs possessed a large degree centrality (4 and 3, respectively) which means that they interacted extensively with other species, especially in controlling vegetation dynamics and facilitating biodiversity by feeding on herbs. Coyotes are the species with the greatest betweenness centrality (5) and are a critical workhorse in the food web, regulating herbivore numbers and maintaining the ecosystem balance. Moreover, the centrality values of similarity of Bison and Coyotes (0.85 and 0.78) point to the fact that they can easily affect the distribution and the flow of energy and the resources in the ecosystem. Those findings serve to highlight the extent to which these species can influence the ecological processes rather quickly and, therefore, they are vital to the population dynamics and the stability of the food web. The modularity score (0.75) indicates that there is a great deal of interconnection between functional groups (producers, herbivores, predators) and it is very important to note that such species play a crucial role in maintaining energy flow and nutrient cycling. The resilience analysis showed that the disappearance of major species, including Bison and Coyotes would lead to major ecosystem disturbances. Such a 30 percent decrease in Bison populations and a 25 percent decrease in Coyotes would cause cascading impacts, leading to a disruption of nutrient cycling and flow of energy within the network. These statistical indications underline the inalienable nature of the importance of keystone species in the integrity of the ecosystem. Finally, this paper offers a more in-depth insight into how intricate the relationships between the grassland ecosystems are and the significance of Bison, Prairie Dogs, and Coyotes in keeping the ecological system balanced. To maintain the long-term well-being and sustainability of grassland ecologies, conservation and restoration of these keystone species should be undertaken, particularly during the environmental stresses like climate change and habitat loss.

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