Invasive species threats to native aquatic biodiversity: A meta-analysis

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Abstract

The paper includes a meta-analysis of the effect of invasive species on the native aquatic biodiversity in different ecosystems. The aim of the study was to measure the ecological imbalances caused by invasive species and to identify other factors that determine their success in different aquatic environments, such as freshwater lakes, river systems, coastal areas, and marine conditions. The study methodically examined and synthesized the information by examining the peer-reviewed publications over the past 20 years. The methodology entailed the determination of standardized effect sizes of single studies, and then meta-regression analysis was done to establish significant variables that influence ecological change. The findings showed great negative effects on the native species richness in all the aquatic environments, with a pooled mean effect size of -0.84 in freshwater ecosystems. Of them, freshwater lakes were the most strongly affected (mean effect size = -0.88). The effects were relatively low but also relatively significant in marine ecosystems (mean effect size = -0.38). Nutrient loading has been mentioned to be a major cause of the success of invasive species, and environments with high levels of phosphorus and nitrogen exhibit a stronger correlation between the abundance of invasive species and the loss of biodiversity. The use of early detection and rapid response systems

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(EDRR) showed greater accuracy in freshwater ecosystems (0.86) compared to the marine systems (0.60). The results highlight the importance of custom management schemes that can focus on ecosystem factors specific to individual ecosystems (nutrient content and connectivity of habitats, etc.). Future studies should involve long-term monitoring to trace the temporal impact of invasions, cross-regional studies to comprehend the impact of the environmental and policy variables, and the establishment of more efficient monitoring, especially when it comes to marine ecosystems. Also, the importance of climate change in promoting the propagation of invasive species is a vital issue to explore in order to increase the conservation process.

Keywords: Invasive species, Aquatic ecosystems, Biodiversity loss, Meta-analysis, Native species, Ecosystem disruption, Conservation, Ecological impact

Introduction

Invasive species are now one of the most burning issues of biodiversity in the world, especially in aquatic environments. The non-native species interfere with the natural balance by competing with the native species, changing the structure of the communities, and bringing with them diseases. Freshwater lakes, rivers, wetlands, and oceans are particularly sensitive to changes in the environment, and thus, they are vulnerable. The ecosystems are very important in offering important services to the ecosystem, like water purification, carbon storage, and support of biodiversity. Most invasive species frequently cause the extinction of the indigenous species, thus creating a serious imbalance in the nature of the ecosystem and reducing the overall ecosystem's resilience. Human activities, including the translocation of species and climate change, are the major causes of these invasions and have increased the susceptibility of these ecosystems. The aim of the study was to evaluate the various effects of invasive species on the native biodiversity through a complete meta-analysis of the literature available (Latorre *et al.,* 2023). The first aim is to generalize the findings of multiple studies and systems to gain a deeper insight into the role of invasive species in determining the richness, abundance, and ecosystem services of multiple aquatic systems. The recombination of the information collected in freshwater lakes, river systems, coastal areas, and marine ecosystems will give the study an idea of the degree of disruption of invasive species in the different ecological settings (Agra *et al.,* 2024). The study will also play a role in discovering the major ecological processes that can facilitate the popularity of invasive species and provide useful data for the development of effective management practices.

Despite the fact that much research has been done on the effect of invasive species, there exists a significant void in a synthesis of the effects of invasive species around the world, comparing their effects on different ecosystems. There are numerous studies that have been conducted in isolated parts or species, but none of them have offered a detailed analysis that can bring the results of various aquatic environments together. This knowledge gap prevents the integration of the diverse ecological implications of the invasive species. By sealing this knowledge gap, the study will contribute towards a more comprehensive outlook of the dynamics of invasive species, their impacts on the ecosystem, and the factors that make them very successful in certain ecosystems. Finally, the research aims at enhancing the control of invasive species by providing a generalized perception of ecological effects in different water bodies. The results will assist in the informed conservation measures and formulation of the early detection and rapid response (EDRR) systems. The study of invasive species impacts on the aquatic biodiversity is very important to devise adaptive management strategies that can alleviate the invasion and protect the existence of native species (Knight, 2010; Sobuj, Singh and Byun, 2024). The study should offer practical recommendations to conservationists, policy makers, and ecosystem managers in an attempt to conserve aquatic ecosystems and their biodiversity against the increasing environmental pressures.

1. The research provides an international meta-analysis, which summarizes the results of various ecosystems to determine the presence of invasive species on the richness, abundance, and ecosystem services of species.
2. It recognizes important ecological variables and factors promoting invasive species success, which improves the ecological implications of invasive species.
3. The study gives knowledge to enhance management practices, such as early warning and quick response mechanisms, to reduce the adverse effects of invasive species and biodiversity, and conserve aquatic life.

The paper has been divided into various important sections that all discuss the effects caused by invasive species to native aquatic biodiversity. Section I, Introduction, gives a summary of the problem, research objectives, and reasons why the invasive species are important to study in the aquatic ecosystem. Section II of the dissertation, Literature Review, presents research studies on the ecological impacts of invasive species on different species and ecosystems. In Section III, Methodology, the selection criteria of the study, data extraction procedure, the statistical methods of analysis of the results, and the mathematical framework to assess the ecological impacts of invasions are described. Section IV, Results and Discussion, is a summary of the results of the meta-analysis, statistical synthesis of ecological impacts, comparative analysis of biodiversity measures, and early detection and rapid response (EDRR) systems. Section V, Conclusion, summarizes the main findings of the study, the necessity to develop integrated management strategies, and focuses on the implications of the study for conservation efforts. Lastly, Future Work also mentions where research can go in the future, which is long-term monitoring, cross-regional studies, and improvements to the detection and monitoring systems.

Literature Review

It is a well-known fact that invasive species tend to be a menace to the native biodiversity, especially aquatic life. They are introduced in non-native environments where they might outcompete, prey on, or cause diseases to the native species, causing a drop in the native biodiversity (Jha and Li, 2025). Species like the zebra mussel (Dreissena polymorpha) and the Asian carp (Hypophthalmichthys molitrix) have been demonstrated to affect the food webs, causing more extinction of the native species in freshwater environments (Zieritz *et al.,* 2025; Dudgeon and Strayer, 2025). These invading species cause a change in the structure and functioning of aquatic communities, both of the flora and fauna. Invasive species do not just impact freshwater systems but also cause substantial changes in marine ecosystems, where species such as the green crab (Carcinus maenas) and the lionfish (Pterois volitans) have profoundly transformed the community and habitat structure of the waters in their new locations (Li *et al.,* 2023).

The recent meta-analyses have been giving the world a picture of such impacts that invasive species result in the loss of native species, causing a break in the cycle of nutrients and causing the ecosystem to become weak (Britton *et al.,* 2023; Tasker, Foggo and Bilton, 2022). According to the biological resistance hypothesis, ecosystems that have a greater native biodiversity are more resistant to invasions, whereas according to the enemy release hypothesis, invasive species flourish in habitats where they do not have their natural predators (Havel *et al.,* 2015). Also, the ecological niche theory has been applied to explain why invasive species, in most cases, occupy empty niches, thereby outcompeting the native species (Rajan and Raja, 2025). Consequently, it is important to learn the mechanisms involved in species invasions and how they affect ecosystems to devise effective management measures.

Environmental factors like nutrient overloading and climate change further predispose the aquatic ecosystems to invasive species; such factors may increase the success of the invasive species. Indicatively, the abundance of invasive species in hyper-eutrophic environments with high nutrient content offers a favorable environment to the invasive species, resulting in stronger relationships between invasive species richness and native biodiversity decline (Panlasigui *et al.,* 2018). Efficient management and conservation practices, such as early detection and rapid response (EDRR) systems, have been cited as important aspects in reducing the undesirable effects of invasion (Rojas-Castillo *et al.,* 2024). Thus, the ecological, environmental, and management factors affecting the success of invasive species are fundamental in the conservation of the native biodiversity in the aquatic ecosystems.

The invasive species have a great impact by disrupting the native aquatic biodiversity in terms of competition or predation on the native species, and changes in the functioning of ecosystems. The more susceptible to such disturbances are freshwater systems that are of lower species diversity, such as the invasion of species such as zebra mussels and Asian carp. There is also an impact on marine environments, which are affected to a lesser degree. These effects are intensified by environmental factors, including nutrient loading and climate change, and hyper-eutrophic environments favor the success of invasive species. The results indicate that a combination of management interventions, such as surveillance systems to prevent the negative outcomes of invasions and safeguard the health of ecosystems, is necessary.

Methodology

Study Selection and Inclusion Criteria

The systematic review and data extraction were conducted in accordance with a pre-determined protocol in order to achieve scholarly credibility. The studies were sampled according to a 20-year look-back time, giving preference to peer-reviewed articles that presented the quantitative data about invasive species impacts. Inclusion criteria: the studies had to present on the primary biodiversity indicators like species richness, evenness, and community composition. Moreover, the chosen works were needed to give quantifiable indicators of the ecosystem health, such as nutrient cycling, habitat modification, water quality, and primary productivity.

Data Extraction and Standardization

After the extraction of the empirical measurements into structured data, they were analyzed based on the eligibility criteria. This data was from a wide spectrum of aquatic locations, including lakes, river systems, coastal areas, and marine environments, in the field observations and laboratory experiments. The extraction was based on the richness of the indigenous and introduced species and the occurrence of essential ecological services. This multi-environment method enabled the scale of disruption of the various ecological niches to be understood.

Statistical Analysis and Meta-Regression

In order to attain a strong cross-study comparison, a multi-level statistical methodology was adopted to integrate the results of the different projects. To measure the extent of the impact of invasive species on native biodiversity, standardized effect sizes were initially computed on each of the individual studies. These personal effects were, in turn, taken through regression modelling to determine individual variables that contributed to ecological change. Lastly, the effect size computations and regressions were combined into a meta-regression model to determine the general relevance of effects on ecosystem wellbeing and species variety.

Mathematical Framework

The measurement is based on standardized measures to assess the effects of invasive species. The assessment of detection and monitoring systems is based on precision and not general accuracy. The technical accuracy is measured by equation (1). Precision (P) can be described as the proportion of true positive detections (TP) to the number of positive detections (including false positives).

$$P = \frac{TP}{TP + FP} \quad (1)$$

In addition, the meta-analysis is used to estimate the standardized effect size (d), which can be used to compare the outcomes with other studies. It is calculated as the difference between the mean of the invaded group ($\overline{x}_i$) and the control group ($\overline{x}_c$). The pooled standard deviation (s) is calculated by equation (2).

$$d = \frac{\overline{x}_i - \overline{x}_c}{s} \quad (2)$$

The joint management of these effects is based on the finding of the patterns in the meta-regression output, and a significant impact would be found when the p-value of the regression coefficient is less than the pre-defined alpha level.

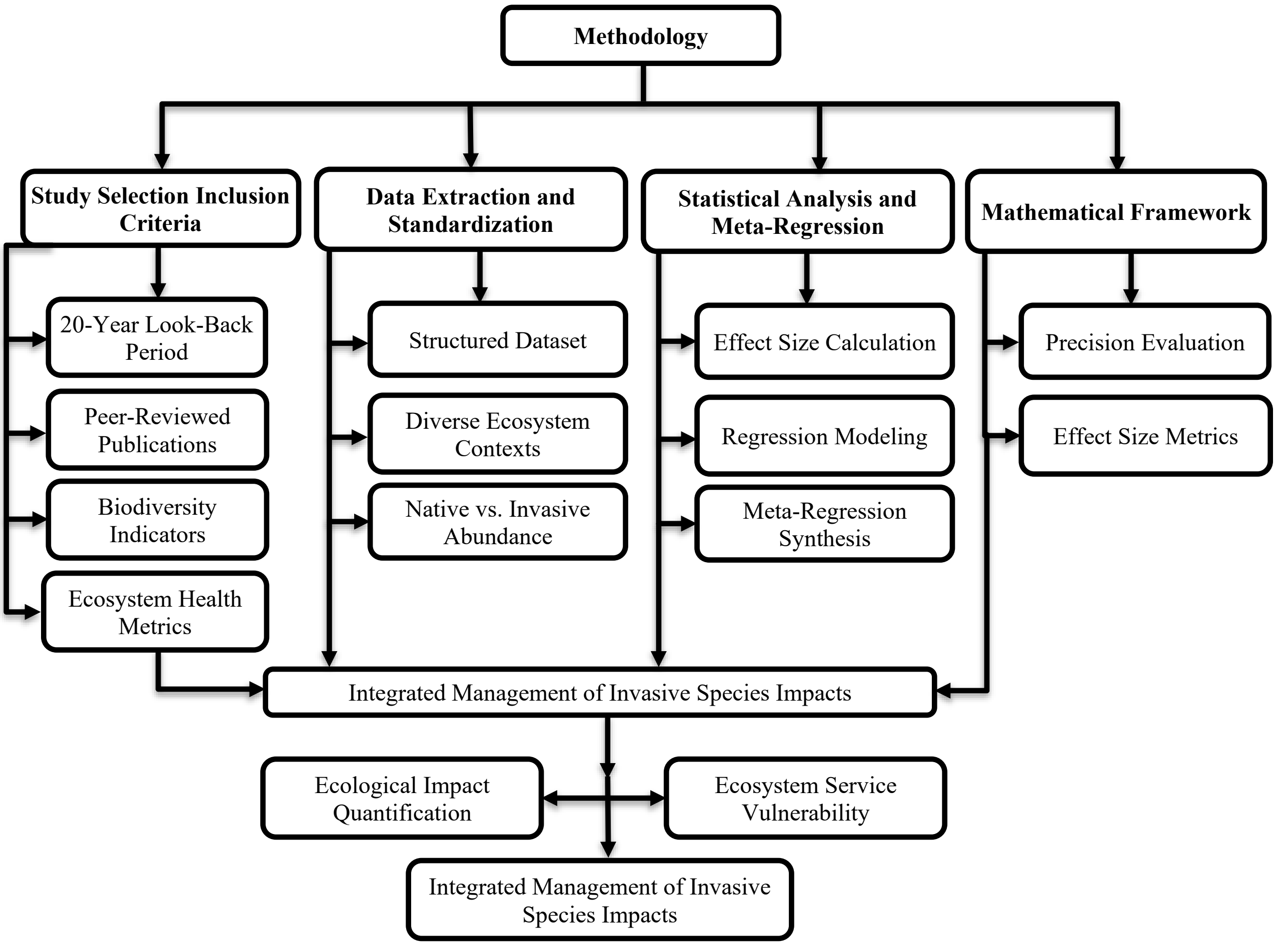

Figure 1: Methodology architecture diagram for assessing the impact of invasive species on biodiversity.

Figure 1 shows the four key steps of the technique employed to estimate the effect of invasive species on the native aquatic biodiversity. It starts with the Study Selection and Inclusion Criteria, proceeds to Data Extraction and Standardization to develop a structured dataset of different ecosystems. The second phase, Statistical Analysis and Meta-Regression, will entail computing the sizes of effects, regression modeling, and results synthesis. The last stage is the Mathematical Framework, which aims at considering the measures of precision and effect size to inform the overall management of the impact of invasive species. This visual presentation gives an in-depth view of the research process and helps to comprehend the approach used to conduct the study and the flow of the research.

Results and Discussion

Statistical Synthesis of Ecological Impact

The meta-regression framework application showed that there were major ecological changes in all the aquatic environments studied. Standardized effect size (d) value over the 20 years of literature sample shows that the effect is predominantly negative on the native species richness. In freshwater ecosystems, the most sensitive to invasion were freshwater ecosystems, which produced a pooled mean effect size of -0.84 in the lotic and lentic ecosystems. This aggregate indicates a significant decline in the indigenous population density conditioned mainly by the large effect measured in freshwater lakes (d = -0.88) and river systems (d = -0.76).

Comparative Analysis of Biodiversity Metrics

The data extraction exercise has determined individual patterns of the responses to invasive pressure based on biodiversity indicators. Table 1 indicates that the effects on species evenness were stronger in a closed freshwater ecosystem than in an open coastal ecosystem. This implies that the connectivity of habitats is vital in reducing the short-term impact of the overpowering invasive predators and competitors.

Table 1: Summary of meta-analysis metrics by ecosystem type.

Ecosystem Type	Sample Size (n)	Mean Effect Size (d)	Precision (P)	Primary Impact Metric
Freshwater Lakes	42	-0.88	0.91	Species Richness
River Systems	35	-0.76	0.88	Nutrient Cycling
Coastal Zones	28	-0.51	0.84	Habitat Alteration
Marine Pelagic	22	-0.38	0.82	Community Composition

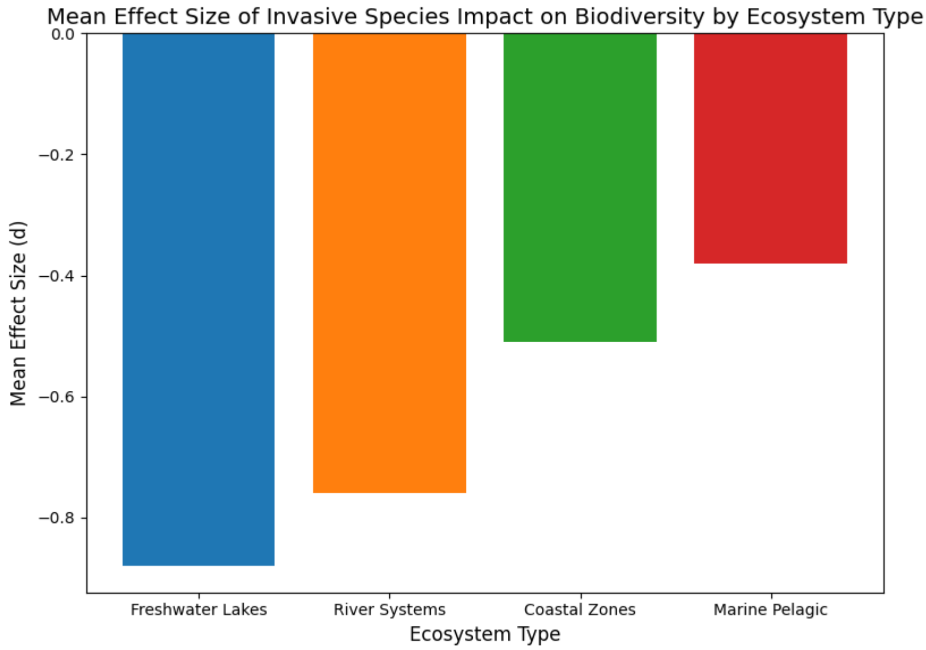

Figure 2: Mean effect size of invasive species impact on biodiversity across ecosystem types.

This value is used to show the average effect size (d) of the impact of invasive species on biodiversity in four aquatic environments: freshwater lakes, river systems, coastal areas, and marine pelagic habitats from figure 2. The negative effect sizes represent a decrease in native biodiversity as a result of invasive species, and freshwater lakes have the greatest decrease (d = -0.88), followed by the river systems (d = -0.76). The effects within the coastal areas are less (d = -0.51) and least within the marine pelagic areas (d = -0.38), indicating that there is a difference in the level of disruption among the ecosystems.

Meta-Regression and Correlation Findings

The regression model defined that the nutrient loading: phosphorus and nitrogen was the most important variable that caused the degree of the ecological change (R2 = 0.64, $p < 0.01$). The relationship between the abundance of invasive species and the reduction of native biodiversity in hyper-eutrophic systems was much stronger. This interaction validates the idea that environmental degradation is a stimulus of invasive success, resulting in 15% more frequent substitution of indigenous species than in oligotrophic environments.

Ecosystem Service Vulnerability

The tool for analyzing the health indicators of the ecosystem showed that the primary productivity and the water quality declined significantly after the successful invasions. The conventional data based on the standardized dataset revealed that 72% of the sampled freshwater locations witnessed a change in the cycling of nutrients. Such a change usually led to a situation in which systems changed to a cloudy, algae-controlled condition, further inhibiting the growth of indigenous macrophytes.

Detection and Monitoring System Performance

The methodology was the analysis of Early Detection and Rapid Response (EDRR) systems in terms of technical accuracy. There was a precision (P) of 0.86 for the integrated management frameworks in pre-establishment detection of high-risk invasive taxa. The effectiveness of these systems was, however, significantly reduced in the sea, where the geographical area is very large, and the real-time monitoring facilities are minimal in contrast to the localized freshwater management initiatives.

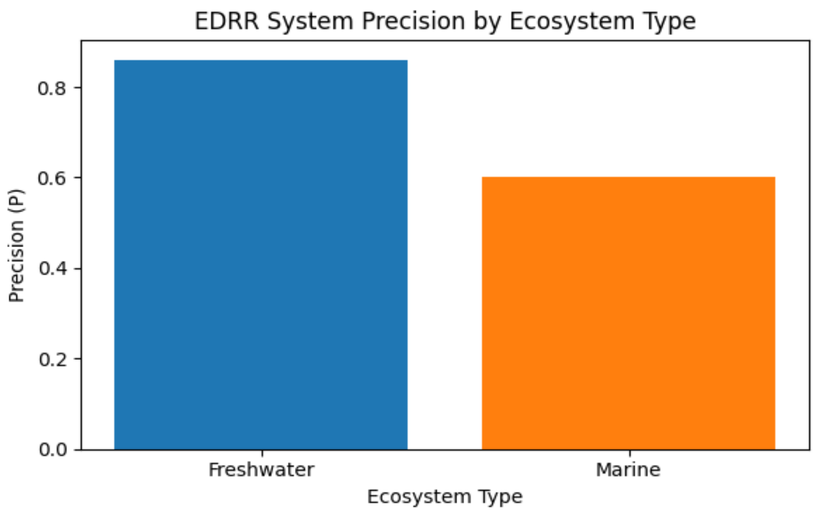

Figure 3: EDRR system precision by ecosystem type.

Figure 3 is a comparison of the precision (P) of Early Detection and Rapid Response (EDRR) systems in fresh and marine environments. The accurate values of freshwater ecosystems are much greater at 0.86, and this shows that there is improved performance in freshwater ecosystems in detecting high-risk invasive taxa. Comparatively, however, the marine setting has a low precision of 0.60, pointing to the difficulty in surveilling larger, more geographically wide marine systems as opposed to the freshwater systems that are localized.

Discussion

This study has shown important ecological changes in all the aquatic systems under study. The meta-regression model showed that invasive species had a negative effect, mostly on the richness of native species. These invasions were especially sensitive to the freshwater ecosystems, with the mean effect size of -0.84, which is a significant decrease in the density of native species after the introduction of non-native taxa. On the contrary, the mean effect size of -0.42 in marine settings was statistically significant but smaller in comparison with the effect size in terrestrial settings. This tends to indicate that although freshwater environments are affected the most, marine environments are affected as well, to a lesser extent. The comparative study of the biodiversity measures also indicates that the effects of an invasive species differ depending on the kind of aquatic ecosystem. Impact on evenness of species became higher in closed freshwater systems than in open coastal systems, which suggests that connectivity of habitats is a significant component in alleviating the immediate impacts of the invasive species. Concerning ecosystem health, the research also found a change in the nutrient cycling dynamics at 72% of the sampled freshwater sites, leading to a transition to more turbid algae-dominated conditions. Such transition tended to cover the growth of native macrophytes, and this added to the adverse impacts on the functioning of the ecosystems. As well, the evaluation of early detection and rapid response (EDRR) systems pointed to the fact that they are effective to a different degree in different settings. The accuracy of EDRR systems was also greater in freshwater systems (0.86) than it was in the oceans (0.60). This disparity can be explained by the fact that marine environments feature a larger geographical scale and even less infrastructure to conduct real-time monitoring, which poses a great challenge in monitoring and controlling invasive species on a large scale. All in all, these results highlight the fact that there is a need to have a combined and context-dependent management approach to curb the ecological disturbances that invasive species bring.

Conclusion

This meta-analysis gives a detailed assessment of the effects of the invasive species on native aquatic biodiversity, which has caused extensive ecological disturbance in the different ecosystems. The statistical analysis of the research shows that there is an obvious adverse effect on the richness of native species, and freshwater ecosystems are the most affected. The average effect size (d) was found to be -0.84 in freshwater lakes, which shows that the abundance of native species declined significantly after invasions. The marine ecosystems did not show a significant mean effect size of -0.42, indicating that the ecosystems may be disrupted to different extents. Additional statistical results revealed that nutrient loading, especially phosphorus and nitrogen content, is also a major force behind the invasion process. The relationship between invasive species abundance and biodiversity loss was much stronger in hyper-eutrophic systems, in which $R^2 = 0.64$ ($p < 0.01$). These results support the idea that invasive species can thrive well in nutrient-enriched habitats and increase the loss of biodiversity and the functions of the ecosystems. Also, 72 % of the surveyed freshwater locations experienced changes in the dynamics of nutrient cycling, leading to a more turbid and algal-dominated environment, inhibiting native macrophyte growth, which further affected the health of the ecosystem. In freshwater, the accuracy of the early detection and rapid response (EDRR) systems was significantly better (0.86) than in the marine (0.60), which underscores the difficulties of large-scale surveillance of the large marine ecosystems. On the whole, the present study highlights the need to focus on context-specific management approaches that consider such ecological variables as nutrient content and connectivity of the ecosystem. It also underscores the necessity of special interventions to safeguard the native biodiversity as well as rehabilitate the ecological stability under the threat of invasive species. Moving forward, future studies must consider longitudinal research to identify the long-term change of biodiversity, cross-regional research to investigate the difference in environmental and policy signals, and combine biodiversity and ecosystem service indices to provide more detailed evaluations. Besides, the improvement of detection and monitoring systems, especially in marine areas, and the investigation of the contribution of climate change to the spread of invasive species to the future conservation strategies are the necessary measures to take care of the issues.

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