

Ecological Impacts of Invasive Species in Aquatic Ecosystems and Management Strategies

^{1*} Hamid Nouri, Iran Future Innovation Development Centre, Isfahan, Iran.

² Leila Mohammadi, Iran Future Innovation Development Centre, Isfahan, Iran.

Abstract: The world's oceans, lakes, rivers, and wetlands (collectively known as aquatic ecosystems) are in a dire state of crisis due to the widespread introduction of non-native aquatic organisms (known as invasive aquatic species, or IAS) by humans. IAS are causing ecological disruption to naturally occurring habitats and food web (trophic) disruption or cascade effects. IAS are being introduced to these ecosystems through multiple anthropogenic means; such as through the global expansion of international commerce, ornamental fish trade, or expansion of native ranges due to climate change. This review presents an overview of the various ecological effects IAS have on different types of aquatic systems through examples from various aquatic ecosystems. *Pterois volitans*, *Dreissena polymorpha*, and *Eichhornia crassipes* Native flora and fauna can compete for resources in the environment, which could lead to degraded water quality and significant monetary losses for tourism and commercial fishing. To counter these biological threats, it proposes the use of IPM as a multi-layered management strategy focusing primarily on preventing the introduction of these species through early detection using advanced technologies such as eDNA (Environmental DNA) and targeted physical/chemical/biological controls. Successful management of these types of species will require a transition from a strategy based on passive removal (eradication) to one based on active restoration of ecosystems over the long term in order to decrease opportunities for re-invasion and improve resiliency to future invasions. Additionally, it outlines significant challenges that inhibit effective management, including high costs associated with implementation; lack of international cooperation among countries/regions, and complications arising from Climate Change. Taken as a whole, these indicate an urgent need for proactive science-based transboundary policy initiatives to ensure the sustainability and productivity of aquatic ecosystems globally in light of increasing threats posed by biological invasives.

Keywords: Invasive Aquatic Species; Biodiversity Loss; Trophic Cascades; Environmental DNA; Integrated Pest Management; Ecosystem Restoration; Climate-Driven Invasion.

(Submitted: January 03, 2025; Revised: February 04, 2025; Accepted: February 21, 2025; Published: March 31, 2025)

I. Introduction

Aquatic ecosystems, including fresh and saltwater systems, are the foundation for all global biodiversity and many ecological services (Thomsen et al., 2011; Britton, 2023). Various invasive aquatic species (also known as invasive species or "IAS") are now being transported between aquatic ecosystems, which threatens the overall integrity of aquatic ecosystems and the native plant and animal communities within them (Karatayev et al., 2009; Thomaz et al., 2015). "IAS" are organisms that are not naturally found in an ecosystem, and when they become established in their new home, they adversely affect the ecosystem, economy, and/or human health (Leprieur et al., 2008). Distinguishing IAS from species that occur naturally in an ecosystem is that these organisms reproduce quickly, can possess phenotypic plasticity, and thrive in disturbed environments, enabling them to overcome natural barriers to disperse, and thus place extreme stress on native plants and animals.

Aquatic bio-invaders have become a serious worldwide issue, primarily due to an increasing number of anthropogenic pressures on aquatic ecosystems (Rajan, 2025; Havel et al., 2015). The most significant vector is international shipping, especially the discharge of ballast water and hull fouling, which allows for the transoceanic movement of non-native organisms and thus erodes the natural separation between marine basins. In addition, many non-native species are being introduced into degraded natural ecosystems through the global pet, aquarium trade, and live bait trades due to intentional releases and accidental escapes. These vectors are being exacerbated by climate change, because water temperatures are rising, changes to flow patterns, and other habitat changes are creating "invasion windows" that allow for non-native species that

can tolerate warmer waters to expand their distributions into higher latitudes, and habitat degradation (e.g., eutrophication) is undermining the ability of native species to outcompete IAS.

Objective

This article has focused on the ecological dangers associated with aquatic invasive species. This study will:

- Identify how invasive species alter community structure; initiate trophic cascades; and degrade vital ecosystem services in aquatic ecosystems.
- Evaluate and classify current mitigation strategies, focusing on reactive eradication methods in comparison to proactive, scientifically based management techniques.
- Create an organized framework for future conservation initiatives that emphasize the use of novel monitoring technology, transnational cooperation in policy, and long-term ecosystem restoration.

The format for this paper will include the following sections: Section 1 is the introduction which describes the drivers, goals and scope of IAS-related research; Section 2 is the ecological impacts of IAS which explain how IAS affect biodiversity, community structure, trophic cascades and ecosystem service(s) of the affected areas; Section 3 is the management strategy section which discusses preventing IAS, early detection methods (e.g., eDNA), controlling/removing IAS and restoring ecosystems as part of an integrated management strategy; Section 4 is the discussion/future outlook that discusses operational, financial and climatological issues involved in managing IAS while considering policy implications; and Section 5 consists of the conclusion which describes the need for science-based transboundary measures to protect aquatic biodiversity and the functional integrity of aquatic ecosystems. Figures and tables will provide supplementary information supporting the key points made regarding cascading effects and links between the density of IAS and degradation of ecosystem service(s).

II. Ecological Impacts

Biodiversity and Community Structure

Invasive species significantly alter the makeup of local ecosystems by outcompeting native species for key resources (e.g., food, breeding sites, and sunlight). This is usually a result of these communities not having to cope with the same number of natural enemies and being able to outcompete indigenous organisms for available resources; this phenomenon is sometimes attributed to what is referred to as the “enemy release hypothesis.” The result is an absence of predation or parasitism, allowing the establishment of an abundance of invasive species (e.g. the proliferation of the Lionfish (*Pterois volitans*) in both the Western Atlantic and Caribbean, the rapid colonization of reefs by species such as groupers and snappers through predation of prey has led to a severe reduction of the diversity of reef fish, as well as an effective takeover of the ecological niche of top-tier predators.

In this figure 1 shows the primary routes by which the aquatic invasive species are swapping out other ecosystems. On the left side is the “Pre-Invasion Stable State.” The middle sections depict three (i.e., A: biodiversity/community structure, B: Trophic cascades, C: Ecosystem services/socioeconomic) scales of biology through which organisms (invasives) take over and create a degrading state for each other from the invasion mechanism. Lines provide directional impacts, and feedback loops define degradation. Some specific illustrative examples are Lionfish. (*Pterois volitans*) (A), Zebra Mussels (*Dreissena polymorpha*) (B), and Water Hyacinth (*Eichhornia crassipes*).

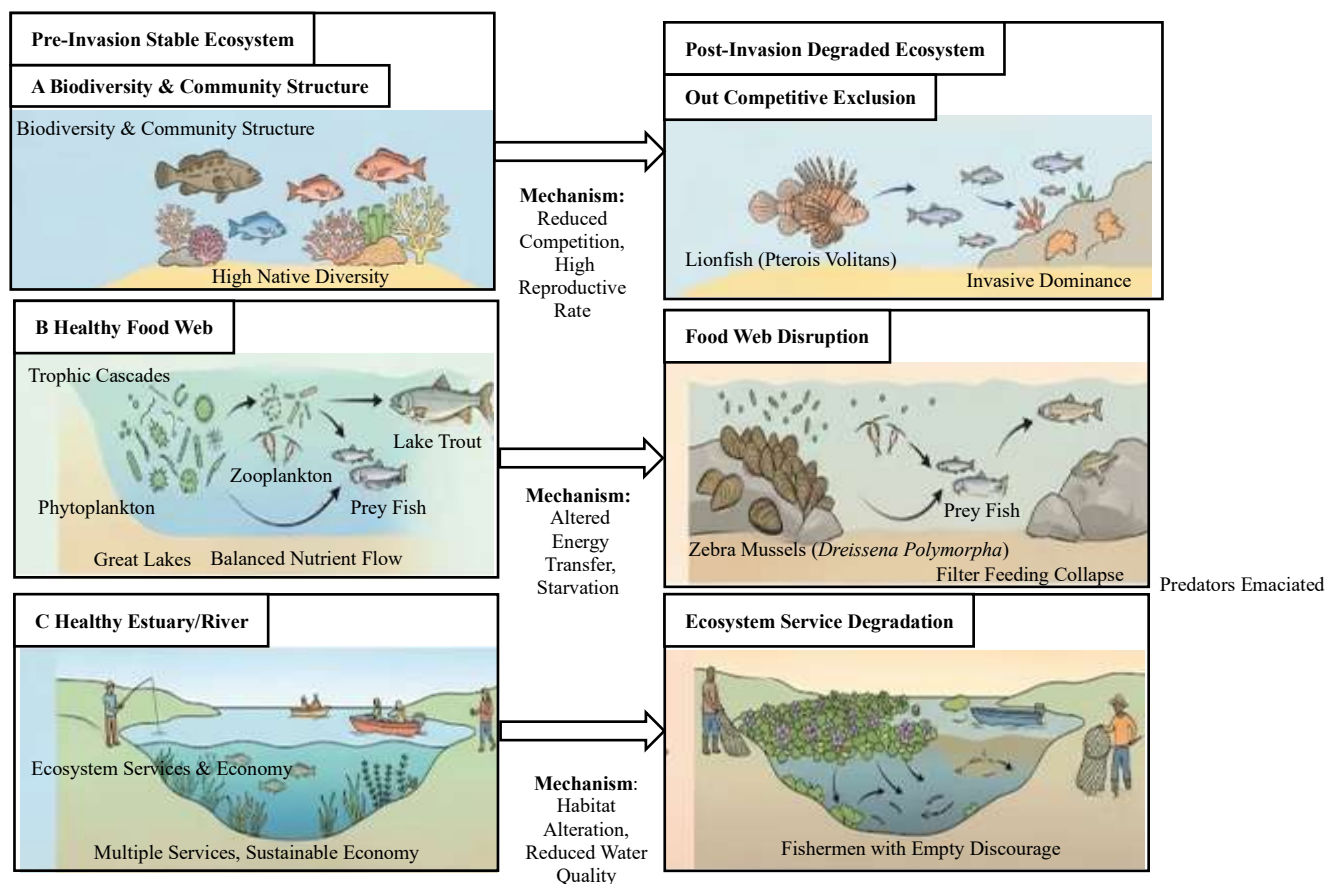


Figure 1: The Cascading Ecological Impacts of Aquatic Invasive Species

Trophic Cascades and Food Web Disruption

The introduction of invasive species usually results in either a bottom-up or a top-down trophic cascade, which often destabilizes food webs. The introduction of an invasive predator may create an unsustainable level of predation pressure on primary or keystone consumers, resulting in the population of those consumers collapsing and affecting the entire ecosystem downstream of those consumers. This can be seen very dramatically in the Great Lakes region of North America. One example of this is the invasion of the Zebra Mussel (*Dreissena polymorpha*). They have diverted nutrient flow from native fish species by filtering huge amounts of phytoplankton (the foundation of the aquatic food web), resulting in less recruitment of commercially important fish populations and reducing energy transfer efficiency throughout the entire lake ecosystem.

Impact on Ecosystem Services and Socioeconomics

Invasive species negatively affect ecosystem services and have an associated economic impact on activities like commercial fishing, aquaculture, and tourism. Moreover, they can also change the chemical composition of the waters they invade by changing turbidity or causing hypoxic conditions, resulting in poorer quality water and less productive populations of native fishes. An example is the spread of the Water Hyacinth (*Eichhornia crassipes*). In a variety of freshwater systems in tropical areas have developed into thick grassy masses that block out light to the aquatic plants and limit the amount of oxygen available, as well as impede navigation, destroy artisanal fishing operations, and decrease tourism, thus directly hurting the individuals who depend on those healthy and thriving waters for their livelihoods.

III. Management Strategies

Prevention and Early Detection

Cost-effectiveness and environmental soundness are represented in prevention as an overall management plan; containment (of invasive species) before the establishment of sustainable populations should be the highest management priority. Thus, it need to ensure proper regulatory frameworks at the international level, such as following ballast water management convention regulations and using strict screening methods in the international live trade industry to prevent unintentional introduction of invasive species. The use of more advanced early detection tools and technologies, especially focusing on the use of eDNA (environmental DNA) monitoring of environmental samples to assist in quickly identifying non-native species (including their presence at low densities), along with targeted public awareness programs that provide local stakeholders and recreational users with the tools to take action to protect their ecosystems, are key components and provide the first line of defense against biological invasions through preventative measures.

Table 1: Impact of Invasive Species on Aquatic Ecosystem Functions and Socioeconomic Services

Invasive Species	Ecosystem Impact	Trophic Level Affected	Key Ecosystem Service Altered	Socioeconomic Effect
Pterois volitans (Lionfish)	Outcompetes native fish	Predator	Biodiversity, community structure	Decline in reef fish fisheries
Dreissena polymorpha (Zebra Mussel)	Alters nutrient flow	Primary consumer	Nutrient cycling, water filtration	Reduced commercial fish recruitment
Eichhornia crassipes (Water Hyacinth)	Blocks light & oxygen	Primary producer	Water quality, carbon sequestration	Navigation hindrance, tourism loss

In this table 1 report describes the various invasive species identified in the literature; their ecological impacts; impacts on different trophic levels; changes to ecosystem services; and associated socio-economic costs. It presents a concise summary comparison of all invasive species that identifies priority management intervention activities for each type of invasive species.

Control and Eradication Measures

When an invasive species has been detected and management is needed, there are a few options for controlling or eradicating those invasive species. The options for management will depend on the biology of the invasive species and whether the invasive species has been located at a vulnerable (or not susceptible) area. If the invasive species has been located within a localized area (for example, a lump fish or a vine), then removing those invasive species manually (for example, through harvesting) and/or removing those invasive species using mechanical methods (for example, through trapping) are still effective control methods, but this option is very labor-intensive. If the invasive species has been located in an isolated area of an ecosystem (for example, a single invasive tree), then using chemicals to control invasive species can sometimes be very effective; however, care must be taken to ensure that the use of chemicals to control an invasive species does not also have the unintended effect of killing or harming native species. Finally, establishing biological controls can also be used to help control invasive species long-term; however, the use of imported predators or pathogens as biological controls requires extensive testing to ensure that the introduction of a biological control will not result in additional invasive species being introduced to the area.

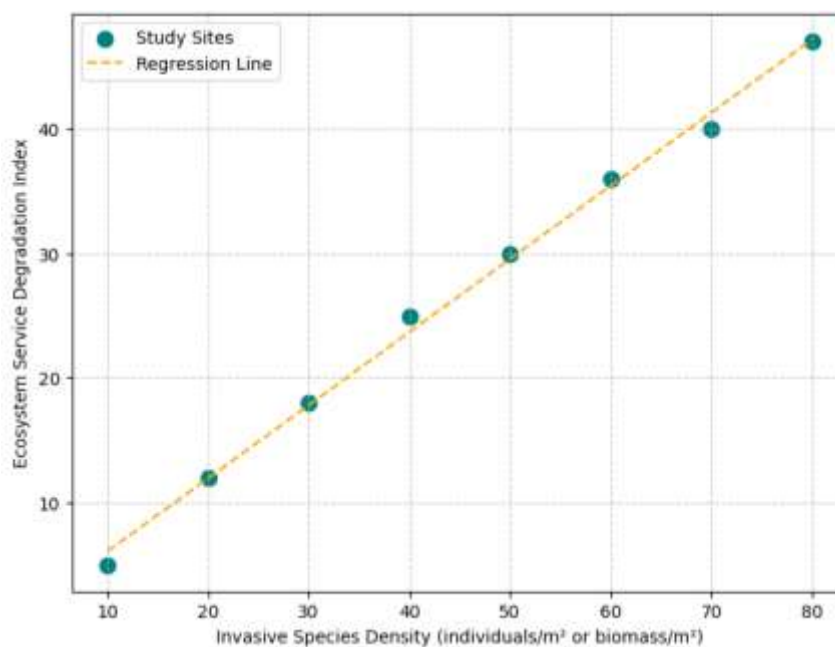


Figure 2: Correlation between Invasive Species Density and Ecosystem Service Degradation

In this figure 2 illustrates the positive link between the density of invasive species and the level of degradation of ecosystem services in impacted aquatic systems, indicating an urgency in controlling biological invasions from an ecological viewpoint.

Restoration and Integrated Management

Invasive species management can be effective over the long term only if it is accomplished through an Integrated Pest Management (IPM) approach that does not rely on a single control method, but instead, uses multiple synergistic and complementary methods to control invasive species in real time by monitoring the changes in the ecosystem. The simple removal of an invasive species may not be enough because it can create a niche vacuum (i.e., vacant ecological space) in which there is a risk of being reinvaded or being dominated by secondary invasive species. Therefore, the management of an invasive species must be followed by active restoration efforts within the ecosystem that include the re-establishment of native vegetation, re-enforcing populations of endemics, and restoring natural hydrological and/or nutrient cycling processes. By combining these approaches for the control of invasive species with longer-term science-based restoration efforts as part of an overall IPM strategy, management programs can go beyond temporary solutions and develop the long-term ecological resilience necessary to prevent future biological encroachment.

IV. Discussion and Future Outlook

Barriers to Effective Management

The challenges faced in managing invasive species are compounded by logistical and financial difficulties. Many aquatic habitats lack visibility, which creates difficulty in monitoring where an invasion starts or resumes when management efforts fail, and therefore makes it difficult to assess how successful the management effort was in controlling an aquatic (or similar) plant or animal. There has also been rapid recolonization in previously managed areas because of the extensive connectivity between various water bodies. Proactive management in comparison to reactive treatment options for controlling invasive plant and animal species has seen significantly fewer dollars spent on it than the costs associated with the remediation of existing infestations. Inconsistent reporting of data between countries and the lack of

collaborative coordination hampers any efforts that would help to create a unified approach to managing or controlling the presence of some types of aquatic invasive plant or animal species.

The Escalating Influence of Climate Change

The rise of global temperatures and top-to-bottom patterns of climate change, as well as extreme weather events (e.g., floods, droughts), are creating opportunities for invasive species to occupy previously unsuitable habitats by moving into areas that may have otherwise been uninhabitable before the introduction of invasive species (Ricciardi & Kipp, 2008; Poulin et al., 2011). The opportunity created by the rise of global temperatures due to climate change and extreme weather events creates an "opportunity window" by putting additional stress on native biota, which promotes the movement of invasive organisms. In addition, through interactions with climate change, invasive organisms may evolve resistance to current control technologies; for example, increasing atmospheric CO₂ may lead some invasive plants to become resistant to herbicides (Rilov et al., 2024; Strayer, 2010). In summary, the synergistic interaction between climate change and biological invasion holds the potential to increase the rate of loss of biodiversity and challenge the validity of existing conservation practices (Gallardo et al., 2016; Tricarico et al., 2016).

Policy Recommendations

Governments and environmental agencies need to adapt to these increasing risk factors by moving to a more proactive, scientifically proven policy framework. At the same time, improving current international and local standards for ballast water management should be given priority since shipping is still the main method for introducing new species. In order to stop new invasions before they can spread, agencies should work to build EDRR systems using new technology such as eDNA testing to find new species and restrict the spread of those species when they are first located. Lastly, more transboundary collaboration through policy is required; this includes 1. implementing joint plans for managing species that cross boundaries, and 2. providing funding sources to implement long-term ecological restoration instead of increasingly expensive and short-term reactive methods of restoration (Gutiérrez et al., 2014; Tasker et al., 2022).

V. Conclusion

The increasing threat from invasive freshwater species is a major conservation challenge worldwide, requiring a fundamentally different way it manage the water resources. In this synthesis, invasive species disrupt the native composition of species (community structure), create major trophic cascades, and negatively impact the ability of ecosystems to provide the essential services on which humans depend. The consequent socio-economic impacts on both fisheries and local economies are extensive. Current management is hindered by numerous barriers, which include high management costs, a lack of coordinated international approaches, and new invasions resulting from increased global climate change, which is further exacerbating the global ranges of non-native species and creating additional windows of opportunity for invasive organisms. Moving into the future, to address this crisis, it need to move from reactive, stand-alone eradication initiatives towards an Integrated Pest Management (IPM) approach that emphasizes maintaining ecological resilience over the long term. This new paradigm should include monitoring technologies, such as environmental DNA (eDNA) sampling, along with the establishment of comprehensive, cross-border policy frameworks for regulating primary pathways of introduction, such as through international shipping. For management efforts to succeed, there must also be restoration of the ecosystem resources, so that upon removal of invasive species, there is also a restoration of the native species and natural processes (nutrient cycling). Long-term preservation of aquatic biodiversity will require a proactive, science-based approach to both mitigating the impacts of biological invasions and preserving the long-term sustainable health and functional integrity of oceans and all other freshwater environments everywhere in the world. By utilizing a collaborative, evidence-informed approach to resolve issues related to the impacts of biological invasions on aquatic ecosystems, it can help protect and preserve these dynamic systems for the benefit of future generations.

References

- [1] Rajan, C. (2025). Influence of Invasive Species on Native Forest Regeneration and Ecological Stability. *National Journal of Forest Sustainability and Climate Change*, 2(1), 24-30.
- [2] Gallardo, B., Clavero, M., Sánchez, M. I., & Vilà, M. (2016). Global ecological impacts of invasive species in aquatic ecosystems. *Global change biology*, 22(1), 151-163.
<https://doi.org/10.1111/gcb.13004>
- [3] Thomsen, M. S., Olden, J. D., Wernberg, T., Griffin, J. N., & Silliman, B. R. (2011). A broad framework to organize and compare ecological invasion impacts. *Environmental research*, 111(7), 899-908. <https://doi.org/10.1016/j.envres.2011.05.024>
- [4] Karatayev, A. Y., Burlakova, L. E., Padilla, D. K., Mastitsky, S. E., & Olenin, S. (2009). Invaders are not a random selection of species. *Biological Invasions*, 11(9), 2009-2019.
<https://doi.org/10.1007/s10530-009-9498-0>
- [5] Havel, J. E., Kovalenko, K. E., Thomaz, S. M., Amalfitano, S., & Kats, L. B. (2015). Aquatic invasive species: challenges for the future. *Hydrobiologia*, 750(1), 147-170.
<https://doi.org/10.1007/s10750-014-2166-0>
- [6] Rilov, G., Canning-Clode, J., & Guy-Haim, T. (2024). Ecological impacts of invasive ecosystem engineers: A global perspective across terrestrial and aquatic systems. *Functional Ecology*, 38(1), 37-51. <https://doi.org/10.1111/1365-2435.14406>
- [7] Gutiérrez, J. L., Jones, C. G., & Sousa, R. (2014). Toward an integrated ecosystem perspective of invasive species impacts. *Acta Oecologica*, 54, 131-138.
<https://doi.org/10.1016/j.actao.2013.10.003>
- [8] Thomaz, S. M., Kovalenko, K. E., Havel, J. E., & Kats, L. B. (2015). Aquatic invasive species: general trends in the literature and introduction to the special issue. *Hydrobiologia*, 746(1), 1-12.
<https://doi.org/10.1007/s10750-014-2150-8>
- [9] Britton, J. R. (2023). Contemporary perspectives on the ecological impacts of invasive freshwater fishes. *Journal of Fish Biology*, 103(4), 752-764. <https://doi.org/10.1111/jfb.15240>
- [10] Ricciardi, A., & Kipp, R. (2008). Predicting the number of ecologically harmful exotic species in an aquatic system. *Diversity and Distributions*, 14(2), 374-380.
<https://doi.org/10.1111/j.1472-4642.2007.00451.x>
- [11] Poulin, R., Paterson, R. A., Townsend, C. R., Tompkins, D. M., & Kelly, D. W. (2011). Biological invasions and the dynamics of endemic diseases in freshwater ecosystems. *Freshwater Biology*, 56(4), 676-688. <https://doi.org/10.1111/j.1365-2427.2010.02425.x>
- [12] Tricarico, E., Junqueira, A. O., & Dudgeon, D. (2016). Alien species in aquatic environments: a selective comparison of coastal and inland waters in tropical and temperate latitudes. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26(5), 872-891.
<https://doi.org/10.1002/aqc.2711>
- [13] Tasker, S. J., Foggo, A., & Bilton, D. T. (2022). Quantifying the ecological impacts of alien aquatic macrophytes: A global meta-analysis of effects on fish, macroinvertebrate and macrophyte assemblages. *Freshwater Biology*, 67(11), 1847-1860. <https://doi.org/10.1111/fwb.13985>
- [14] Strayer, D. L. (2010). Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. *Freshwater biology*, 55, 152-174.
<https://doi.org/10.1111/j.1365-2427.2009.02380.x>
- [15] Leprieux, F., Beauchard, O., Blanchet, S., Oberdorff, T., & Brosse, S. (2008). Fish invasions in the world's river systems: when natural processes are blurred by human activities. *PLoS biology*, 6(2), e28. <https://doi.org/10.1371/journal.pbio.0060028>