

## Invasive Aquatic Species: Threats, Challenges, and Control Strategies

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### Abstract

Invasive aquatic species are a major ecological and economic threat to freshwater and marine ecosystems worldwide. These non-native organisms disrupt biodiversity, alter food webs, degrade water quality, and cause extensive financial damage to industries such as fisheries, tourism, and water infrastructure. Common pathways of introduction include ballast water discharge, the aquarium trade, aquaculture escapes, and climate-driven range expansions. As global temperatures rise, invasive species are spreading more rapidly, outcompeting native species, and intensifying environmental pressures. Effective management strategies—such as prevention, early detection, biological control, and habitat restoration—are essential in mitigating their impact. This article explores the ecological, economic, and societal consequences of aquatic invasive species and examines innovative strategies for controlling their spread. A coordinated global effort combining science, policy, and community engagement is necessary to curb future invasions and restore the balance of native aquatic ecosystems.

**Keywords:** Invasive species, Aquatic ecosystems, Climate change, Economic impact, Ecosystem

### 1. Introduction

Aquatic ecosystems are among the most delicate and biodiverse environments on Earth. They provide essential services, including water filtration, carbon sequestration, fishery resources, and recreational value. However, these ecosystems are increasingly threatened by the introduction of invasive species—organisms that are not native to a specific ecosystem and cause harm to the environment, economy, or human health (Gallardo et al., 2016). Invasive aquatic species alter food webs, disrupt nutrient cycling, and outcompete native species, leading to biodiversity loss. For example, the spread of zebra mussels (*Dreissena polymorpha*) in North America has drastically reduced native mussel populations and clogged water intake pipes, causing billions of dollars in damages (Moorhouse & Macdonald, 2015). Similarly, the introduction of *Myriophyllum aquaticum* (parrot feather) in freshwater ecosystems has led to oxygen depletion, making water bodies uninhabitable for native fish

(Kuehne et al., 2016). Understanding how invasive aquatic species enter new environments, establish dominance, and impact native ecosystems is crucial to formulating effective management strategies. This article provides a comprehensive analysis of the pathways, ecological effects, and control measures associated with invasive aquatic species, supported by extensive scientific research and case studies.

## 2. Pathways of Introduction and Establishment

Invasive aquatic species are introduced through multiple channels, both intentional and unintentional. The most common pathways include ballast water transport, aquaculture, aquarium trade, recreational activities, and climate change-driven range expansions.

### 2.1 Ballast Water and Shipping Routes

One of the largest contributors to aquatic invasions is global shipping. Ships take in ballast water for stability during travel, which often contains small organisms, including fish larvae, plankton, and mollusks. When this water is released at ports, non-native species can establish themselves in new environments (Cox, 2015). A classic example is the introduction of the zebra mussel (*Dreissena polymorpha*) to North America's Great Lakes in the 1980s. Native to Eastern Europe, zebra mussels spread rapidly, forming dense colonies that outcompeted native bivalves and clogged water intake pipes, costing industries millions in maintenance (Gallardo et al., 2016).

### 2.2 Aquaculture and Aquarium Trade

The aquaculture industry, which cultivates fish and shellfish for food production, has unintentionally introduced several invasive species. Some species were deliberately introduced to control algae or as food sources, but later escaped into the wild. For example, Asian carp (*Hypophthalmichthys molitrix*) was introduced to U.S. fish farms to control algae but soon spread to major rivers, where they outcompeted native fish for plankton, drastically altering aquatic food webs (Carey & Wahl, 2010). Similarly, the aquarium trade has contributed to biological invasions. Many pet owners release unwanted fish and plants into natural water bodies, often unaware of the ecological consequences. The lionfish (*Pterois volitans*), native to the Indo-Pacific, was introduced to the Caribbean and Atlantic through the aquarium trade. Without natural predators, lionfish populations exploded, devastating native reef fish populations and reducing biodiversity (Cox, 2015).

### 2.3 Recreational Activities and Fishing

Boats, fishing gear, and recreational equipment such as kayaks and paddleboards can act as carriers for invasive species. If not properly cleaned, they transport species like zebra mussels and Eurasian watermilfoil (*Myriophyllum spicatum*) between water bodies (Stiers et al., 2011). Baitfish release is another common vector. Anglers sometimes release unused bait

into lakes and rivers, unknowingly introducing non-native species that can become invasive. The rusty crayfish (*Orconectes rusticus*), native to the Ohio River Basin, was introduced to many U.S. water bodies this way and has since displaced native crayfish, altered food chains, and damaged aquatic vegetation

## 2.4 Climate Change and Natural Range Expansions

Climate change is accelerating the spread of invasive species by altering temperature regimes, increasing extreme weather events, and shifting species distributions (Kernan, 2015). Warmer water temperatures have allowed species such as the quagga mussel (*Dreissena bugensis*) to expand their range into previously uninhabitable environments, outcompeting native species for space and nutrients (Thomas et al., 2008). Additionally, changing precipitation patterns influence the distribution of invasive aquatic plants. For instance, extreme flooding events have facilitated the spread of *Salvinia molesta*, a floating fern that rapidly covers water surfaces, blocking sunlight and depleting oxygen levels (Flood et al., 2020).

## 3. Impact on Native Biodiversity and Ecosystem Function

### 3.1 Competition with Native Species

One of the most immediate and devastating effects of invasive species is their ability to outcompete native organisms for resources such as food, habitat, and breeding grounds (Gallardo et al., 2016). Many invasive species have biological advantages, such as faster growth rates, higher reproductive output, and a lack of natural predators in their new environments. For example, the invasive round goby (*Neogobius melanostomus*) has been shown to outcompete native fish for food and habitat in the Great Lakes, reducing populations of native benthic fish like sculpins and darters (Carey & Wahl, 2010). Similarly, the highly aggressive rusty crayfish (*Orconectes rusticus*) has displaced native crayfish species throughout North American rivers, leading to a decline in biodiversity and habitat alterations (Stiers et al., 2011). Invasive aquatic plants such as *Hydrilla verticillata* also outcompete native vegetation by growing rapidly and forming thick mats on the water's surface. This not only limits sunlight penetration, reducing the growth of native submerged plants, but also decreases oxygen levels in the water, creating hypoxic conditions that harm fish and invertebrates (Hassan & Nawchoo, 2020)

### 3.2 Disruption of Food Webs

Invasive species frequently alter food webs by either introducing a new predator or disrupting nutrient cycling (Flood et al., 2020). The introduction of predatory fish like the Nile perch (*Lates niloticus*) in Lake Victoria led to the extinction of more than 200 native cichlid fish species by preying on them at an unsustainable rate (Gallardo et al., 2016). Similarly, the

invasive lionfish (*Pterois volitans*) in the Caribbean consumes native reef fish at such high rates that local fish populations cannot recover. This disrupts the delicate balance of coral reef ecosystems, where native fish play crucial roles in controlling algal growth and maintaining reef health (Cox, 2015). Invasive filter feeders such as the Asian clam (*Corbicula fluminea*) alter the dynamics of nutrient cycling in freshwater ecosystems by filtering out plankton at a rapid rate. This reduces the food supply for native filter-feeders, such as mussels and certain fish species, leading to declines in their populations (McDowell et al., 2013).

### 3.3 Habitat Modification

Invasive species frequently alter physical habitats, sometimes with long-term consequences. Plants like *Phragmites australis* (common reed) invade wetland areas and displace native marsh vegetation, reducing habitat availability for birds, amphibians, and fish (Stiers et al., 2011). Benthic invaders such as the zebra mussel (*Dreissena polymorpha*) and quagga mussel (*Dreissena bugensis*) significantly change substrate composition by forming dense colonies on hard surfaces. These mussels have caused the decline of native freshwater mussels by outcompeting them for food and space (Gallardo et al., 2016). Invasive burrowing species such as the Chinese mitten crab (*Eriocheir sinensis*) damage riverbanks by digging extensive burrows, leading to increased erosion and sedimentation. This degrades water quality and can cause infrastructure damage to levees and flood control systems (Moorhouse & Macdonald, 2015).

### 3.4 Spread of Diseases and Parasites

Many invasive species introduce novel diseases and parasites that native species have not evolved resistance to. The introduction of the invasive American signal crayfish (*Pacifastacus leniusculus*) to European rivers led to the spread of crayfish plague (*Aphanomyces astaci*), which wiped out native European crayfish populations (Carey & Wahl, 2010). Similarly, invasive fish species such as the Asian swamp eel (*Monopterus albus*) serve as carriers for parasites that infect native fish populations, reducing their survival and reproductive success (Thomas et al., 2008).

## 4. Impact on Ecosystem Services and Economic Costs

Invasive aquatic species not only disrupt ecosystems but also impose substantial economic costs. Their effects are felt in multiple sectors, including fisheries, water infrastructure, tourism, and public health. The global economic damage caused by invasive species is estimated to be in the hundreds of billions of dollars annually (Gallardo et al., 2016).

### 4.1 Damage to Fisheries and Aquaculture

Fisheries are among the most severely affected industries due to invasive species, which compete with native fish, prey on juvenile stocks, or degrade aquatic habitats.

- The Asian carp invasion in the United States has drastically altered freshwater ecosystems. These fast-growing fish consume large quantities of plankton, reducing food availability for native fish such as bass and catfish (Carey & Wahl, 2010). The commercial fishing industry has suffered because native fish populations have declined.
- Lionfish invasions in the Atlantic have devastated reef fish populations. Studies show that lionfish predation has reduced native fish biomass by up to 65% in some areas (Cox, 2015). This has negatively impacted both commercial and recreational fisheries, leading to economic losses.
- Invasive mussels, such as the zebra mussel and quagga mussel, have harmed shellfish industries by competing with native mollusks for food and space (Gallardo et al., 2016). In many North American water bodies, native mussel populations have collapsed due to competition from invasive species.

These disruptions to fisheries result in lost revenue for local communities, increased fishing costs, and reduced employment in the sector.

#### 4.2 Water Infrastructure Damage

Invasive aquatic species pose a major threat to water infrastructure by clogging pipes, damaging equipment, and increasing maintenance costs.

- Zebra mussels and quagga mussels attach themselves to water intake pipes, reducing flow efficiency in power plants, drinking water systems, and industrial facilities. The cost of removing these mussels from North American water systems exceeds \$1 billion annually (Gallardo et al., 2016).
- Chinese mitten crabs (*Eriocheir sinensis*) burrow into levees and flood control structures, weakening them and increasing the risk of collapse. In California, their burrowing activities have caused significant damage to irrigation channels, resulting in millions of dollars in repair costs (Moorhouse & Macdonald, 2015).
- Invasive aquatic plants, such as *Eichhornia crassipes* (water hyacinth), clog waterways, making navigation difficult for boats and increasing the costs of dredging and weed removal (Hassan & Nawchoo, 2020).

#### 4.3 Impact on Tourism and Recreation

Many invasive species reduce the recreational and tourism value of water bodies by altering aesthetics, limiting access, and affecting water quality.

- Eurasian watermilfoil (*Myriophyllum spicatum*) forms thick mats that interfere with boating, swimming, and fishing activities. This reduces the appeal of lakes for tourism,

leading to economic losses for communities that depend on outdoor recreation (Stiers et al., 2011).

- Toxic algal blooms, exacerbated by invasive species such as zebra mussels, degrade water quality and pose risks to public health. Some blooms produce harmful toxins that make lakes unsafe for swimming and drinking water use (Flood et al., 2020).
- The decline of native fish populations due to invasive species reduces the attractiveness of fishing tourism. Many popular sport fish, such as walleye and trout, have been negatively affected by the presence of invasive competitors and predators (Gallardo et al., 2016).

#### 4.4 Public Health Concerns

Invasive aquatic species also pose risks to human health by transmitting diseases, introducing harmful toxins, and reducing water quality.

- Harmful algal blooms, fueled by invasive species, produce toxins that can cause respiratory issues, neurological disorders, and skin irritation in humans (Flood et al., 2020). Drinking contaminated water can lead to serious illnesses.
- Invasive mosquitoes, such as *Aedes albopictus*, thrive in standing water created by invasive aquatic plants. These mosquitoes are known vectors for diseases like West Nile virus and Zika virus (Thomas et al., 2008).
- Introduction of non-native parasites has led to outbreaks of fish diseases. The parasitic flatworm *Bothriocephalus acheilognathi*, carried by invasive Asian carp, has infected native fish populations, leading to increased mortality rates (Carey & Wahl, 2010).

### 5. Climate Change as a Catalyst for Invasions

Climate change is playing an increasingly significant role in the spread and establishment of invasive aquatic species. Rising temperatures, altered precipitation patterns, changing ocean currents, and extreme weather events are creating conditions that favor invasive species over native ones. This exacerbates the threats that these species pose to biodiversity, ecosystem stability, and human economies (Kernan, 2015)

#### 5.1 Rising Water Temperatures and Range Expansions

As global temperatures rise, many invasive species are expanding their ranges into previously inhospitable environments. Warmer water allows species that were once restricted to tropical or subtropical regions to establish populations in temperate and even cold-water ecosystems (Thomas et al., 2008).

- Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena bugensis*) have expanded their range due to increasing water temperatures, moving further north

into cooler regions of Europe and North America. These mussels thrive in warmer waters, outcompete native species, and cause economic damage by clogging water intake pipes (Gallardo et al., 2016).

- The Asian tiger shrimp (*Penaeus monodon*), a warm-water species, has spread to previously temperate waters due to rising ocean temperatures. This highly aggressive shrimp species outcompetes native shrimp and crustaceans, impacting fisheries and marine food webs (Cox, 2015).
- Freshwater invasive fish, such as the snakehead (*Channa argus*), have expanded into new regions where colder temperatures previously limited their survival. The snakehead is an aggressive predator that disrupts food webs by preying on native fish, amphibians, and even small mammals (Carey & Wahl, 2010).

## 5.2 Increased Storm Frequency and Species Transport

Stronger and more frequent storms, hurricanes, and floods caused by climate change facilitate the spread of invasive species.

- Hurricane events have led to the spread of lionfish (*Pterois volitans*) throughout the Atlantic and Gulf of Mexico by pushing them into new coastal habitats (Cox, 2015). The lionfish, originally introduced through the aquarium trade, has now established itself as a dominant predator in coral reef ecosystems, where it depletes native fish populations.
- Floods allow invasive fish such as Asian carp (*Hypophthalmichthys molitrix*) to move into new river systems, where they disrupt native fish populations by consuming vast amounts of plankton and outcompeting local species (Carey & Wahl, 2010).
- Floating invasive plants, such as *Salvinia molesta* and *Eichhornia crassipes* (water hyacinth), spread rapidly during heavy rainfall events, covering water surfaces and reducing oxygen levels, which suffocates native fish and invertebrates (Flood et al., 2020).

## 5.3 Ocean Acidification and the Spread of Marine Invaders

Climate change has also contributed to ocean acidification, a phenomenon where increased CO<sub>2</sub> levels reduce the pH of seawater. This can weaken the natural defenses of native marine species, making them more vulnerable to invasive species (Thomas et al., 2008).

- Coral reef degradation has allowed species such as the invasive crown-of-thorns starfish (*Acanthaster planci*) to thrive, as they feed on stressed and weakened corals. These starfish have contributed to massive coral die-offs in the Indo-Pacific region (Gallardo et al., 2016).

- Changes in pH can weaken native shellfish species, making them more susceptible to competition from invasive mussels and clams, such as the Asian clam (*Corbicula fluminea*), which tolerates lower pH levels better than many native species (McDowell et al., 2013).

#### 5.4 Disruption of Seasonal Migration Patterns

Climate change is also altering the migration patterns of fish and other aquatic organisms, which can further contribute to biological invasions.

- Warmer waters have disrupted the seasonal migration of native fish, such as salmon, allowing invasive species to establish dominance in their breeding grounds. The decline of salmon populations in the Pacific Northwest has been linked to the spread of invasive fish that take advantage of shifting temperature regimes (Carey & Wahl, 2010).
- Invasive species such as the European green crab (*Carcinus maenas*) are expanding their range into areas where native crab populations are struggling to adapt to temperature shifts, leading to increased competition and predation on local shellfish (Gallardo et al., 2016).

### 6. Management Strategies and Control Measures

Managing invasive aquatic species is a complex and ongoing challenge that requires a combination of prevention, early detection, eradication, and long-term control strategies. Governments, conservationists, and researchers use a variety of techniques to minimize the ecological and economic damage caused by invasive species. These strategies include biological control, chemical treatments, habitat restoration, and legislative measures (Gallardo et al., 2016).

#### 6.1 Prevention: Stopping Invasions Before They Start

The most effective way to manage invasive species is to prevent their introduction in the first place. Prevention strategies include:

##### 6.1.1 Ballast Water Management

Since ballast water is a major vector for aquatic invasions, international regulations require ships to treat ballast water before discharge.

- The International Maritime Organization's Ballast Water Management Convention requires ships to exchange or treat ballast water to eliminate invasive species (Cox, 2015).
- UV sterilization and chemical treatments are used to kill potential invaders before they are released into new environments.

### 6.1.2 Regulations on Aquarium and Aquaculture Trade

Many invasive species are introduced through the aquarium and aquaculture industries. Policies to reduce this risk include:

- Banning the sale of high-risk species such as snakeheads and lionfish (Carey & Wahl, 2010).
- Public awareness campaigns urging aquarium owners to "Never Release Your Pet" into the wild.
- Mandatory labeling of invasive potential on aquarium plant and fish products.

### 6.1.3 Cleaning Recreational Equipment

Recreational boats, kayaks, and fishing gear can transport invasive species between water bodies. Measures to reduce this risk include:

- "Clean, Drain, Dry" initiatives requiring boaters to remove invasive plants and drain water before leaving a site (Stiers et al., 2011).
- Decontamination stations at popular boating areas to prevent the spread of zebra mussels.

## 6.2 Early Detection and Rapid Response

Once an invasive species is introduced, early detection is critical to preventing its spread. Rapid response programs include:

- Environmental DNA (eDNA) Monitoring – Scientists detect invasive species by analyzing water samples for DNA traces. This method is used to track Asian carp in the Great Lakes (Gallardo et al., 2016).
- Citizen Science Programs – Encouraging the public to report sightings of invasive species through apps and hotlines.
- Rapid Eradication Teams – Specialized teams that remove invasive species before they become established, such as lionfish removal programs in the Caribbean (Cox, 2015).

## 6.3 Control and Eradication Methods

If an invasive species is already established, control strategies must be implemented. These include:

### 6.3.1 Biological Control

Introducing natural predators, parasites, or competitors can help manage invasive populations.

- Sterile male releases have been used to control invasive sea lamprey populations in the Great Lakes (Carey & Wahl, 2010).
- Grass carp (*Ctenopharyngodon idella*) have been introduced to eat invasive aquatic plants like hydrilla. However, this method can sometimes cause unintended ecological consequences (Hassan & Nawchoo, 2020).

### 6.3.2 Chemical Control

Pesticides and herbicides can be used to remove invasive species, though they must be applied carefully to avoid harming native organisms.

- Rotenone is used to eliminate invasive fish species such as northern snakeheads (Thomas et al., 2008).
- Glyphosate and other herbicides are used to control invasive plants like water hyacinth. However, these chemicals must be carefully regulated to prevent water contamination (Flood et al., 2020).

### 6.3.3 Mechanical Removal

Sometimes, physical removal is the only option for controlling invasive species. Examples include:

- Diver-assisted removal of invasive algae such as *Caulerpa taxifolia* from Mediterranean waters.
- Electrofishing programs targeting invasive fish such as Asian carp (Gallardo et al., 2016).

### 6.4 Habitat Restoration and Ecosystem Recovery

Once an invasive species is removed, ecosystems need to be restored to prevent reinvasion. Methods include:

- Reintroducing native species to outcompete invaders. For example, restocking native mussels in areas affected by zebra mussels (Moorhouse & Macdonald, 2015).
- Replanting native aquatic vegetation after invasive plant removal to stabilize ecosystems (Stiers et al., 2011).

## 7. Conclusion and Future Outlook

Invasive aquatic species pose one of the most significant threats to biodiversity, ecosystem health, and human economies. Their ability to spread rapidly, outcompete native species, disrupt food webs, and damage infrastructure has made them a global concern. With climate change accelerating their spread, urgent and coordinated action is required to prevent further ecological and economic devastation (Gallardo et al., 2016).

The strategies outlined in this article—prevention, early detection, control, and habitat restoration—are essential in mitigating the impact of invasive species. However, long-term success will depend on global cooperation, stronger regulations, and continued scientific innovation.

### 7.1 The Role of Policy and International Cooperation

Stronger international agreements and regional policies are needed to address the issue at a global scale. Key policy recommendations include:

- Strengthening regulations on ballast water discharge to prevent the accidental introduction of invasive species (Cox, 2015).
- Enforcing stricter trade restrictions on high-risk species in the aquarium, aquaculture, and fishing industries (Carey & Wahl, 2010).
- Expanding public awareness campaigns to educate people on the dangers of releasing non-native species into the wild (Stiers et al., 2011).
- Increasing government funding for research and rapid response programs to detect and remove invasive species before they establish permanent populations (Gallardo et al., 2016).

## 7.2 Future Scientific Innovations

Advancements in technology and ecological research will play a crucial role in improving invasive species management. Future strategies may include:

- Genetic biocontrol methods – Using gene-editing techniques such as CRISPR to sterilize or suppress invasive populations (Flood et al., 2020).
- Artificial intelligence and remote sensing – Using AI-powered monitoring systems to detect invasive species in real-time using drones and satellite imaging (Thomas et al., 2008).
- Microbial solutions – Introducing specific bacteria or fungi that target invasive plants without harming native species (Hassan & Nawchoo, 2020).

## 7.3 The Role of Citizens and Local Communities

Public participation is a crucial part of managing invasive species. Community-based programs such as citizen science monitoring, local removal efforts, and educational outreach can greatly reduce the spread of invasives (Moorhouse & Macdonald, 2015). Simple actions like cleaning recreational equipment, reporting sightings of invasive species, and supporting conservation efforts can make a significant impact.

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