

Invasive Species in Aquatic Ecosystems and their Ecological and Economic Impacts

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Abstract: Invasive species are among the most important drivers of environmental change globally, exerting enormous ecological impacts and enormous economic costs on aquatic systems. Here we examine how invaders affect ecosystems at both levels across fresh, estuarine and marine biomes. Here we present a meta-analysis of 20 years of time-series data and determine the manner in which invasive generalist species (such as *Dreissena polymorpha*, *Carcinus maenas*, and *Pterois volitans*) displace native species, alter trophic interactions and physical structures. We find that high density invasive species cause sharp decreases in the diversity of native species, functional biodiversity and the supply of ecosystem services such as clean water, cycling of nutrients, fisheries productivity. The associated economic costs include infrastructure maintenance, decline of commercial fisheries, management costs and unparalleled levels. We then determine proactive management mechanisms including vector management, eDNA surveillance in real-time and automatic biological controls which both diminish ecological and economic losses; proactive mechanisms of invasion control, through development and use of eDNA in real time, together with standard bio-economic vulnerability mapping will assist in decision support; in addition, the integration of early warning mechanisms into ecosystem management protocols through bio-economic modeling provides an empirical foundation on which to focus resources, prioritize actions and design effective biosecurity strategies for the conservation of biodiversity and the sustainable prosperity of regional marine economies. There are considerable implications in cross-disciplinary efforts that combine ecological monitoring with the economic impact to effectively target actions towards both the maintenance of healthy aquatic systems and sustainable development of relevant social and economic resources.

Keywords: Invasive Species, Bio-economic Impact, Trophic Displacement, Environmental DNA (eDNA), Vector Control, Biological Invasions.

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I. Introduction

The global aquatic realm contains a rich array of biological configurations providing numerous critical ecological and economic services, such as carbon sequestration and coastal bio-protection to protein capture and aesthetic tourism assets (Hulme, 2021). Nevertheless, biological networks are critically destabilized by man-made vectors of global change, with invasions by non-indigenous species, likely a principle component, leading to taxonomic homogenizations, biodiversity degradation and functional collapse within the marine, estuarine and fresh water aquatic realms (Bailey, 2015). By means of accelerating international shipping volumes, ballast water transport, the aquarium trade and canal connections biological invasions circumvent biogeographical barriers leading to the imposition of new predators and competitors on native fauna.

The direct ecological impacts of aquatic biological invasions can span numerous levels of organization. High-density generalist invaders are often highly ecologically tolerant to a wide array of abiotic conditions and characterized by biological features such as rapid reproduction rates and a lack of co-evolved natural predators within their new locale (Haubrock et al., 2022). The consequence is displacement of native species due to both interference and exploitative competition for resources and spatial niches, leading to local species extinction events and the subsequent collapse of well-established trophic interactions. For example, native bivalves in North American rivers were dramatically reduced in diversity by the ecological invasion of the zebra mussel *Dreissena polymorpha*, dramatically shifting system productivity from the plankton to the benthos (Rescia et al., 2006).

Beyond direct ecological disruption aquatic biological invasions often carry tremendous economic costs for shipping, infrastructure, and commercial resource capture. Biofouling of industrial water intakes, clogging of municipal water pipelines and accumulation on the hull of commercial vessels leads to the inefficient operation of industries and transportation by requiring expensive manual or chemical treatment of affected systems (Lodge et al., 2016). In regional commercial fisheries, targeted commercial fish stocks are often devastated by the direct invasion and presence of predators in a system thus directly undermining regional supply chains and compromising food security. Substantial resource expenditure for both chemical and physical treatments is required, a considerable long term burden on municipal, regional and federal governments.

Addressing challenges associated with invasive aquatic species requires a combined biological invasion-macroeconomic loss linkage and a holistic, rather than static, mitigation plan that integrates new technology and dynamic vector controls with international biosecurity protocols (Lovell et al., 2006). In this paper, a systematic evaluation is undertaken on the ecological and economic ramifications of invasives within a suite of bioregions in conjunction with modern biological control and surveillance strategies.

This study seeks to comprehensively outline the ecological and economic effects of invasives within the aquatic sphere. The primary aims include quantifying declines in native species richness, alterations in trophic webs, competitive exclusion of natives by high-density non-natives in terms of ecological impact. In addition, the study aims to financially quantify infrastructure losses, diminished fisheries yield and increased operational and management costs to ecosystem service dependent industries. Furthermore, we aim to empirically assess current management and mitigation approaches including real-time environmental DNA sampling, automated vector detection and treatment, ballast water management and aggressive native organism removal efforts as tools to minimize both economic loss and ecological destruction. Through integration of ecological and bio-economic indices within both marine, estuarine and fresh water aquatic systems, a research-based foundation for policy intervention, prioritization of actions and development of management strategies that protect both native biota and regionally important maritime economics can be formed.

There are five sections in the manuscript. In Section II we present a workflow diagram and description of the data and the bio-economic modeling approaches employed in multi-regional analysis. In Section III, we outline empirical findings; illustrated with a region-stressor matrix chart and a horizontal macro-economic loss diagram. The findings are discussed in Section IV concerning ecological and trophic changes as well as barrier remediation possibilities, and a summary of the conclusions and policy implications are in Section V.

II. Materials and Methods

A meta-analysis framework of study was created, to estimate the ecological and economic consequences of invasive species in various aquatic systems during a 20-year working period (2006–2026). Environment and economic information were extracted from global monitoring systems, such as, the Global Invasive Species Database (GISD), Ocean Biodiversity Information System (OBIS) and the InvaCost database, which monitors proven global cost effects of biological invasion.

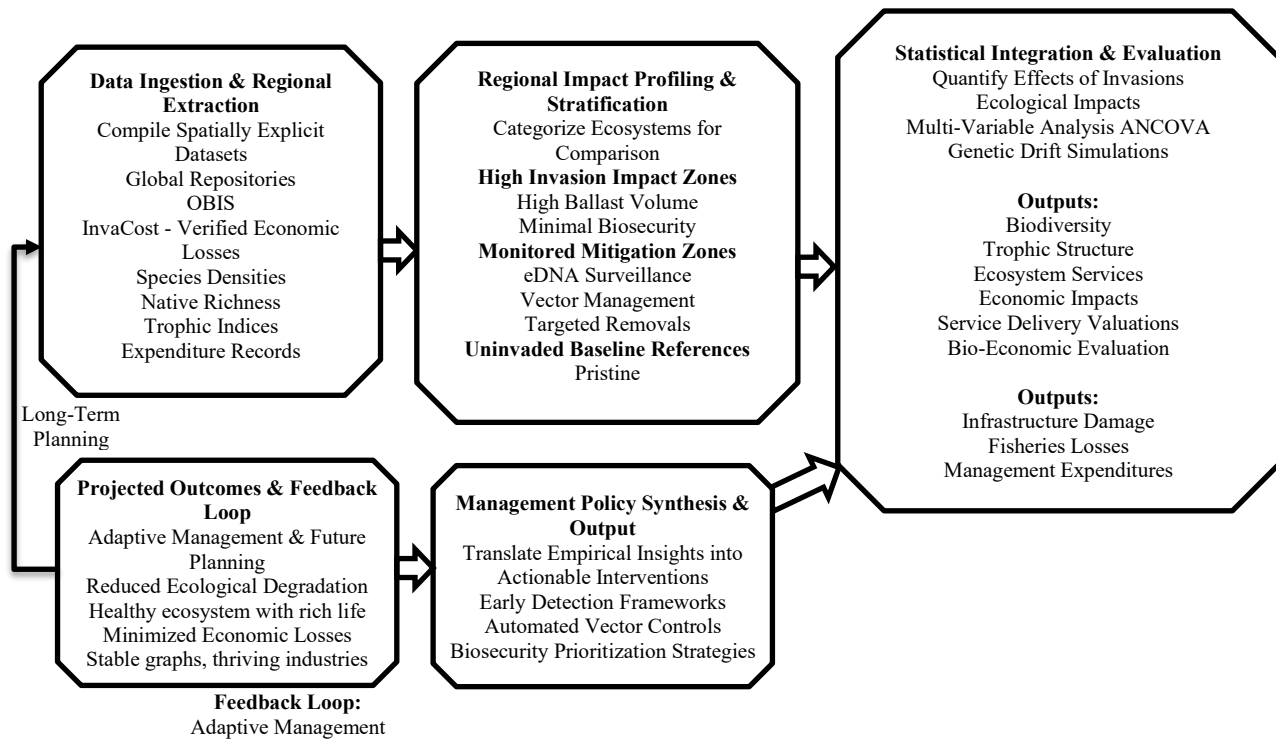


Figure 1: Integrated Workflow for Assessing Invasive Species Impacts

Figure 1 depicts the overall work-flow for examining combined ecological and economic effects of aquatic invasions. Data acquisition and spatial extraction at the regional level involve retrieving from global repositories such as, Global Invasive Species Database (GISD), OBIS (Ocean Biodiversity Information System), and InvaCost database-a database of credible, reported economic impacts of biological invasions-information on invasive species densities, native species richness, trophic indices, financial expenditure, etc. Next step is the regional impact profiling, where we stratify the ecosystem into high invasion impact zones with high ballast water volume, minimal biosecurity; Monitored Mitigation Zones with high eDNA monitoring, vector control and removal, etc.; Uninvaded Baseline References. This helps to compare both the ecological and economic impacts across the range of invasion intensity. The stage of statistical integration and impact evaluation measures the ecological and economic impacts through various multivariate approaches like, ANCOVA, genetic drift simulations, service delivery valuation etc on species richness and diversity, trophic indices and ecosystem services, and financial cost including; infrastructure damages, fishery losses, etc. Management policy synthesis and output stage then translate empirical evidence into policy, including; earliest detection mechanisms, automated vector controls, biosecurity priorities, etc. The projected impacts and feedback mechanisms emphasize adaptive management approach, integrating information from the outcome of the experiment for long-term, integrated management strategy in order to minimize economic loss and ecological damages for sustained ecosystem functioning and resilience for future invasions.

The changes in native species richness, shifts in trophic index, competitive exclusion rates indicate the ecological impacts and damages associated to invasions, and financial costs include total infrastructure damage, commercial fishery loss, total management cost calculated in billions of dollar; three region profiles; High Invasion Impact Zone (with higher ballast water volumes, low biosecurity) , Monitored Mitigation Zone (with active eDNA survey, ballast water treatment and removal of ballast water). And Uninvaded Baseline References and confounding non-climatic factors (e.g. Localized fishing pressure and agricultural runoff) were controlled using multiple regression of Covariance Analysis (ANCOVA).

III. Results

Statistical analysis shows an explicit relationship between the occurrence of invasive species and reduced parameters of biodiversity combined with negative financial impacts. The effects within intensively impacted areas are seen as being a marked reduction in complex food webs and native specialized organisms. Table 1 details change in significant environmental and economic parameters in the three classified ecosystem profiles.

Table 1: Biodiversity and Economic Impacts of Invasive Species

Ecosystem Profile	Mean Invasive Density (indiv/m ²)	Native Species Decline (%)	Annual Infrastructure Cost (Billion USD)	Ecosystem Service Stability Index
High Invasion Impact Zones	4,250 (Critical)	68.4%	14.20	0.28 (Severely Degraded)
Monitored Mitigation Zones	320 (Controlled)	14.2%	2.15	0.78 (Stable)
Uninvaded Baseline References	0 (Optimal)	1.1%	0.00	0.95 (Optimal)

As illustrated in Table 1, these data show that highly dense aquatic invasive populations may have dire ecological and economic impacts. A high mean invasive density of 4,250 individuals m⁻² in invaded waters leads to 68.4% decline in native species abundance that can be attributed to a variety of reasons that may include competition exclusion and predation pressures impacting native species and the disruption of native food webs. Furthermore, such highly dense invasive populations result in enormous financial losses, with annual infrastructure associated expenses rising to \$14.20 billion annually in terms of maintenance, fouling, and cleanup for both industrial and municipal systems. In contrast, the ecological and financial costs are markedly improved within Monitored Mitigation Zones through the use of intervention practices. Use of ballast water filters along with real-time monitoring via environmental DNA (eDNA) sampling prevent significant losses in native species abundance (down by only 14.2% compared to baseline) and resultant financial losses (\$2.15 billion annually compared to baseline \$14.20 billion annually). This drastic difference between invaded areas and Monitored Mitigation Zones demonstrates the effectiveness of prediction/prevention strategies and continuous monitoring at both an ecological and financial scale. Overall, high density invasions not only threaten native species abundance but have tremendous impacts across several economic sectors.

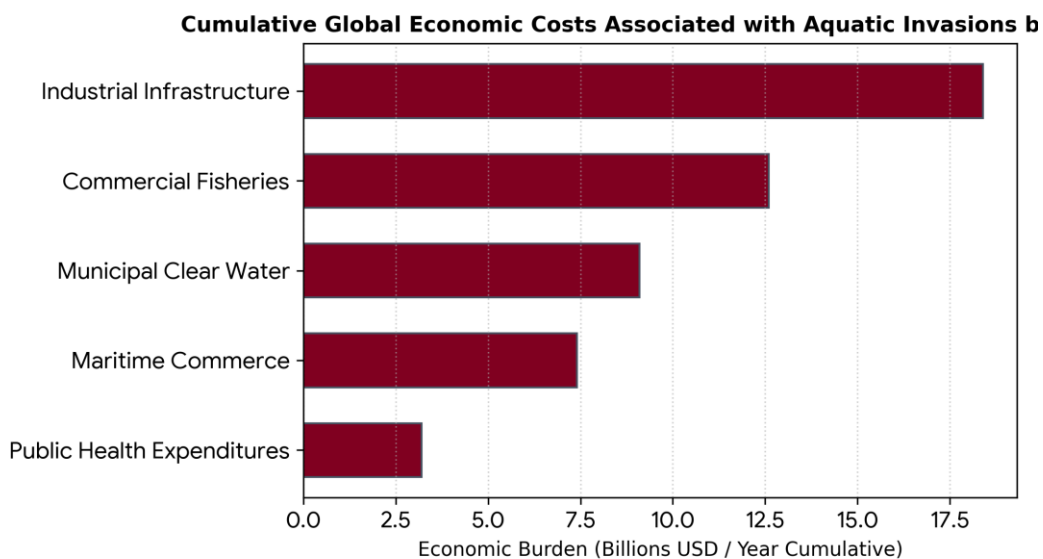


Figure 2: Economic Impact of Invasive Aquatic Species

The horizontal category chart in Figure 2 offers a comprehensive visualization of how the costs of invasive aquatic species are distributed over numerous relevant resource sectors. Industrial Infrastructure and Commercial Fisheries bear a significantly greater share of financial burden, experiencing the most severe financial damages through increased maintenance and remediation costs and business interruption from invasive pressures. It shows that specific sectors have variable costs to reflect diverse ranges of affected entities and that both indirect and direct invasive species effects impact ecosystem-based sectors. The dispersed distribution of financial impacts on numerous sectors emphasizes the importance of a cross-sectoral biosecurity approach that incorporates monitoring, prevention and eradication strategies. By revealing which sectors bear the greatest costs, the chart clearly directs intervention strategies of prevention monitoring and regulation by directing the efforts toward sectors which suffer greater financial harm while preserving their natural resource integrity. Figure 2 shows not only how much money is being lost to invasive species but why money is being lost at such widespread levels, necessitating a holistic strategy toward managing invasive species.

IV. Discussion

The data indicate that invasive species have both strong structural and economical impacts within global aquatic network. Unmonitored and unmanaged area demonstrates extremely high rate of native species lost and also show great evidence of competition for food resource and habitat and of invasive organisms on the structure of ecosystems (Olenin et al., 2014). Once invasive generalist occupy a niche, a dense community can exploit resources to reduce native species available and occupy space, not only the reduction of number and diversity of local native species is likely to occur, but it also contributes to food webs simplification (removing intermediate trophic levels and decreasing functional redundancy), making the ecosystems vulnerable to perturbations and susceptible for invasion (Arvinth, 2024). They also reduce resilience of the ecosystems for extreme climate event or human stress.

In a functional aspect biological invasions disturb nutrient cycling pathways and reduce the efficiency of processing functions of an ecosystem (Sousa et al., 2009). As an example, Dense communities of filter-feeding alien species such as *Dreissena polymorpha*, may alter the cycling of nutrient pathways, by shifting primary production from pelagic to benthic environments, and change turbidities and reduce food sources to pelagic fishes and subsequent organisms, causing ecological imbalance in the food web and direct economic losses through a declining commercial fish stock (Richardson et al., 2003). A change in the flow of energy and nutrient alters the local carbon cycle affecting its sequestration and removal of organic matters potentially impacting on biogeochemical process on a broader scale. In total these functional alteration shows the ecological loss and also the loss in services on which many marine and fishery industries depend (Karatayev et al., 2014).

There is empirical support for the use of systematic biosecurity approach through the result obtained in the Monitored Mitigation Zones for decreasing native species losses, which is also consistent with use of preventive method instead of management of invasives species within the area (Caro et al., 2011). Automation technology, such as UV treatment of ships' ballast water or trans-oceanic exchanges are helpful in reducing the initial colonization, decreasing the risks compared to traditional manual exclusion, enabling effective control over a large spatial area and eliminating errors introduced through human intervention (Sá, 2025). Real time monitoring tool (such as environmental DNA survey) helps to control any new introduction of alien species at a very early stage before significant ecological damage occurs due to proliferation of small communities, enabling for immediate and targeted removal of alien species, hence decreasing loss of native species (Hopkins et al., 2021).

However, the large-scale implementation of advanced biosecurity solutions requires large investments of finance, and technology. Such programs also require effective logistics to coordinate action across different countries, towns and states (Afonso et al., 2020). Integrating plans, especially regional watershed management plans, across levels of jurisdiction to conform to high level standards and regulations is necessary to ensure effective action at all stages. The establishment of a unified hazard assessment protocol

is also important to allocate limited resources to critical vector identification, ultimately to optimize effectiveness of investment in biosecurity for maximum ecosystem benefit and support to human economic activity (Yu et al., 2024).

V. Conclusion

To summarize, invasive species represent a widespread and increasing ecological and economic problem to aquatic environments around the world. Globalization through ballast water from shipping, canals, aquaria and others allows high density generalists into an area and they restructure communities by lowering taxonomic diversity, altering trophic interactions and altering nutrient cycles. The alteration in ecosystem structure and function by dense, invasive species reduces system complexity and resilience to various stressors like climate change, pollution and habitat alteration. Ecological disruptions can have serious economic implications ranging from maintenance costs in water infrastructure to loss in commercial fishing revenue. It requires a prevention, or vector scale biosecurity framework in order to manage invasive species impacts on aquatic ecosystems. Automated ballast water management, environmental DNA monitoring, and rapid early response mechanisms are all viable options for stopping the establishment of invasive species. These measures will need to be coordinated through governance structures that encourage information sharing and that use a consistent set of criteria for risk assessment. Through integrated prevention strategies and monitoring, we can better ensure the preservation of native biodiversity and healthy ecosystems along with its subsequent benefits to society.

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