JOURNAL OF ECOLOGY AND CONSERVATION
Jan-Mar 2024, VOL. 2, ISSUE 1, pp. 1-4
https://doi.org/10.61577/jec.2024.100001

RESEAPRO JOURNALS

MINI REVIEW

OPEN ACCESS

Keystone species and their impact on the ecosystem: Current trends

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ABSTRACT

Keystone species are relatively rare, but enormously influential organisms in their respective ecosystems. The concept was first articulated by ecologist Robert Paine in 1969 and emphasizes the role of a particular species in maintaining ecological structure. This stems from a shift in ecological research that recognizes the powerful effects of these species on population dynamics, competitive interactions, and biodiversity. Although the early studies centred on predators, mutualists and ecosystem engineers are increasingly involved in more recent research. It seems critical to find key keystone species that can and must be preserved before they are gone forever through destruction of habitat or climate change. They control the size and numbers of prey species, create mutually beneficial interactions among other wildlife populations, modulate ecosystems that many plants require insects to facilitate reproduction from males to females. Keystone species' complex roles at different levels, like genetic analysis or remote sensing, are now known much better than they were in the past because of technological advancement. Integrating traditional ecological knowledge with modern science will help immensely in boosting our understanding. Future research needs to intensify the pursuit of interdisciplinary approaches to keystone species interactions and impacts for global conservation effort and health in our natural worlds.

KEYWORDS

Climate change; Biodiversity; Ecosystem engineers; Habitat destruction; Mutualists

ARTICLE HISTORY

Received 09 January 2024;
Revised 05 February 2024;
Accepted 12 February 2024

Introduction

Keystone species are pivotal organisms with a disproportionately large impact on their ecosystems relative to their abundance. The term "keystone species" was coined by ecologist Robert Paine in 1969 and it originates from the concept of a keystone in an arch without which, the entire structure collapses [1]. These species play critical roles in maintaining the structure, diversity, and functioning of the ecological communities [1,2].

Understanding the influence of keystone species is crucial as they regulate population dynamics, control competitive interactions, and foster biodiversity [3]. Historically, recognizing keystone species marked a paradigm shift in ecology, emphasizing the importance of individual species in ecosystem stability. Early research primarily focused on predatory species, but recent studies have expanded to include a variety of organisms, such as mutualists and ecosystem engineers [3,4].

In the current ecological context, keystone species research is vital for conservation efforts, particularly in the face of habitat destruction and climate change [5,6]. By studying keystone species globally, we can gain insights into ecosystem health and resilience, aiding in developing more effective conservation strategies [6,7]. This review aims to comprehensively overview keystone species worldwide, examining their roles, impacts, and the latest research trends.

Definition and Characteristics of Keystone Species

Keystone species are defined by their critical role in maintaining the structure and functionality of their ecosystems. Unlike dominant species, which are abundant and have significant biomass, keystone species can be relatively low in abundance but exert substantial influence [8]. These species can affect various ecological processes, including predation, competition, and nutrient cycling [8].

One defining characteristic of keystone species is their ability to control the population sizes of other species, thereby maintaining balance within the ecosystem [9]. For instance, removing a keystone predator can lead to a trophic cascade, where the absence of predation pressure allows herbivore populations to explode, resulting in overgrazing and habitat degradation [9,10].

Examples of keystone species across different ecosystems illustrate their diverse roles. The grey wolf (*Canis lupus*) in North America regulates prey populations, such as elk, preventing overgrazing of vegetation. The grey wolf was exterminated approximately 250 years ago as part of a global eradication campaign, despite being a native of Scotland. The population of the world has recently increased, occupying 67% of its previous range [11]. The fig tree (*Ficus spp*.) serves as a keystone mutualist in tropical forests, providing year-round fruit for various animal species that disperse its seeds [12,13].

Identifying keystone species involves assessing their impact on the ecosystem through empirical studies and modeling. Criteria include their influence on species diversity, ecosystem processes, and structural changes within the community [14]. Recent advances in ecological modeling and network analysis have refined our ability to identify and understand keystone species [14].

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Types of keystone species

Keystone species can be categorized based on their ecological roles and functions. The primary types include predators, mutualists, ecosystem engineers, and keystone plants.

Predators

Keystone predators control the prey species' population, preventing any single species from dominating the ecosystem. The grey wolf in Yellowstone National Park is a classic example; its reintroduction has led to the restoration of vegetation and increased biodiversity by regulating elk populations [15]. In South America, the jaguar (*Panthera onca*) plays a similar role, maintaining balance in tropical ecosystems [16].

Mutualists

These keystone species engage in mutualistic relationships crucial for ecosystem functioning. Bees, for instance, are global pollinators essential for the reproduction of many plants, thereby supporting food webs and biodiversity [13]. Fig trees in tropical forests provide critical resources for various frugivores, illustrating the interdependence within ecosystems [12].

Engineers

Ecosystem engineers modify the environment to create new habitats and alter resource availability. In North America, Beavers (*Castor canadensis*) build dams that create wetlands, benefiting numerous aquatic and terrestrial species [17]. In Africa, elephants (*Loxodonta africana*) are keystone engineers that shape landscapes by uprooting trees and creating water holes, influencing the distribution of other species [18].

Plants

Certain plants act as keystone species by providing essential resources and habitat structures. Mangroves in coastal regions protect shorelines from erosion and provide nursery habitats for many marine species [19]. Kelp forests, such as those formed by *Macrocystis pyrifera*, support diverse marine communities by offering food and shelter [20].

Keystone species in various ecosystems

Keystone species are found in various ecosystems worldwide, each playing unique roles in maintaining ecological balance.

Terrestrial Ecosystems: In terrestrial environments, keystone species influence vegetation patterns, prey populations, and overall ecosystem structure. The African elephant is a prime example, creating clearings in forests and savannas that promote plant diversity and provide habitats for other species [18]. Grey wolves in Yellowstone have demonstrated how apex predators can reshape entire landscapes through trophic cascades [11]. In Asia, tigers (*Panthera tigris*) help maintain the health of forest ecosystems by controlling herbivore populations.

Aquatic Ecosystems: Aquatic keystone species often influence water quality and habitat structure. Sea otters (*Enhydra lutris*) in the North Pacific are known for their role in maintaining kelp forests by preying on sea urchins, which would otherwise decimate the kelp [21]. Beavers in North America create wetlands that support diverse communities of plants and animals, enhancing biodiversity [17]. Freshwater mussels in rivers worldwide filter water, improving clarity and quality, which benefits other aquatic organisms [22].

Marine Ecosystems: Keystone species often significantly impact biodiversity and habitat health in aquatic environments. Starfish (*Pisaster ochraceus*) in the Pacific Ocean are keystone predators that regulate the population of mussels, allowing for greater species diversity in intertidal zones [1]. Sharks, as apex predators, help maintain the balance of marine ecosystems by controlling the populations of their prey [23]. Coral species in tropical seas are foundational keystone organisms that provide habitat and structure for numerous marine species, supporting complex reef ecosystems [24].

Impact on biodiversity and ecosystem stability

Keystone species play a critical role in maintaining biodiversity and ecosystem stability. By regulating populations and facilitating interactions among species, they help preserve the intricate balance of ecosystems [13].

The presence of keystone species is often linked to higher species diversity. There have been conjectures on genes having "keystoneness", and potential genes that have a disproportionately significant impact on communities have been identified. Ecosystems may be impacted by *Bt* genes that are purposely put into transgenic plants. It is recently known that a keystone gene affects the species diversity of an artificially created experimental community [25].

Keystone species also contribute to ecosystem resilience by enhancing stability and facilitating disturbance recovery. For example, reefs, supported by keystone coral species, are more resilient to environmental changes when their biodiversity is maintained [24]. Grazers and whelks exhibited different effects on compositional spatial variability; grazers consistently contributed favorably. Furthermore, compared to plots with ambient environmental conditions, these contributions were lower across all stressor scenarios [26].

Case studies illustrate the profound impact of keystone species. The removal of wolves in Yellowstone led to overgrazing by elk, resulting in the degradation of riparian habitats and a decline in biodiversity [11]. Conversely, the introduction of wolves has reversed these effects, demonstrating the essential role of keystone predators in ecosystem management.

Current trends and research in keystone species

Recent research on keystone species has focused on understanding their complex roles and the mechanisms underlying their influence on ecosystems. Technological advancements, such as genetic analysis and remote sensing, have provided new tools for studying these species.

Recent studies have highlighted the global importance of keystone species. For example, research in the Amazon rainforest has identified large frugivores, such as the lowland tapir (*Tapirus terrestris*), as keystone species due to their role in seed dispersal, which affects forest composition and regeneration [27]. In marine ecosystems, remote sensing has improved our understanding of how keystone predators like sharks influence the behavior and distribution of prey species, shaping entire marine communities [28].

Technological advancements have also facilitated interdisciplinary approaches in keystone species research. Combining ecological data with genetic information has enabled researchers to track keystone species' movement and genetic diversity, providing insights into their population

https://doi.org/10.61577/jec.2024.100001

dynamics and conservation needs [25]. Remote sensing technologies have allowed for monitoring habitat changes and keystone species' impacts across large spatial scales [28].

Discussion

The roles and impacts of keystone species vary across ecosystems and regions, but their significance in maintaining ecological balance is universally recognized. Comparisons of keystone species in different environments reveal common themes, such as their ability to regulate populations and facilitate biodiversity. However, their influence's specific mechanisms and outcomes can differ based on ecological contexts and species interactions.

Recent research findings underscore the importance of keystone species in global conservation efforts. The recognition of keystone species' roles in promoting biodiversity and ecosystem stability has led to targeted conservation strategies, such as protecting keystone predators and restoring keystone habitats [6]. Climate keystone species identification can be an effective supplemental conservation strategy to preserve biological groups and the ecosystem services they provide [29]. The relationship between academic ecological knowledge (AEK) and traditional ecological knowledge (TEK) has drawn the attention of researchers. Complex predictive resources that are generally underrepresented in ecological research, conservation strategies, and ecosystem services are included in TEK [30]. Negotiating discrepancies between knowledge systems presents methodological and political difficulties to knowledge integration. There is a need for more comprehensive studies across diverse ecosystems and integrating traditional ecological knowledge with modern scientific approaches [30].

Conclusions

Keystone species are integral to the health and stability of ecosystems worldwide. Their ability to regulate populations, maintain biodiversity, and enhance ecosystem resilience highlights their critical role in ecological dynamics. Future research should continue to explore the complex interactions involving keystone species, utilizing advanced technologies and interdisciplinary approaches. Conservation efforts must prioritize the protection and restoration of keystone species to ensure the sustainability of ecosystems and the services they provide. Through global collaboration and innovative research, we can better understand and preserve these vital components of our natural world.

Disclosure statement

No potential conflict of interest was reported by the author.

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