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Invasive Species and Biodiversity: Mechanisms, Impacts, and Strategic Management for Ecological Preservation

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Invasive species, or non-native organisms, pose significant threats to global biodiversity, ecosystems, and economies. This review provides a comprehensive analysis of invasive species, their impact on native biodiversity, and the mechanisms driving their success. Invasive species

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outcompete native species for resources, disrupt ecosystem functions, and alter habitats, potentially leading to the extinction of native species. The review highlights the ecological, economic, and social implications of invasive species, emphasizing the urgent need for effective management strategies. It examines the invasion pathways, factors influencing their establishment and spread, and the competitive dynamics between invasive and native species. Various assessment methods, including ecological surveys, modelling, and genetic analyses, are discussed to understand and mitigate the impacts of invasions. The review also explores international efforts and policies to manage invasive species and suggests future research directions to enhance conservation strategies. By addressing these issues, this review aims to contribute to the preservation of native biodiversity and the maintenance of ecological balance.

Keywords: Invasive species; Native biodiversity; Ecosystem disruption; Species management; Ecological impact.

1. INTRODUCTION

Invasive species, also known as alien or non-native species, are organisms introduced to ecosystems where they are not native, with the potential to cause harm to the environment, economy, or human health [1]. These species can outcompete native species for resources, disrupt ecosystem functions, alter habitats, and even drive native species to extinction, posing a significant threat to global biodiversity [2,3].

Introducing invasive species can lead to changes in habitat conditions, making ecosystems more vulnerable to further infiltration and spread of non-native species, especially in protected areas [4]. The impact of invasive species on native plant communities can vary based on environmental factors, yet their overall effect on biodiversity remains a critical issue (Wilsey). Beyond ecological implications, invasive species also cause substantial economic losses in sectors such as agriculture, fisheries, and international trade [5].

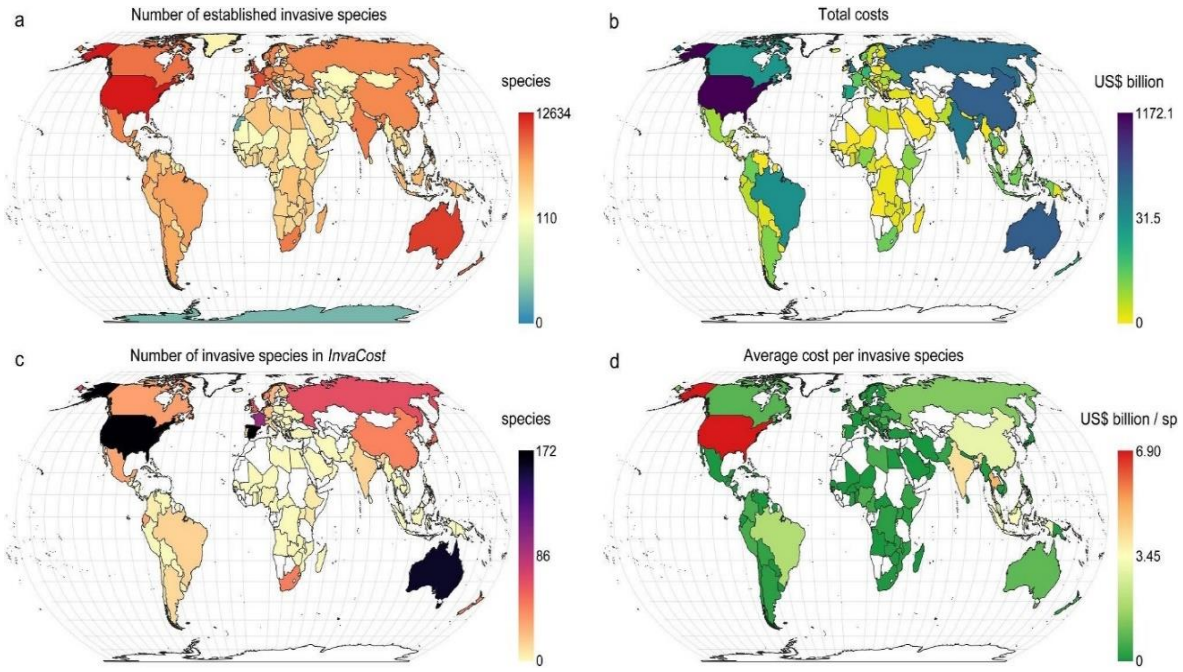

Fig. 1. Shows global maps showing (a) number of established invasive species per country, (b) total costs of invasive species (US$ billion, 2017 value; log10 scale) per country, (c) number of invasive species reported in InvaCost per country, and (d) average cost (US$ billion 2017 value) per invasive species reported in InvaCost in each country. The blank countries indicate an absence of data. Source [3]

Climate change is expected to exacerbate the ecological impacts of invasive species by enhancing their competitive and predatory effects on native species and facilitating the spread of diseases [6]. The spread of invasive species has been recorded across continents, contributing to the decline of native species populations globally [7]. Understanding the mechanisms driving the spread and impact of alien species is crucial for effective management and conservation efforts (Pawaskar).

The study of invasive species and their impact on native biodiversity is essential for preserving ecosystems, protecting native species, and maintaining ecological balance. By investigating the factors contributing to the success of invasive species and their effects on biodiversity, researchers can develop strategies to mitigate the negative consequences of invasions and promote the conservation of native flora and fauna.

2. METHODOLOGY

This comprehensive review of invasive species and their impact on native biodiversity was conducted using a systematic literature search and analysis approach. The methodology consisted of several key steps.

We performed an extensive search of peer-reviewed literature using major scientific databases including Web of Science, Scopus, Google Scholar, and PubMed. The search terms included combinations of keywords such as "invasive species", "alien species", "non-native species", "biodiversity impact", "ecological impact", "native species", "ecosystem disruption", and "species management". The search covered literature published from 2000 to 2024 to ensure the inclusion of both foundational and recent research.

Studies were included if they met the following criteria: a) Focused on invasive species and their impacts on native biodiversity, b) Published in peer-reviewed journals, c) Written in English, and d) Provided empirical data, theoretical models, or comprehensive reviews. Initial screening was conducted based on titles and abstracts. Full-text articles were then reviewed for those that passed the initial screening. Two independent reviewers performed the screening and selection process to minimize bias.

Relevant information was extracted from selected articles, including definitions and classifications of invasive species, ecological impacts on native biodiversity, mechanisms of invasion, assessment methods for invasive species impacts, management strategies and their effectiveness, and global perspectives and policy implications. The quality of included studies was assessed using standardized tools appropriate for different study designs (e.g., PRISMA for systematic reviews, STROBE for observational studies).

A narrative synthesis approach was used to integrate findings from diverse studies. Where possible, quantitative data were summarized using descriptive statistics. To ensure comprehensive coverage and interpretation of the literature, we consulted with experts in the field of invasion ecology and biodiversity conservation.

This review did not involve primary data collection from human subjects or animals, therefore ethical approval was not required. We acknowledge potential limitations such as publication bias towards positive results and the exclusion of non-English language publications.

3. DEFINITION AND CLASSIFICATION

Invasive species are non-native organisms that when introduced to a new environment, have the potential to cause harm to the ecosystem, economy, or human health [8]. They often possess superior resource acquisition traits compared to native species, which contribute to their success in new environments [9]. Invasive species can significantly alter the population abundance and community dynamics of native species, often reaching higher densities and exhibiting higher variance than native species [10]. These differences in traits and population dynamics suggest that invasive species are functionally distinct from native species, which aids in their successful establishment and spread [11].

In terms of ecological impacts, invasive species can outcompete native species for resources, leading to changes in community composition and structure. They can inhibit the establishment and growth of native species, resulting in negative relationships between invaders and native plant biomass [12]. Additionally, invasive species can form dense mono-dominant stands in invaded areas, impacting the biodiversity and ecosystem functions of the invaded habitat [13]. The competition between invasive and native species can be intense, affecting the

reproductive success and performance of native species [14].

Invasive species can be introduced accidentally or intentionally, and their impacts on native ecosystems can vary based on the mode of introduction [15]. For instance, the allopathic potential of invasive species compared to native species can influence the displacement of native species in Mediterranean ecosystems [16]. Furthermore, the physiological responses of invasive species to environmental stressors, such as temperature changes, can affect their success in new environments [17].

Invasive species differ from native species in their traits, population dynamics, and ecological impacts. Understanding these differences is crucial for effective management and conservation strategies to mitigate the negative effects of invasive species on native ecosystems.

3.1 Ecological Impacts

Invasive species have significant direct and indirect effects on native biodiversity, altering ecosystems, disrupting food webs, and competing with native organisms. Research indicates that invasive non-native plants can have a more significant impact on neighboring native species compared to other non-natives [18]. This suggests that invasive species may create a positive feedback loop that promotes further invasions, necessitating active management strategies to restore native species and aid in the recovery of invaded ecosystems.

Studies have shown that invasive plant species often outcompete native species due to their superior competitive abilities [19,20]. The competitive interactions between invasive and native plants are crucial mechanisms underlying the impacts of invasive species on terrestrial ecosystems [21]. Invasive plants can have enhanced resource acquisition traits compared to native non-dominant species, which contributes to their success in ecosystems [9]. Additionally, invasive plants may interfere directly with native species, intensifying competition and leading to more severe ecological impacts on local communities and ecosystems [22].

Invasive species can disrupt mutualistic relationships in ecosystems, affecting ecosystem processes indirectly. They can also impact the competitive dynamics within communities, as seen in the disruption of ant-plant mutualisms by invasive ants, leading to increased damage to savanna trees by elephants [23]. Furthermore, invasive species can alter marine vertebrate behaviour, influencing the movement of nutrients across ecosystems and negatively impacting ecosystem function [24].

The competitive advantage of invasive species is often attributed to factors such as high growth rates and stress tolerance, enabling them to outcompete native species. However, native species may also exhibit strategies to avoid competition with invasives, such as higher organic nitrogen acquisition [25,26]. Understanding these competitive dynamics is essential for managing the impacts of invasive species on native biodiversity and ecosystem stability.

Invasive species pose significant challenges to native biodiversity through competition, alteration of ecosystems, and disruption of ecological interactions. Effective management strategies that consider the competitive abilities of invasive and native species are crucial for mitigating the ecological impacts of invasions and promoting the resilience of native ecosystems.

3.2 Mechanisms of Invasion

Invasive species spread through various pathways such as trade, climate change, and human activities like the transportation of goods. These pathways (Fig. 2) can facilitate the introduction of non-native species into new environments, where they can establish and spread rapidly [27].

Factors contributing to the successful establishment and spread of invasive species include landscape structure, which can affect the invasibility of communities by influencing dispersal vectors and species interactions [29]. Additionally, high productivity and fecundity play a role in invasion success by supporting population growth [30]. Climate suitability and anthropogenic influences also determine the pattern of spread of invasive species, highlighting the interplay of biotic and abiotic factors in invasion dynamics [31].

The invasion success of species is influenced by various factors such as introduction effort, habitat suitability, and species characteristics [32]. The number of introduced species and their environmental match with the new habitat can impact the likelihood of establishment and invasiveness [33]. Linear infrastructures like canals can serve as pathways for the spread of

invasive species, emphasizing the role of human-made structures in facilitating invasions [34]. Moreover, the disturbance associated with roads and railways can provide invasive species with exploitable habitats, aiding in their spread to new areas [35].

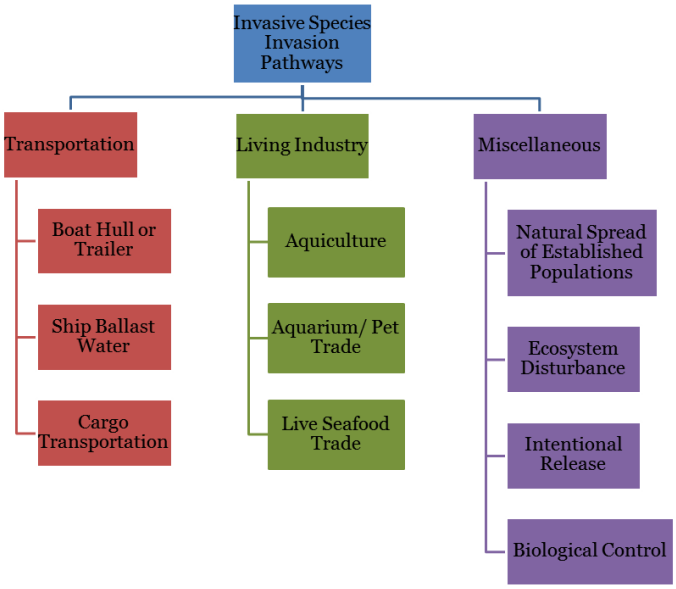

Fig. 2. A flow chart illustrating the pathways through which invasive species are introduced and spread, including human activities like trade and transportation

Source: [28]

Table 1. Compares different assessment methods (e.g., ecological surveys, modeling, genetic analyses) in terms of their effectiveness, advantages, and limitations

Method	Effectiveness	Advantages	Limitations
Ecological Surveys (e.g., population counts, species richness surveys)	High (direct data)	- Provides baseline data on native species abundance and distribution - Captures direct interactions between invasive and native species	- Time-consuming and labor-intensive - May not detect subtle changes or long-term impacts - Prone to observer bias
Modeling (e.g., species distribution models, population growth models)	High (predictive power)	- Can assess impacts across large areas or predict future effects - Useful for identifying potential invasion threats	- Relies on accurate data and assumptions - Models may not capture complex ecological relationships
Genetic Analyses (e.g., DNA barcoding, population genetics)	High (identifies subtle changes)	- Detects changes in native species' genetic diversity - Can reveal competition or hybridization with invasive species	- Requires specialized equipment and expertise - May not directly translate to population-level impacts
Exclosure Experiments (e.g., fencing plots to exclude invasive species)	High (controlled study)	- Measures direct impact of invasive species on native communities - Provides strong evidence of cause-and-effect relationships	- Logistically challenging and may not be feasible in all ecosystems - Results may not be easily extrapolated to larger scales
Remote Sensing (e.g., satellite imagery, drone surveys)	Moderate (indirect data)	- Rapidly assesses changes in habitat quality and land cover - Covers large areas and can be used for long-term monitoring	- Requires specialized equipment and data analysis skills - May not directly measure changes in biodiversity

Invasive species spread through multiple pathways facilitated by human activities and environmental factors. The successful establishment and spread of invasive species are influenced by landscape structure, productivity, climate suitability, introduction effort, and habitat characteristics. Understanding these mechanisms and factors is crucial for effective management and control of invasive species to mitigate their environmental and economic impacts.

3.3 Assessment Methods

Various methods are employed to assess the impact of invasive species on native biodiversity, including ecological surveys, modeling, and genetic analyses. Ecological surveys play a crucial role in understanding the ecological impacts of invasive species by observing changes in native biodiversity resulting from invasions [36]. Modeling approaches aid in predicting the ecological impacts of invasive species, allowing for the assessment of existing and potential invaders [37]. Genetic analyses provide insights into the mechanisms by which invasive species affect native biodiversity, offering a deeper understanding of the impacts exerted [38].

Moreover, the use of functional responses and the abundance of invasive species can help in assessing their ecological impacts and predicting their effects on native ecosystems [39]. By developing metrics like Relative Impact Potential (RIP), the ecological impacts of invasive species can be quantified based on their functional and numerical responses [40]. These approaches provide a mechanistic understanding of invasive species impacts, aiding in risk assessments and management prioritization [41].

A combination of ecological surveys, modeling, genetic analyses, and functional response assessments offers a comprehensive framework for evaluating the impact of invasive species on native biodiversity, enabling effective conservation and management strategies.

3.4 limitations and Challenges in Assessing the Impacts of Invasive Species on Native Biodiversity

Assessing the impacts of invasive species on native biodiversity presents various limitations and challenges across different methodologies. Ecological surveys, which are commonly used to evaluate the effects of invasive species, face difficulties due to the rapid disassembly of communities caused by invasives, leading to altered community organization [42]. Additionally, the invasiveness of a species does not necessarily predict its impact, complicating assessments based on this criterion [27]. Genetic analyses, such as those focusing on genetic diversity, can also be challenging, as invasive species may exhibit low genetic diversity despite multiple introductions, impacting their ability to adapt and persist in new environments [43].

Modelling approaches to assess the ecological impacts of invasive species face limitations as well. For instance, studies aiming to evaluate the impacts based on functional responses and abundances of invasives may struggle with the allocation of limited resources towards mitigating species with the highest ecological impacts [40]. Furthermore, the lack of consistency in abundance-impact relationships across invasive species and ecological impact metrics can hinder the development of generalized models for assessing their effects on native biodiversity [44].

Invasive species can rapidly alter genetic diversity, genetic structure, and genetic relationships with native species, posing challenges for genetic analyses aimed at understanding their impacts on biodiversity [45]. Hybridization with invasive species represents a major threat to the genetic persistence of native organisms globally [46]. Despite facing genetic bottlenecks, invasive species can still undergo rapid evolution, impacting ecosystems and biodiversity [47].

The assessment of invasive species impacts on native biodiversity through ecological surveys, modelling, and genetic analyses is complex and multifaceted. The rapid disassembly of communities, unpredictability of impacts based on invasiveness, low genetic diversity of invasives, and challenges in establishing consistent abundance-impact relationships all contribute to the difficulties in accurately evaluating the effects of invasive species on native biodiversity.

4. MANAGEMENT STRATEGIES

4.1 Strategies for Preventing and Controlling Invasive Species

Invasive species pose a significant threat to ecosystems worldwide, leading to biodiversity

loss and ecological imbalances. To prevent and control invasive species, various strategies have been proposed based on scientific research and practical applications.

Early detection plays a crucial role in managing invasive species. Recent theoretical advancements highlight the complexity of invasive species spread, emphasizing the impact of long-range dispersal events on expansion rates [48]. By detecting invasive species early, interventions can be implemented swiftly to prevent further spread and establishment.

Eradication of invasive species, particularly on islands, has been proven to be an effective conservation strategy. Eradicating invasive mammals from islands has been shown to prevent biodiversity loss and benefit highly threatened vertebrates [49]. Successful eradication campaigns on numerous islands worldwide have demonstrated the feasibility and importance of this approach [50].

Restoration efforts following invasive species eradication are essential for ecosystem recovery. After invasive species alternative communities, eradication programs aim to restore ecosystems to their pre-invasion state [51]. This restoration process is crucial for reestablishing native biodiversity and ecological balance.

Strategic planning is vital in the eradication of invasive species. Managers need to prioritize eradication actions based on feasibility, conservation value, and potential ecological benefits [52,53]. Optimal eradication schedules, considering the target species, timing, and budget constraints, are necessary for successful invasive species control [54].

Moreover, the economic aspects of controlling invasive species are significant. Stochastic optimization models have been developed to identify optimal strategies for dealing with invasive species, considering spatial and dynamic processes [55]. These economic models can assist decision-makers in allocating resources efficiently for invasive species management.

Preventing and controlling invasive species requires a multi-faceted approach that includes early detection, eradication, and restoration efforts. By leveraging scientific research and strategic planning, it is possible to mitigate the negative impacts of invasive species on ecosystems and safeguard biodiversity.

4.2 Evaluating the Effectiveness of Different Management Approaches

Effective management approaches are essential for achieving objectives in various fields, including fisheries, natural resource conservation, and organizational performance. Management strategy evaluation (MSE) is a valuable tool that involves simulating different management strategies to assess their effectiveness in meeting specific objectives [56,57,58]. This approach allows for the comparison of various data collection methods, analysis techniques, and management actions to determine the most suitable strategy [57].

In the context of ecosystem-based fisheries management (EBFM), MSE has been extended to support the development and testing of strategies that consider the broader ecosystem impacts of fishing activities. By incorporating ecosystem-level considerations, MSE helps in designing more holistic and sustainable management approaches for fisheries [56].

Furthermore, MSE involves selecting operational management objectives, defining performance measures, specifying alternative strategies, and evaluating these strategies through simulation. This process enables stakeholders to define clear objectives and priorities, which are essential for effective decision-making in resource management [58].

In addition to fisheries, MSE has been applied in bio-economic evaluations for deepwater stocks, demonstrating its versatility across different sectors. By evaluating management strategies through simulation before implementation, MSE allows for the identification of robust strategies that can adapt to changing conditions [59].

Moreover, the balanced scorecard approach has been highlighted as a valuable tool for sustainable performance management in organizations. By integrating sustainability measures into performance evaluation, organizations can enhance their efficiency and effectiveness while ensuring long-term sustainability [60].

Overall, the synthesis of these references underscores the importance of MSE as a versatile tool for evaluating and developing

effective management strategies across various domains. By incorporating stakeholder priorities, ecosystem considerations, and performance metrics, MSE facilitates the design of robust and sustainable management approaches that can adapt to dynamic environments.

4.3 Global Perspectives and Policy Implications

4.3.1 International efforts to address invasive species

Invasive species pose a significant threat to biodiversity, ecosystem services, and human livelihoods worldwide. International efforts to address this issue have been emphasized in scientific literature. Improved international cooperation is crucial to reduce the impacts of invasive alien species on various aspects of the environment [61]. Invasive plants, for example, can reduce biodiversity, alter ecosystem functions, and have considerable economic impacts [62]. Prevention of new introductions is a high priority for addressing the harm caused by invasive species, but unfortunately, efforts to prevent new introductions do not address the economic harm that is presently manifested where invasive species have already become established [63].

Efforts to address invasive species require enabling decisions that make a difference, including guidance for improving access to and analysis of invasive species information. This involves mobilizing invasive species occurrence data into publicly available information systems, sharing data among primary invasive species information systems, and developing data standards for invasive species biology [64]. International cooperation is essential in addressing the global problem of invasive species. Factors behind the growth of invasive species as a global issue and the potential for international cooperation in addressing this problem have been highlighted [65].

Various international policy options have been proposed to reduce the environmental impacts of invasive species. Some categories of invasive species, such as diseases of humans and livestock, are addressed by international agreements that coordinate efforts to reduce their spread [66]. Successful invasive species management requires collaborative efforts from all stakeholders, including government agencies, international and national non-governmental organizations, academic researchers, and local individuals [67]. The International Maritime Organization (IMO) has been working with member states to adopt global conventions aimed at preventing invasive species transfer through shipping, highlighting the importance of international bodies in addressing invasive species issues [68].

Addressing invasive species globally requires enhanced international cooperation, data sharing, policy coordination, and stakeholder engagement. By working together across borders and disciplines, countries can better prevent, manage, and mitigate the impacts of invasive species on biodiversity and ecosystems.

5. POLICIES, REGULATIONS, AND COLLABORATIONS OF INTERNATIONAL EFFORTS TO ADDRESS INVASIVE SPECIES

Invasive species pose a significant threat to ecosystems, biodiversity, and economies worldwide. Addressing this challenge requires robust policies, regulations, and international collaborations. Various studies highlight the importance of collective action, cross-boundary efforts, and cooperation at different levels to effectively manage invasive species.

Schneider et al. [69] emphasize the shift towards holistic, multiscalar, cross-boundary, and collaborative efforts in invasive species management, moving away from individual-focused approaches. Seydel et al. [70] stress the need for federal leadership and cooperation among different government levels to prevent, detect, respond to, and control invasive species effectively. They recommend specific actions for the federal government to enhance invasive species management.

Furthermore, [71] suggest the establishment of an international body responsible for invasive species management to coordinate global efforts and provide support to vulnerable countries. (64) propose actions to improve access to and analysis of invasive species information, emphasizing the importance of data sharing and standardized metrics.

International cooperation is crucial in addressing invasive species risks, as highlighted by [65]. They discuss the potential for international collaboration in tackling invasive species as a global problem. Additionally, [72] stress the

importance of building partnerships and bridging science and policy to address the invasive species crisis comprehensively.

Effective invasive species management requires a combination of policies, regulations, and collaborations at local, national, and international levels. By adopting collective action, cross-boundary efforts, and data-sharing practices, stakeholders can enhance their capacity to prevent, detect, and control invasive species, ultimately mitigating the threats they pose to ecosystems and economies.

5.1 Economic and Social Implications of Invasive Species Management

Invasive species management involves a complex interplay of economic and social implications that require careful consideration. The economic impacts of invasive species are significant, with estimates suggesting global costs amounting to around US$1.5 trillion annually, highlighting the urgency and significance of effective management strategies [73]. These economic costs arise from the disruption of native ecosystems and adverse effects on various economic interests, underlining the need for robust management policies [74]. Furthermore, invasive species not only impact ecosystems but also influence the delivery of ecosystem services crucial for human economic activities, emphasizing the importance of managing these species to safeguard economic interests [75].

Invasive species management also has social implications that must be taken into account. While the primary goal of management is to prevent or mitigate the impacts of introduced species, it is essential to recognize that management interventions themselves can generate social impacts that need to be understood and addressed [76]. Understanding social preferences for invasive species management is crucial for informing economically efficient management strategies and policies, highlighting the need for improved knowledge in this area [77]. Additionally, stakeholder participation in decision-making related to invasive species management is vital for achieving management objectives, particularly given the challenges posed by funding limitations and the occurrence of invasive species on both private and public land [78].

The management of invasive species requires a multidisciplinary approach that integrates science, economics, and social considerations. Economic models play a crucial role in informing policymakers and the public about the economic consequences of invasive species and the implications of different management strategies, emphasizing the importance of considering economic factors in decision-making processes [79]. Moreover, the benefits of invasive species management are not excludable, leading to strategic dilemmas akin to the "Tragedy of the Commons," highlighting the need for effective governance structures to address these challenges [80].

The management of invasive species necessitates a comprehensive understanding of both the economic and social implications involved. By considering the economic costs, social impacts, stakeholder preferences, and the interdisciplinary nature of invasive species management, policymakers and stakeholders can develop more effective strategies to mitigate the negative effects of invasive species on ecosystems, economies, and societies.

6. CONCLUSION

In conclusion, this review underscores the critical threat that invasive species pose to native biodiversity, ecosystems, and economies worldwide. The findings highlight the competitive advantages of invasive species, such as rapid growth rates and adaptability, which enable them to outcompete native flora and fauna. The pathways of invasion, often facilitated by human activities and environmental changes, complicate management efforts and necessitate a multifaceted approach to address these challenges effectively.

To mitigate the adverse impacts of invasive species, it is essential to implement early detection, eradication, and restoration strategies. The integration of ecological surveys, modelling, and genetic analyses is vital for assessing the impacts of invasions and informing management practices. Furthermore, the economic and social implications of invasive species management call for robust policies, regulations, and enhanced international cooperation.

Future research should focus on understanding the mechanisms driving invasions and their ecological consequences, while also developing comprehensive management strategies that

incorporate scientific insights, policy coordination, and stakeholder engagement. By fostering collaboration and improving data-sharing practices, we can better address the threats posed by invasive species and promote the resilience of native ecosystems, ultimately contributing to the preservation of global biodiversity and ecological balance.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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