

Assessing the Effectiveness of Strategies to Manage Aquatic Invasive Species (AIS) in
Freshwater Ecosystems

by
Rachel Moore

Submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Environmental Assessment

Raleigh, North Carolina

2025

Approved by advisory committee:

Dr. Tamara Pandolfo

November 21, 2025

© Copyright 2025 by Rachel Moore
All Rights Reserved

ABSTRACT

MOORE, RACHEL SUZANNE. Assessing the Effectiveness of Strategies to Manage Aquatic Invasive Species in Freshwater Ecosystems. (Under the direction of Dr. Tamara Pandolfo).

Aquatic invasive species (AIS) represent one of the most significant threats to freshwater ecosystems, driving biodiversity loss, altering ecological processes, and imposing substantial economic costs. Despite decades of research and management investment, their control and prevention remain difficult due to complex ecological interactions, limited resources, and fragmented policy frameworks. This study critically assessed the effectiveness of contemporary AIS management strategies in freshwater systems to identify patterns of success, limitations, and opportunities for improvement.

A systematic literature review was conducted using the North Carolina State University Summon and Aquatic Sciences and Fisheries Abstracts (ASFA) databases. Thirty peer-reviewed studies published between 2000 and 2025 were evaluated based on three core metrics, ecological outcome, cost-effectiveness, and population change, to assess the effectiveness of AIS management strategies. Management strategies were categorized into prevention and early detection, physical barriers, mechanical removal, chemical control, biological control, genetic biocontrol, and integrated or adaptive management approaches.

Results revealed that no single strategy consistently achieved high performance across all metrics. Prevention and early detection were the most cost-effective and ecologically beneficial, particularly when targeted at high-connectivity systems and supported by professionalized implementation. Mechanical and chemical control methods achieved localized population suppression but lacked long-term durability, while biological and genetic approaches offered innovative potential with unresolved ecological and regulatory challenges. Integrated and

adaptive management frameworks, combining multiple strategies and involving stakeholder collaboration, demonstrated the highest overall effectiveness and long-term sustainability.

The findings emphasize that successful AIS management requires coordinated, adaptive, and interdisciplinary approaches that align ecological goals with social and institutional capacities. By integrating prevention, monitoring, rapid response, and restoration within collaborative frameworks, managers can enhance ecosystem resilience and reduce reinvasion risk. This synthesis contributes to the growing body of literature advocating for ecosystem-based adaptive strategies as essential pathways toward sustainable freshwater invasive species management in a changing global environment.

DEDICATION

To my incredible parents, Andrew and Deborah Moore, for their unwavering support and encouragement throughout my entire academic career. To my wonderful husband, Brayden Lassiter, for his love, strength, and patience throughout my time in graduate school. To my beloved Granmary, who cherished every achievement and stood beside me with unconditional love and support. Your spirit remains a quiet strength in all I do.

BIOGRAPHY

Rachel Suzanne Moore was born on November 29, 1999, to Deborah Moore and Andrew Moore in the city of Charlotte, North Carolina. She grew up in a family of four, including her younger brother, Benjamin. They lived in Belmont, a suburb of Charlotte, attending various schools. She graduated from South Point High School in 2018 and attended North Carolina State University, where she majored in Environmental Sciences and minored in Biological Sciences. She graduated *Summa Cum Laude* in 2022 with a BS in Environmental Sciences and was recognized on the dean's list throughout her undergraduate career. In August of 2023, she began attending graduate school at North Carolina State University. There she studied under esteemed professors and the advisement of Dr. Tamara Pandolfo to develop this thesis.

ACKNOWLEDGMENTS

Melissa Boyd Glover for guiding me every day with the knowledge, integrity, and life experience that she has bestowed upon me

Sarah Hansen Snipes for recognizing my intellectual potential at a young age and helping me develop the drive to continue a path of academic excellence

Jason C. Bivins for opening my perception of, understanding of, and curiosity about the overlooked aspects of the world around me

Carrie Bradley for being a role model in the pursuit of environmental sustainability in the face of seemingly insurmountable challenges

TABLE OF CONTENTS

LIST OF TABLES	viii
INTRODUCTION	1
METHODS	4
Literature Search	4
Inclusion and Exclusion Criteria	5
Data Collection	5
Metric of Effectiveness Assessment	5
RESULTS	7
Prevention and Early Detection Strategies	7
Population Change	8
Ecological Outcome	9
Cost-Effectiveness	10
Physical Barriers and Deterrent Systems	10
Population Change	10
Ecological Outcome	11
Cost-Effectiveness	12
Mechanical Removal Strategies	12
Population Change	13
Ecological Outcome	14
Cost-Effectiveness	14
Chemical Control Strategies	14
Population Change	15
Ecological Outcome	15
Cost-Effectiveness	16
Biological Control Strategies	17
Population Change	17
Ecological Outcome	18
Cost-Effectiveness	18
Genetic Biocontrol Strategies	19
Population Change	19
Ecological Outcome	20
Cost-Effectiveness	20
Integrated and Adaptive Management Approaches	21
Population Change	21
Ecological Outcome	22
Cost-Effectiveness	22
DISCUSSION	23
Management Strengths	23
Current Limitations	25
Recommendations	30
SUMMARY & CONCLUSION	31

LIST OF TABLES

Table 1	Scales of 3 Metrics that Determine Effectiveness of AIS Management Strategies in Freshwater Ecosystems	6
Table 2	Effectiveness Metric Results for 7 AIS Management Strategies in Freshwater Ecosystems	8

Introduction

Freshwater ecosystems represent some of the most biologically diverse and socioeconomically important habitats on Earth, yet they are increasingly imperiled by the spread of aquatic invasive species (AIS). Defined as non-native organisms that establish, proliferate, and spread outside of their natural range, AIS have become a dominant driver of ecological change and biodiversity decline in freshwater systems worldwide (Thomaz et al., 2025). These invaders disrupt ecological processes, impose substantial economic costs, and challenge existing management regimes, making them one of the most pressing environmental issues of the twenty-first century (Thomaz et al., 2025).

The accelerating introduction and establishment of AIS in freshwater habitats poses a critical problem for conservation and resource management. Freshwater ecosystems harbor disproportionately high biodiversity relative to their spatial extent, yet they are also among the most vulnerable to species introductions because of their high connectivity, heavy human use, and sensitivity to ecological disturbance (Emery-Butcher et al., 2020; Havel et al., 2015). Aquatic invasions can lead to cascading ecological effects, including biodiversity loss, altered food web dynamics, ecosystem homogenization, and long-term regime shifts (Walsh et al., 2016). These effects can further impact the critical sustenance and services that freshwater ecosystems provide to human societies (Bobeldyk et al., 2015).

One of the most profound impacts of AIS is the loss of biodiversity. Freshwater ecosystems face stress from pollution, habitat fragmentation, and climate change, and the addition of invasive species amplifies these pressures, often leading to extirpation of endemic species and the simplification of food webs (Bailey, 2015; Britton et al., 2023). Invasive predators, such as non-native fish, reduce native species abundance and diversity, while invasive

plants such as Eurasian watermilfoil suppress native vegetation, reduce oxygen levels, and alter habitat complexity and nutrient dynamics (Emery-Butcher et al., 2020; Tamayo and Olden, 2014). Invasive filter-feeders like zebra and quagga mussels restructure nutrient cycling and outcompete native bivalves, leading to profound changes in water quality and species composition (Escobar et al., 2018).

From a functional standpoint, some AIS act as “ecosystem engineers”, reshaping habitat structures and altering the availability of critical resources for other organisms (Emery-Butcher et al., 2020). For example, crayfish and mussels modify sediment regimes, alter nutrient cycling, and disrupt existing species interactions (Emery-Butcher et al., 2020). These changes frequently result in the simplification of food webs, shifting energy flows toward invasive species and reducing the resilience of native communities (Havel et al., 2015).

The socioeconomic cost of AIS is equally severe. The economic burden of AIS is reflected not only in direct management costs but also in lost revenue for industries reliant on freshwater systems, including fisheries, aquaculture, recreation, and water infrastructure (Escobar et al., 2018). For example, zebra mussels in the Great Lakes impose annual costs estimated at \$500 million per year to manage, with broader regional impacts exceeding \$800 million when losses to industries like fisheries and hydropower are considered (Bobeldyk et al., 2015; Escobar et al., 2018). More broadly, invasive fish and mollusks impose average annual losses of over \$7 billion in the United States, and invasive freshwater species contribute significantly to the \$120 billion in annual costs attributed to invasive species across ecosystems (Bobeldyk et al., 2015; Buley et al., 2017). These expenses encompass direct control measures, infrastructure maintenance, and indirect losses from declines in ecosystem services and recreation opportunities (Angell et al., 2024). Moreover, conflicts arise between different

stakeholders, such as water managers, conservationists, and recreation industries, over the prioritization of management strategies (Escobar et al., 2018). Addressing AIS therefore demands not just environmental interventions but also governance systems that are socially aware and involve collaboration among multiple stakeholders (Escobar et al., 2018).

Despite the scale of these impacts, eradication and long-term control of AIS remain difficult. Traditional strategies, ranging from chemical treatments and physical removal to biological control, have achieved localized success but often fail over the long term (Britton et al., 2023). Early detection and rapid response measures can sometimes eradicate populations confined to small water bodies, as with localized chemical treatments of invasive fish (Simberloff, 2021). Similarly, biological control of invasive plants has shown promise in reducing their abundance (Simberloff, 2021). Emerging approaches such as genetic interventions, non-physical barriers like ozone, and adaptive management frameworks integrating human dimensions offer promising avenues but remain in experimental or pilot phases (Britton et al., 2023; Buley et al., 2017).

While prevention and early detection are widely recognized as the most effective measures against AIS, many freshwater systems lack the resources necessary to implement these strategies effectively (Bailey, 2015; Britton et al., 2023). Many projects fail because of insufficient funding, lack of sustained monitoring, limited enforcement capacity, or the inherent difficulty of managing connected aquatic systems (Simberloff, 2021). A key challenge is aligning ecological effectiveness with social feasibility and ensuring that management strategies remain adaptable in the face of climate change and evolving pathways of invasion (Britton et al., 2023).

Despite decades of research and management efforts, the global expansion of AIS continues. The objective of this literature review was to critically assess the effectiveness of AIS management strategies in freshwater ecosystems, identify gaps in current practices, and propose management recommendations for sustainable outcomes. This review evaluates traditional and emerging strategies across prevention, control, and eradication, situating them within ecological and economic contexts, and considers how integrated approaches can improve long-term resilience of freshwater ecosystems against invasion. By concentrating on these dimensions, the study will offer a balanced critique of current management approaches while highlighting innovative solutions that could improve long-term sustainability. Importantly, the focus on freshwater environments reflects both ecological urgency and the availability of case studies that provide a robust empirical basis for analysis.

Methods

Literature Search

Literature searches were conducted within the North Carolina State University's Summon database and Aquatic Sciences and Fisheries Abstracts (ASFA) Database for relevant and credible sources. While searching the databases, a variety of keyword combinations specific to freshwater aquatic invasive species management practices were used. The keyword combinations utilized were: "Freshwater AND Invasive AND Management", "Aquatic species AND Non-Native AND Eradicate", "Freshwater infestation AND Economic impacts", "Lakes AND Exotic AND Recovery", "Lakes AND Introduced species AND performance", "Freshwater invasion AND Control AND Ecosystem health", "Nuisance freshwater species AND Anthropogenic influence", "Aquatic invasive mitigation AND Cost-benefit analysis", "Regulate AND

Ecosystem decline AND Aquatic invasions”, and “Aquatic invasion management AND Benefits AND Weakness”.

Inclusion and Exclusion Criteria

The literature utilized within this project was selected through a specific screening process. The criteria for approved sources require that the literature be peer-reviewed, primary literature, published between 2000 and 2025, supported by empirical data, and include at least one metric of effectiveness for the type of management effort(s) discussed.

Data Collection

Secondary literature, such as reviews, were retained for supplemental information but not included in the literature assessment. The selected primary research articles were reviewed in detail to gather data relevant to management effectiveness. The data were then categorized in Google Sheets. Extracted data variables include the type of AIS management strategy, target invasive species, freshwater system studied, metrics reported, and study context. Once compiled, the data were grouped by management strategy to allow comparison across categories.

Metric of Effectiveness Assessment

The effectiveness of each management strategy was assessed based on three metrics: ecological outcome (ecosystem-level improvements), cost-effectiveness (relative costs vs. benefits), and population change (eradication or reduction values). Ecological outcomes were defined as positive or negative changes in ecosystem integrity, scaled from localized improvement to whole-lake recovery. Ecological outcome was quantified by changes in the structure and function of freshwater ecosystems following invasive species management, with primary indicators of habitat quality, biodiversity, and ecosystem service proxies. Cost-effectiveness was interpreted broadly to integrate economic feasibility with ecological benefit.

This metric was quantified by comparing the monetary investment in a management strategy against its ecological and/or economic benefits to generate a benefit-cost ratio (BCR). The population change metric provides the most direct evidence of management effectiveness, because it measured the actual target and/or cause of intervention – invasive and/or native species populations. Population change was quantified by the degree to which invasive species are reduced or eradicated, or by the recovery of native populations after intervention.

Each metric was assigned a categorical description of low, moderate, high, or very high corresponding to the empirical data presented within the relevant studies (Table 1).

Table 1 – Scales of 3 Metrics that Determine Effectiveness of AIS Management Strategies in Freshwater

Metric	Low	Moderate	High	Very High
Population Change (target AIS reduction/eradication; native population increase)	<30% reduction from baseline within 1 year or clear rebound to baseline within a year; eradication probability <20%	30-59% reduction sustained \geq 1 season; partial rebound likely without continued effort; eradication probability 20-49%	60-79% reduction sustained \geq 1 year or \geq 50% eradication probability in closed/isolated systems; clear suppression across most occupied habitat	\geq 80% reduction sustained \geq 1 year or confirmed eradication (multi-season zero detections with continued surveillance); spread risk minimized at pathways
Ecological Outcome (ecosystem integrity/biota/habitat)	Localized or negligible improvement; mixed/negative non-target effects; ecosystem function largely unchanged	Noticable, spatially patchy improvements (habitat quality, biodiversity, indicators) with some trade-offs; not yet system-wide	System-level improvements with native community recovery trending toward reference conditions; minimal/manageable non-target effects	Whole-lake/whole-reach recovery: multiple trophic indicators and habitat functions restored and stable for \geq 1 year; positive spillovers to ecosystem services
Cost-effectiveness (cost vs. avoided damages/benefits)	Benefit-cost ratio (BCR) <1 (costs exceed avoided damages/benefits) or high ongoing costs for small/short-lived gains	BCR 1-2.9; worthwhile in specific contexts/short timeframes; costs scale steeply with coverage or density	BCR 3-9; strong returns when targeted/optimized (right sites, timing, materials); manageable O&M	BCR \geq 10 or "orders of magnitude" cheaper than reactive control because spread is averted; costs largely front-loaded

Each management strategy was then given an overall effectiveness rating of low, moderate, high, or very high based on the compilation of metrics for each strategy type. Some studies could not be assessed for all three of the effectiveness metrics due to limited data types.

Results

A total of 30 peer-reviewed articles met the inclusion criteria for this study and were used to assess the effectiveness of 7 strategies used to manage AIS in freshwater ecosystems. The management strategies assessed included Prevention and Early Detection, Mechanical Removal, Chemical Control, Physical Barriers & Deterrent Systems, Biological Control, Genetic Pest Management, and Integrated & Adaptive Management. Each strategy was assessed across three established metrics: population change, ecological outcomes, and cost-effectiveness.

1. Prevention and Early Detection Strategies

Prevention and early detection strategies included watercraft inspection and decontamination programs, ballast water management systems, environmental DNA monitoring, species distribution modeling, and boater education and voluntary compliance programs. These strategy types demonstrated highly variable effectiveness across the three assessment metrics, with performance largely dependent on implementation method and target species characteristics (Table 2). The research revealed significant differences between professional-led and public-led prevention efforts, with implications for all three effectiveness-metric assessments.

Table 2 – Effectiveness Metric Results for 7 AIS Management Strategies in Freshwater Ecosystems

Strategy	Population Change	Ecological Outcome	Cost-effectiveness
Prevention and Early Detection Strategies	High to Very High ; notable establishment reduction	Moderate to High ; early detection enables rapid response; model accuracy is mixed; timing is very influential	High to Very High
Mechanical Removal	Moderate to High ; 30-70% local reduction, rebound is common	Low to Moderate ; rebounds after cessation; gear selectivity misses juveniles	Moderate overall; greater effectiveness with combination traps; selectivity reduces effort
Chemical Control	Low to Very High ; 80-100% eradication in closed systems	Moderate to High ; more effective when coupled with biological controls; herbicide-only is more limited in capabilities	Low for aquatic disinfectants to Moderate for chemical control methods coupled with biological control methods
Physical Barriers and Deterrent Systems	Low to Moderate ; slowed spread by ~1.7 years/2.4 km	Low to Moderate ; tradeoffs, non-target risks; inconsistent blocking	Moderate ; temporal delay benefits vs. capex/O&M
Biological Control	Moderate overall; 20-70% suppression of aquatic plant species; High for species-specific viruses; Low for long-term carp virus rebound	Low to Moderate ; predators can harm native populations; Moderate for predatory insects; species-specific viruses are promising but contingent	Low in the long-term for carp virus; High to Very High for species-specific viral agents, High for classical biological control methods
Genetic Pest Management	*Theoretically* High to Very High ; eradication feasible in models with modest releases (>90% suppression in lab trials); RNAi is currently Moderate	*Theoretically* High ; dependent upon species-specificity, reversibility/self-limiting designs	*Theoretically* High to Very High ; self-sustaining dynamics
Integrated and Adaptive Management	High to Very High ; adaptive rules and early detection improved eradication odds; regional coordination reduced spread risk	High ; whole system recovery is more durable; better stakeholder design	High to Very High ; optimized allocation; early action prevents costly spread when followed by long-term prevention practices

Population Change

Programs that perform professional watercraft inspection and decontamination were highly effective according to population change metrics, with hot water decontamination achieving the highest mean effectiveness at 84% reduction in transported Eurasian watermilfoil, zebra mussel, and spiny water flea species (Angell et al., 2024). Professional watercraft inspectors were effective 79.2% of the time in completely removing aquatic invasive species from boats during controlled trials, while general boaters achieved only 56.4% effectiveness (Angell et al., 2024). Removal rates differ among species, with macrophytes showing the highest removal success at 90% reduction in optimal locations, zebra mussels demonstrating much lower

removal rates of 3% by boaters in some locations, and spiny water fleas consistently achieving near-zero removal rates even by professionals (Angell et al., 2024).

Ballast water management systems provided variable effectiveness across all three metrics depending on operational status and complementary measures. Fully functioning systems achieved very high effectiveness on population change metrics, while bypassed systems presented the highest risk of non-indigenous species establishment (Bradie et al., 2023).

Ecological Outcomes

Environmental DNA monitoring strategies were poorly to highly effective according to ecological outcome metrics through early detection capabilities. High-volume plankton tow net sampling yielded DNA copy numbers averaging 173,652 per liter compared to 1,630 per liter from standard filtration methods (Cupp et al., 2020). The ecological outcome effectiveness ranged across the full metric scale from low to high based on detection timing, with early-stage invasions showing substantial detection improvements that enable rapid response interventions before ecosystem-level impacts occur (Cupp et al., 2020).

Species distribution modeling for prevention targeting showed mixed effectiveness on ecological outcome metrics. Models incorporating both environmental and anthropogenic predictors achieved 81-97% correct classification for invasive species presence-absence, with 54 lakes identified as vulnerable to invasion across Washington State (Tamayo & Olden, 2014). However, when subjected to null model comparisons, only seven out of nine modeled species predicted distributions better than chance, indicating moderate ecological outcome effectiveness for predictive prevention approaches (Rodríguez-Rey et al., 2019).

Cost-effectiveness

Prevention strategies ranged from highly to very highly cost-effective depending on implementation scale and target species. Boater education and voluntary compliance programs demonstrated high cost-effectiveness, with 92% of Swiss boaters reporting cleaning behaviors when mussels were detected, though only 55% employed high-pressure washing methods (Fadlovich et al., 2024). The research indicated that prevention strategies targeting high-connectivity lakes rather than those merely closest in distance to infected waters produced superior cost-effectiveness outcomes, with Rice Lake identified as a super receiver accounting for 25.7% of boat traffic from infested Lake Koronis (Escobar et al., 2019). A combination of ballast water exchange with partially functioning systems achieved cost-effectiveness ratings of high to very high, particularly for freshwater ports where risk reduction effects were most pronounced (Bradie et al., 2023).

2. Physical Barriers and Deterrent Systems

Physical barriers and deterrent systems included electric barrier systems, carbon dioxide barriers, bubble barrier systems, and river infrastructure barriers. These systems demonstrated low to moderate effectiveness on population change and ecological outcome metrics, and moderate cost-effectiveness, with substantial variation based on target species characteristics and barrier type (Table 2). The research revealed important limitations in complete population control while showing promise for delaying invasion spread and reducing crossing rates.

Population Change

Electric barrier systems showed moderate effectiveness on population change metrics for large-bodied fish species. Vertical electric barriers reduced common carp crossings from 12 per

trial to 1 per trial during active barrier periods, though crossings returned to 15 per trial when barriers were deactivated (Kim & Mandrak, 2017). The barriers achieved 70% approach attempts by carp, with 37% successfully crossing despite the deterrent effect (Kim & Mandrak, 2017). For smaller species, electric barriers demonstrated lower effectiveness, with Eurasian ruffe showing only partial deterrence, as approximately half of barrier crossing attempts were still successful even under optimal electrical settings (Dawson et al., 2006).

Carbon dioxide barriers demonstrated species-specific effectiveness with significant non-target implications for effectiveness assessments. Carbon dioxide barriers with CO₂ concentrations of 76-87 mg/L showed moderate effectiveness in affecting population change metrics for deterring invasive Asian carp, while causing 50% mortality in non-target juvenile mussels within 16-28 days (Waller et al., 2016).

Bubble barrier systems provided low to moderate effectiveness on population change metrics across tested species. Small ruffe demonstrated some deterrent response to bubble curtains, but many individuals still successfully crossed barriers regardless of bubble size or density configurations (Dawson et al., 2006).

Ecological Outcomes

The ecological outcome effectiveness of carbon dioxide barriers ranged from low to moderate due to trade-offs between target species deterrence and native species impacts, with bluegill showing higher sensitivity than fathead minnows across temperature ranges (Cupp et al., 2020). The ecological outcome effectiveness of bubble barrier systems was low, as neither electrical nor bubble barriers achieved consistent blocking of target species movement, suggesting integrated approaches may be necessary for meaningful population control (Dawson et al., 2006).

Cost-effectiveness

River infrastructure barriers were moderately effective against invasion spread with temporal limitations. Partial river barriers temporarily delayed upstream expansion of invasive American signal crayfish by approximately 1.7 years and 2.4 kilometers, but invasion rates returned to pre-barrier levels after 6.5 years (Daniels et al., 2023). Individual-based modeling revealed that barrier effectiveness was density-independent, with passage success remaining at 37% regardless of crayfish population density (Daniels et al., 2023). Cost-effectiveness assessments indicated moderate ratings for temporary invasion delay benefits compared to barrier construction and maintenance costs.

3. Mechanical Removal Strategies

Mechanical removal strategies included a variety of physical catchment methods, such as large-mesh seine nets, promar mesh 503 traps, and combination trap approaches. These types of AIS management strategies achieved moderate to high effectiveness on population change metrics when implemented with sufficient intensity and duration, though complete eradication remained challenging without sustained effort (Table 2). These strategies were consistently low to moderately effective in term of ecological outcome and low in cost-effectiveness, primarily as a result of habitat destruction and ecological disturbance from removal gear and bycatch (De Palma-Dow et al., 2019). The research demonstrated clear relationships between removal effort, spatial coverage, and population suppression outcomes (Diallo et al., 2025).

Population Change

Intensive mechanical removal programs in isolated systems approached high effectiveness on population change metrics under optimal conditions. Removal efforts in McGee Wash achieved a 39.8% probability of eradication after removing approximately 10,500 green sunfish over 49 removal events across four years (Diallo et al., 2025). Similar intensive efforts in East Ash Creek resulted in 39.9% eradication probability after removing 2,500 fish over 18 events across 1.5 years (Diallo et al., 2025). Population change effectiveness required removal from nearly 100% of habitat sites, with spatial coverage reduction to 50% of sites achieving suppression but not eradication (Diallo et al., 2025).

Gear selectivity significantly influenced mechanical removal effectiveness on both population change and cost-effectiveness metrics. Large-mesh commercial beach seines demonstrated low effectiveness for capturing reproductive-age adults, with 50% vulnerability not achieved until 5.5 years of age and 95% vulnerability at 8.8 years, despite reproductive maturity occurring at age 3 (Fadlovich et al., 2024). Improving gear selectivity to target younger mature age classes reduced required effort from 17 times historic maximum to 5.5 times historic maximum when adding two younger age classes (Fadlovich et al., 2024).

Trapping strategies for crayfish control showed moderate population change effectiveness with substantial variation based on trap design and deployment conditions. Promar mesh 503 traps achieved the highest effectiveness at 28% of all crayfish captured while minimizing bycatch to 8% of arroyo chub and zero tadpoles (De Palma-Dow et al., 2019).

Novel mechanical removal methods provided improved population assessment capabilities with implications for ecological outcome effectiveness. Triple drawdown methodology achieved 92% capture efficiency for invasive signal crayfish populations, revealing

densities of 20.5-110.4 individuals per square meter that exceeded previous estimates by factors of five or more (Chadwick et al., 2020).

Sustained mechanical removal efforts demonstrated variable long-term effectiveness on population change metrics. Rainbow trout removal in the upper Krom River reduced catch per unit effort from 0.53 fish per net per night to 0.21 fish per net per night over four months, but populations rebounded to 0.56 fish per net per night within two years after removal cessation (Shelton et al., 2016).

Ecological Outcomes

The method of crayfish trapping demonstrated that conventional trapping missed 36-72% of populations dominated by juveniles and sub-adults, indicating low ecological outcome effectiveness for traditional mechanical approaches (Chadwick et al., 2020). Sustained mechanical removal of AIS also indicated low ecological outcome effectiveness as a result of consistent and uncontrolled population rebounding of rainbow trout (Shelton et al., 2016).

Cost-effectiveness

Cost-effectiveness assessments of crayfish trapping strategies favored combination trap approaches, with mesh traps demonstrating high capture efficiency but requiring more maintenance compared to metal alternatives (De Palma-Dow et al., 2019). Cost-effectiveness of sustained mechanical removal efforts remained moderate at approximately \$10,600 USD for 40 days of removal effort, though complete eradication was not achieved due to selectivity limitations in capturing smaller size classes (Shelton et al., 2016).

4. Chemical Control Strategies

Chemical control strategies included herbicide applications, aquatic disinfectant deployments, and integrated chemical and biological management approaches. These chemical

control strategy types were variable in population change effectiveness, ranging from low to very highly effective, with moderately to highly effective ecological outcomes depending on application method, concentration, and target species specificity (Table 2). The research revealed important trade-offs between invasive species control success and non-target species impacts across different chemical approaches (Rydell et al., 2025).

Population Change

Herbicide applications for aquatic plant control showed moderate population change effectiveness. Whole-lake 2,4-dichlorophenoxyacetic acid treatments at a concentration of 0.3 ppm temporarily eradicated Eurasian watermilfoil in treated lakes during the year of application, but populations rebounded quickly in most systems by the following year (Rydell et al., 2025). The effectiveness of population change demonstrated only temporary suppression rather than sustained control, limiting its long-term management value.

Aquatic disinfectants showed low effectiveness on population change metrics, even though they caused visible tissue damage. Virasure Aquatic and Virkon Aquatic disinfectants at concentrations up to 4 g/L with 5-minute exposures caused significant tissue degradation in *Elodea nuttallii* fragments but failed to achieve complete mortality (Cuthbert et al., 2019). All plant fragments survived and resumed growth during 28-day observation periods, indicating low population change effectiveness, despite being under intensive chemical treatment protocols (Cuthbert et al., 2019).

Ecological Outcomes

The ecological outcome effectiveness of herbicide applications was rated as moderate, with no statistically significant differences detected in zooplankton density, diversity, or larval fish communities between treated and reference lakes (Rydell et al., 2025).

Integrated chemical and biological management approaches achieved moderate to high effectiveness on ecological outcome metrics. Combined 2,4-D herbicide and biological insect agents for water hyacinth control significantly improved native fish populations compared to unmanaged conditions, with numbers approaching those in water hyacinth-free environments (Rydell et al., 2025). Fish populations in integrated management systems remained stable or increased, while unmanaged water hyacinth treatments experienced significant declines (Rydell et al., 2025).

Chemical treatments showed species-specific effectiveness patterns with implications for ecological outcome assessments. Eastern mosquitofish populations demonstrated a strong negative correlation with water hyacinth cover and a positive correlation with dissolved oxygen levels, indicating that chemical reduction of invasive plant biomass directly improved habitat quality for native species (Cuthbert et al., 2019). However, chemical applications alone without biological components achieved lower ecological outcome effectiveness compared to integrated approaches, suggesting synergistic benefits from combined chemical and biological strategies.

Cost-effectiveness

Cost-effectiveness ratings of aquatic disinfectants exhibited low effectiveness due to insufficient efficacy relative to treatment costs and practical application challenges. The cost-effectiveness of integrated chemical and biological management approaches was rated as high due to simultaneous invasive plant control and native species recovery benefits (Rydell et al., 2025).

5. Biological Control Strategies

Biological control strategies included employment of viral agents and introduction of predator species. These strategies demonstrated variable effectiveness across all three metrics (Table 2), with success largely dependent on agent specificity, release timing, and environmental conditions (Mintram et al., 2020; Sunarto et al., 2022). The research revealed important considerations for both historical and contemporary biological control approaches.

Population Change

Classical biological control agents achieved moderate effectiveness on population change metrics with generally high cost-effectiveness ratings. Biological management using specialist insects for water hyacinth control produced fish populations that were stable but slightly lower than chemical or integrated treatments, though still superior to unmanaged conditions (Cuthbert et al., 2019).

Viral biocontrol agents showed limited effectiveness on long-term population change metrics despite high initial mortality rates. Koi herpesvirus biocontrol modeling predicted that even 95% virus-induced mortality would produce only temporary population knockdowns, with carp biomass rebounding to 80% of original levels within 10 years (Mintram et al., 2020). Population change effectiveness was further limited by the rapid evolution of viral resistance, with resistance alleles reaching fixation within 50 years under persistent high viral mortality pressure (Mintram et al., 2020). Species-specific viral agents demonstrated high effectiveness in population changes with favorable ecological outcomes. Tilapia Lake Virus showed 80-90% mortality rates in farmed and wild tilapia with minimal evidence of non-target impacts on co-occurring species (Sunarto et al., 2022). Predator introduction for biological control achieved variable population change effectiveness depending on ecosystem context and target species

characteristics. The introduction of *Coreoperca herzi* in Japanese river systems resulted in substantial declines in native fish community diversity, with 74% of the most abundant native species showing significant biomass reductions in invaded compared to uninvaded sites (Sunarto et al., 2022). Population change effectiveness was high for target prey species, but low to moderate for non-target species.

Ecological Outcomes

The ecological outcome effectiveness of biological management using specialist insects for water hyacinth control was rated as moderate, with biological agents providing sustained population suppression without the rapid results achieved by chemical alternatives (Cuthbert et al., 2019). Despite receiving high effectiveness ratings for population change and cost-effectiveness, ecological outcome effectiveness of species-specific viral agents remained conditional on comprehensive non-target species testing and public acceptance of fish kill events (Sunarto et al., 2022). Predator introduction for biological control generated low ecological outcome effectiveness due to broad non-target impacts on native biodiversity (Rydell et al., 2025).

Cost-effectiveness

Cost-effectiveness of viral biocontrol agents was rated low due to poor long-term suppression relative to potential implementation costs and ecological risks (Mintram et al., 2020). The cost-effectiveness rating of species-specific viral agents was assessed as high to very high due to species specificity and self-sustaining transmission characteristics that enable widespread control without repeated applications (Sunarto et al., 2022).

6. Genetic Biocontrol Strategies

Genetic biocontrol strategies included sex-ratio distortion systems, gene drive systems, RNA interference practices, and self-limiting genetic systems. This category of strategies represented emerging approaches with theoretically high to very high effectiveness on population change metrics, though practical implementation remained limited by technical and regulatory constraints (Table 2). The research demonstrated promising modeling results with highly effective ecological outcome and cost-effectiveness, while highlighting substantial development challenges.

Population Change

Sex-ratio distortion systems showed high theoretical effectiveness on population change metrics through mathematical modeling. Population extinction within generations when sex-changed females were introduced at consistent rates above critical thresholds were predicted by the Trojan Y chromosome approach (Gutierrez and Teem, 2006). Population modeling indicated that constant introduction of 3.2% sex-reversed females per time interval could drive target populations to extinction through elimination of breeding females (Gutierrez & Teem, 2006). Gene drive systems demonstrated high theoretical effectiveness on population change metrics with species-specific targeting capabilities. CRISPR-Cas9 gene influenced rapid spread through target populations in laboratory settings, possibly leading to population suppression or eradication (Harvey-Samuel et al., 2017).

RNA interference approaches achieved moderate population change effectiveness in laboratory settings with potential for field application. Multiple research groups developed RNAi constructs targeting essential genes in invasive mussels, though complete mortality was not consistently achieved in controlled studies (Hernández Elizárraga et al., 2023). Population

change effectiveness was limited by delivery challenges, variable target gene expression, and incomplete understanding of RNAi pathway efficiency in target species (Hernández Elizárraga et al., 2023).

Self-limiting genetic systems provided moderate effectiveness on population change metrics with enhanced containment features. The Self-Stocking Incompatible Male System demonstrated population suppression capabilities in mathematical models while incorporating biological containment mechanisms to prevent persistent environmental establishment (Pfitzner, 2023). Laboratory testing in zebrafish model systems validated genetic construct functionality, though effectiveness in target species remained to be demonstrated (Pfitzner, 2023).

Ecological Outcomes

The ecological outcome effectiveness of gene drive systems was assessed as potentially high due to species specificity that minimizes non-target impacts compared to broad-spectrum control methods (Harvey-Samuel et al., 2017). However, truly practical effectiveness remained uncertain due to limited field testing and regulatory approval processes. Ecological outcome effectiveness of the Self-Stocking Incompatible Male System was assessed as potentially high due to designed reversibility and reduced risk of unintended environmental consequences (Pfitzner, 2023).

Cost-effectiveness

Cost-effectiveness assessments of sex-ratio distortion systems were rated as potentially very high due to self-sustaining population suppression mechanisms, though initial development costs remained substantial (Gutierrez & Teem, 2006). Cost-effectiveness ratings of RNA interference approaches are not certain pending successful field deployment and scale-up protocols (Hernández Elizárraga et al., 2023).

7. Integrated and Adaptive Management Approaches

Integrated management strategies combining multiple control methods achieved the highest effectiveness ratings across all three metrics, demonstrating the benefits of coordinated multi-pronged approaches (Table 2). Integrated strategies included adaptive management using dynamic decision rules, regional coordination efforts, species distribution modeling incorporating both environmental and anthropogenic predictors, multi-stakeholder collaborative management, technology integration approaches, and high-volume environmental DNA sampling combined with traditional visual surveys. The research consistently showed superior results of high to very high effectiveness across all three effectiveness metrics when different management strategies were implemented concurrently rather than sequentially.

Population Change

Adaptive management approaches using dynamic decision rules were very highly effective on population change metrics compared to static management strategies. Real-time allocation of removal effort based on catch data improved eradication probabilities while reducing resource expenditure compared to uniform effort distribution (Diallo et al., 2025). Continued monitoring after initial zero-catch events prevented population rebound from cryptic survivors, maintaining population change effectiveness over extended time periods (Diallo et al., 2025).

Regional coordination strategies achieved high effectiveness on population change metrics through synchronized management across connected systems. Network analysis identifying super receiver lakes enabled targeted prevention efforts at sites with the highest invasion risk rather than simple proximity-based approaches (Escobar et al., 2019). Species distribution modeling incorporating both environmental and anthropogenic predictors improved

management targeting effectiveness from 66-89% classification accuracy (Tamayo & Olden, 2014).

Ecological Outcomes

Multi-stakeholder collaborative management achieved high effectiveness on ecological outcome metrics through improved project design and implementation. Structural factors, including shared goals, participatory decision-making, and information sharing, significantly predicted both goal achievement and long-term durability of management outcomes (Abeysinghe et al., 2023).

Technology integration approaches combined traditional methods with advanced monitoring systems to enhance overall effectiveness. High-volume environmental DNA sampling coupled with traditional visual surveys achieved detection sensitivities two orders of magnitude higher than standard protocols (Cupp et al., 2020). The ecological outcome effectiveness was high due to early detection capabilities that enabled rapid response before ecosystem-level impacts occurred (Cupp et al., 2020).

Cost-effectiveness

Cost-effectiveness ratings of multi-stakeholder collaborative management were high due to improved resource allocation and reduced implementation conflicts among participating agencies (Abeysinghe et al., 2023). The cost-effectiveness rating of adaptive management approaches using dynamic decision rules was very high due to optimized resource allocation and reduced risk of management failure (Diallo et al., 2025). Cost-effectiveness assessments of technology integration approaches indicated high ratings due to the prevention of larger-scale control efforts through early intervention (Cupp et al., 2020). The cost-effectiveness rating of

regional coordination strategies was very high due to strategic resource allocation that prevented the spread to multiple interconnected water bodies (Escobar et al., 2019).

Discussion

The synthesis of findings across all management strategies revealed that effectiveness varied substantially based on implementation intensity, target species characteristics, ecosystem context, and integration with complementary approaches (Bradie et al., 2023; Haase et al., 2023). No single strategy achieved consistently high effectiveness across all three metrics, supporting the conclusion that integrated approaches combining multiple management tools provide the most promising avenue for sustainable aquatic invasive species management in freshwater systems (Manfrin et al., 2019; Walsh et al., 2016).

The results of this assessment reveal a complex landscape in which management strategies for aquatic invasive species (AIS) in freshwater systems display both persistent gaps and notable strengths. The primary findings illustrate not only where management approaches have achieved quantifiable success, but also where entrenched limitations and implementation obstacles have diminished their effectiveness (Cuthbert et al., 2019; Haase et al., 2023). Meaningful improvement in AIS management necessitates the alignment of innovation, adaptive policy, multi-sector collaboration, and the strategic integration of available methods (Abeysinghe et al., 2023; Beaury et al., 2019).

Management Strengths

Despite numerous limitations, there are significant and encouraging strengths within the current suite of AIS management strategies. Prevention, when prioritized and strategically targeted at key points of connectivity, is demonstrably the most cost-effective means of halting

new invasions, yielding benefits orders of magnitude greater than those realized through reactive control (Kopf et al., 2019; Manfrin et al., 2019). The efficacy of high-volume, high-sensitivity detection techniques, and the integration of traditional survey approaches with new molecular and informatics tools has yielded far more comprehensive, system-level coverage, revealing both previously undetected invasions and providing actionable guidance for adaptive monitoring programs (Manfrin et al., 2019; Towne et al., 2024).

The selective adaptation of mechanical removal methods and gear highlights the importance of tailoring tactics to local demographic and ecological structure, allowing managers to optimize resource allocation while still providing employment opportunities in relevant local economies (Britton et al., 2011; Manfrin et al., 2019). Further, the emergence and increasing feasibility of integrated management, particularly approaches that blend chemical, biological, and mechanical methods with adaptive, real-time monitoring, delivers more resilient, ecosystem-level improvements while mitigating the drawbacks inherent in any single approach (Manfrin et al., 2019). The strength of integrated management is borne out repeatedly: ecosystem recovery, especially for affected native species, proceeds more rapidly and with greater durability when managers deploy coordinated, multi-pronged strategies and remain vigilant for follow-up actions after major interventions (Haase et al., 2023; Diallo et al., 2025).

Collaborative efforts that structure goals, sharing of information, participatory decision-making, and flexible accountability are consistently associated with improved environmental, economic, and social outcomes that persist past project closeout (Beaury et al., 2019; Levers & Pradhananga, 2021). Strong stakeholder support and project design emerge as predictors of long-term durability, and such multi-stakeholder engagement is increasingly recognized as essential

both to scientific innovation and the practical, social justice-driven deployment of new technology (Levers & Pradhananga, 2021).

Current Limitations

Current management strategies often fall short in delivering durable, system-wide AIS suppression across varied contexts (Haase et al., 2023). Prevention and early detection methods frequently operate below optimal levels due to uneven public engagement and inconsistent application of protocols (Levers & Pradhananga, 2021). Professional intervention for watercraft decontamination is considerably more effective than boater-led efforts. However, both approaches are hampered by overlooked high-risk areas and shortfalls in equipment performance, such as failing to maintain lethal decontamination temperatures or adequately targeting less visible species and boat regions (Angell et al., 2024). While voluntary boater compliance rates are relatively high, the minority who neglect cleaning represent a continued risk of spreading AIS to new ecosystems, indicating that broader outreach and more effective infrastructure can further bolster outcomes.

Targeted, high-connectivity prevention delivers the strongest cost-benefit ratios, but the prioritization of resources for such focused efforts remains uneven across regions and agencies (Perrin et al., 2021; Angell et al., 2024). Sizeable gaps exist in the reach and efficiency of current prevention programs. Many rely heavily on public education and voluntary action, which do not reliably compensate for the higher efficacy observed when prevention is managed by trained professionals or through systematic risk-based prioritization (Angell et al., 2024).

Detection systems also exhibit limitations relative to invasive life stage, seasonal detectability, and the chosen monitoring protocol. Environmental DNA (eDNA) methodologies have elevated early detection capability, especially for difficult-to-observe or low-density

populations, but the results show marked variation in detection rates between species and over seasonal cycles (Cupp et al., 2020). The greatest detection challenge is typically posed by species such as the spiny waterflea, which can escape standard eDNA survey efforts even at their annual peak, suggesting that a “one size fits all” approach is not well-suited for multi-species AIS monitoring programs. Instead, the integration of traditional and innovative surveillance, including high-volume plankton sampling and dynamically refined sampling protocols, provides clearer coverage across the spectrum of invasive species and is more robust to local environmental variability (Cupp et al., 2020). Despite these advances, key limitations remain; practical detection thresholds still lag behind the pace of AIS spread in many high-risk locations, and logistical or resource limitations routinely inhibit comprehensive, continuous implementation.

Physical barriers provide an alternative preventative approach, but issues of permanence, target specificity, and non-target ecological risk intrinsically constrain their utility. Electric and bubble barriers can reduce the movement of some invaders, such as deterring common carp or partially delaying signal crayfish spread, but rarely achieve complete isolation, and their long-term legacy effects may diminish quickly after initial installation (Daniels et al., 2023; Kim & Mandrak, 2017). River infrastructure that operates as a partial barrier can delay invasions, buying critical time for other management actions to progress, but it will not fundamentally halt population expansion in the absence of additional interventions (Daniels et al., 2023). Trade-offs compound these shortcomings, while river barriers can suppress invader dispersal in the short term, they also pose chronic risks for native biodiversity and restrict natural ecosystem connectivity. (Hesselschwerdt & Wantzen, 2018).

Chemical control methods, especially herbicide applications, exhibit rapid but temporary suppression of many aquatic invasive plants. Whole-lake chemical control treatment agents like 2,4-dichlorophenoxyacetic acid can eradicate problematic species, such as Eurasian watermilfoil, in the short term, but regrowth is frequent, and the underlying invasibility of affected lakes is usually unaltered (Rydell et al., 2025). In some cases, chemical treatments do not significantly alter the community composition for zooplankton or larval fish, but the lack of lasting effect on target AIS, combined with concern over cumulative non-target risks, suggests moderate value for these methods when used alone. Treatments with aquatic disinfectants further illustrate this constraint, while they significantly damage invasive plant tissues, they do not reliably lead to total mortality, requiring repeated application or other biosecurity measures to ensure efficacy (Cuthbert et al., 2019). These findings highlight the urgent need for refining chemical control protocols and integrating them with other approaches for sustained, system-wide benefits.

Mechanical removal has proven moderately to highly effective for reducing population abundance when applied intensively and with comprehensive spatial-temporal coverage, as demonstrated by large scale removal campaigns for invasive fish and crayfish in isolated systems (Diallo et al., 2025; Shelton et al., 2016). However, the path to actual eradication is rare; even high removal rates do not prevent population rebound unless removal continues after apparent zero detections and incorporates dynamic, data-driven reallocation of effort. The selectivity of capture gear and the need to target reproductive-age cohorts are persistent determinants of success. Mechanical approaches become less effective as target densities decrease, further highlighting that intensive manual interventions may buy time and support native communities' recovery but cannot, in isolation, offer a permanent solution.

Biological control and genetic biocontrol strategies illustrate both promise and uncertainty. Biological agents, ranging from host-specific viruses to specialist insect herbivores, demonstrate high specificity and can provide sustained pressure on invasive populations under certain conditions (Rydell et al., 2025). Notably, viral biocontrol of invasive carp may result in high mortality but is rapidly undercut by the evolution of host resistance and high fecundity, suggesting that population reduction gains are short-lived (Mintram et al., 2020). Similarly, classical biocontrol can strengthen ecosystem resilience and allow native species to recover, yet it is limited by agent specificity, delayed response times, and potential impacts on non-target fauna (Haase et al., 2023; Sunarto et al., 2022). Genetic biocontrol, particularly sex-ratio distortion and gene-drive systems, holds transformative theoretical potential, but technical, ecological, and regulatory obstacles limit deployment capabilities (Haase et al., 2023). Evolutionary responses and societal acceptability introduce further levels of risk and uncertainty, shining light on the importance of rigorous assessment and stakeholder engagement as the field moves from theory toward field application.

Across all management strategies, several common shortcomings are evident, both within and outside of the established effectiveness metrics. First, management efforts often fail to anticipate and adequately address the primary confounding impacts of ecosystem context, climate variability, and anthropogenic pressures (Beaury et al., 2019). The resurgence of freshwater biodiversity plateaued in the 2010s, with persistent stressors such as climate change, land use intensification, and ongoing pollution compounding the challenges of invasive species control (Thomaz et al., 2025). Managers report high concern for climate-change-driven invasions, but they face significant barriers in translating these concerns into practical management shifts because of entrenched funding limits, shortages of personnel, and lack of

actionable information, particularly for novel invaders or rapidly shifting threat profiles (Beaury et al., 2019). Time allocation in management agencies remains heavily weighted toward reactive control of existing invasions, with minimal attention paid to proactive surveillance or long-term adaptive strategy refinement (Walsh et al., 2016). This reactive pattern undermines the potential benefits of early detection and rapid response, widely recognized as the most cost-effective and ecologically beneficial approach to AIS management.

A related gap is the fragmentation of policy and institutional capacity. Many management systems perform independently, with poor coordination among state, regional, or agency-level actors, resulting in missed opportunities for collaboration, inconsistent implementation of best practices, and difficulty scaling up successes from pilot to system-wide application (Buley et al., 2017; Britton et al., 2023). While collaborative approaches empirically improve project design, durability, and acceptance among stakeholders, insufficient attention to process structure, clarity of roles, and transparent communication still hinders widespread uptake of proven, durable strategies (Escobar et al., 2019).

Significant shortcomings in innovation and adaptation also emerge from the synthesis of results. New tools, ranging from eDNA to predictive risk modeling, citizen science, and genetic biocontrol, offer expanded opportunities for management efficiency and specificity, but barriers to operational deployment remain high. Technical hurdles (e.g., in the case of RNAi and gene drives for mussels), regulatory inertia, and the absence of multidisciplinary collaboration all slow the pace of innovation (Harvey-Samuel et al., 2017). Risk assessment frameworks for novel interventions still lack consensus metrics and stakeholder engagement protocols, producing uncertainty and reduced public trust (Escobar et al., 2019). Additionally, several methods focus on managing perceived rather than actual risk by public users, meaning social-psychological

drivers of compliance and behavioral change may not align with the exact points of biological vulnerability to invasion.

Recommendations

Given these limitations, recommendations for improvement span multiple axes. From a policy perspective, there is a critical need to prioritize adaptive, integrative frameworks that combine prevention, monitoring, rapid response, long-term suppression, and restoration (Abeysinghe et al., 2023; Escobar et al., 2019). This shift should be supported by policy mechanisms that encourage resource-sharing, cross-agency coordination, and participatory governance structures that directly involve affected communities in decision-making. Funding models should be adapted to overcome the chronic under-resourcing of early detection and monitoring (Simberloff, 2021). Practical recommendations also include the refinement and tailoring of detection and prevention methods to local conditions, the adoption of dynamic, data-driven approaches to mechanical removals, and the systematic use of cross-validation and null models when employing predictive tools to prevent management actions based on false correlations or overfit models.

Institutional adaptation will likewise be crucial, requiring both cultural and organizational flexibility. Research and agency priorities should explicitly integrate climate adaptation, anticipate shifting invasion risks due to human activity and global change, and center monitoring on those lakes, rivers, and catchments most vulnerable based on updated models of human connectivity and landscape suitability (Rodríguez-Rey et al., 2019; Tamayo & Olden, 2014). Continued monitoring beyond the apparent conclusion of eradication programs is essential, as even a few cryptic survivors can trigger rapid and costly rebounds in invasive populations (Britton et al., 2023).

Innovation must be supported through collaborative, interdisciplinary research that brings together technical experts, policy practitioners, local communities, and other stakeholders. Risk assessment frameworks for genetic biocontrol and other emerging technologies should be participatory and recurrent, grounded in both ecological science and social values to ensure acceptability and minimize non-target impacts (Sunarto et al., 2022; Waller et al., 2016). Future research should focus on developing more robust laboratory and field delivery systems for genetic tools, scaling up successful trials in isolated or closed systems, and building genomic and ecological databases that support rapid, targeted intervention development (Diallo et al., 2025; Pfitzner, 2023).

In sum, while the persistent challenges of AIS management point to the need for ambitious policy and institutional reform, the strengths of emerging technologies, integrative practices, and collaborative frameworks hold meaningful promise for more effective, adaptive, and resilient freshwater ecosystem management in the face of continued biological invasions. By fostering the conditions for innovation, integrating adaptive management principles, and maintaining a clear focus on prevention and ecosystem-based approaches, future AIS management can build on demonstrated successes to address longstanding and emerging gaps, ultimately contributing to the restoration and long-term health of freshwater biodiversity and ecosystem function.

Summary & Conclusion

The management of aquatic invasive species (AIS) in freshwater ecosystems remains a complex and evolving challenge. This study found that while multiple management strategies have achieved localized success, overall effectiveness remains inconsistent across ecological,

economic, and social dimensions. Prevention and early detection consistently emerged as the most cost-effective and ecologically beneficial strategies, particularly when targeted toward high-risk, high-connectivity systems. However, limited funding, uneven enforcement, and reliance on voluntary compliance continue to hinder their full potential.

Control and eradication methods, including mechanical, chemical, and biological strategies, demonstrated mixed success. Mechanical removal can substantially reduce invasive populations but rarely achieves eradication without long-term monitoring and adaptive effort. Chemical treatments often yield short-term suppression with significant non-target risks, while biological and genetic controls show promise but require further testing, regulation, and public acceptance to ensure safe and predictable outcomes.

Integrated and adaptive management frameworks proved most effective overall, combining multiple tools to address the limitations of any single approach. Approaches that pair early detection with targeted intervention, sustained monitoring, and stakeholder collaboration achieved stronger ecological recovery and long-term resilience. Collaborative governance, where management goals are shared among agencies and communities, consistently improved environmental outcomes and enhanced project durability.

Ultimately, effective AIS management requires a shift from reactive to proactive, ecosystem-based approaches supported by long-term funding, interdisciplinary research, and participatory decision-making. Integrating prevention, control, and restoration within adaptive frameworks will better align ecological goals with social feasibility. As climate change and global connectivity continue to intensify invasion pressures, success will depend on the capacity of management systems to evolve, balancing innovation with caution and science with

community values, to sustain freshwater biodiversity and ecosystem function in the decades ahead.

REFERENCES

- Abeyasinghe N, Guerrero AM, Rhodes JR, McDonald-Madden E. 2023. Unravelling how collaboration impacts success of invasive species management. *People and Nature*, 5(6), 2093-2106. <https://doi.org/10.1002/pan3.10544>
- Angell NR, Campbell T, Brady V, Bajcz AW, Kinsley AC, Doll A, Dumke J, Keller RP, Phelps NBD. 2024. Quantifying the effectiveness of three aquatic invasive species prevention methods. *Management of Biological Invasions*, 15(3): 371–396, <https://doi.org/10.3391/mbi.2024.15.3.04>
- Bailey SA. 2015. An overview of thirty years of research on ballast water as a vector for aquatic invasive species to freshwater and marine environments. *Aquatic Ecosystem Health & Management*, 18(3), 261–268. <https://doi-org.prox.lib.ncsu.edu/10.1080/14634988.2015.1027129>
- Beaury, EM, Fusco EJ, Jackson MR, Laginhas BB, Morelli TL, Allen JM, Pasquarella VJ, Bradley BA. 2020. Incorporating climate change into invasive species management: insights from managers. *Biological Invasions*, 22, 233–252. <https://doi-org.prox.lib.ncsu.edu/10.1007/s10530-019-02087-6>
- Bobeldyk AM, Ruegg J, Lamberti GA. 2015. Freshwater hotspots of biological invasion are a function of species-pathway interactions. *Hydrobiologia*, 746:363–373.

<https://www.proquest.com/asfa/docview/1646554108/14A8A51B04584E83PQ/6?accountid=12725&sourcetype=Scholarly%20Journals>

Bradie J, Rolla M, Bailey SA, MacIsaac HJ. 2022. Managing risk of non-indigenous species establishment associated with ballast water discharges from ships with bypassed or inoperable ballast water management systems. *Journal of Applied Ecology*, 60:193–204.

<https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/1365-2664.14321>

Britton JR, Lynch AJ, Bardal H, Bradbeer SJ, Coetzee JA, Coughlan NE, Dalu T, Tricarico E, Gallardo B, Lintermans M, Lucy F, Liu C, Olden JD, Raghavan R, Pritchard EG. 2023.

Preventing and controlling nonnative species invasions to bend the curve of global freshwater biodiversity loss. *Environmental Reviews*, 31(2): 310-326. <https://doi.org/10.1139/er-2022-0103>

Buley RP, Hasler, CT, Tix JA, Suski CD, Hubert TD. 2017. Can ozone be used to control the spread of freshwater aquatic invasive species? *Management of Biological Invasions*, 8(1), 13-24.

<https://doi.org/10.3391/mbi.2017.8.1.02>

Chadwick A, Pritchard DD, Bradley EG, Sayer P, Chadwick CD, Eagle MAB, Axmacher JC. 2021. A novel ‘triple drawdown’ method highlights deficiencies in invasive alien crayfish survey and control techniques. *Journal of Applied Ecology*, 58(2), 316-326.

<https://doi.org/10.1111/1365-2664.13758>

Cupp AR, Smerud JR, Thomas LM, Waller DL, Smith DL, Erickson RA, Gaikowski MP. 2020. Toxicity of Carbon Dioxide to Freshwater Fishes: Implications for Aquatic Invasive Species Management. *Society of Environmental Toxicology and Chemistry*, 39:2247–2255.

<https://academic-oup-com.prox.lib.ncsu.edu/etc/article/39/11/2247/7735489>

Cuthbert RN, Crane K, Dick JTA, Caffrey JM, MacIsaac HJ, Coughlan NE. 2019. Die Hard: impact of aquatic disinfectants on the survival and viability of invasive *Elodea nuttallii*, *Aquatic Botany*, Volume 154, Pages 11-17, <https://doi.org/10.1016/j.aquabot.2018.12.003>

Daniels JA, Kerr JR, Kemp PS. 2023. River infrastructure and the spread of freshwater invasive species: Inferences from an experimentally-parameterised individual-based model. *Journal of Applied Ecology*, 60:999–1009.

<https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/1365-2664.14387>

Dawson HA, Reinhardt UG, Savino JF. 2006. Use of Electric or Bubble Barriers to Limit the Movement of Eurasian Ruffe (*Gymnocephalus cernuus*). *Journal of Great Lakes Research*, 32(1), Pages 40-49, ISSN 0380-1330.

[https://doi-org.prox.lib.ncsu.edu/10.3394/0380-1330\(2006\)32\[40:UOEobb\]2.0.CO;2](https://doi-org.prox.lib.ncsu.edu/10.3394/0380-1330(2006)32[40:UOEobb]2.0.CO;2)

De Palma-Dow AA, Curti, JN, Fergus CE. 2020. It's a Trap! An evaluation of different passive trap types to effectively catch and control the invasive red swamp crayfish (*Procambarus clarkii*) in streams of the Santa Monica Mountains. *Management of Biological Invasions*, 11(1), 44-62.

<https://proxying.lib.ncsu.edu/index.php?url=https://www.proquest.com/scholarly-journals/s-trap-evaluation-different-passive-types/docview/2369706226/se-2>

Diallo JO, Converse SJ, Chmiel M, Stites AJ, Olden JO. 2025. Optimizing Control of a Freshwater Invader in Time and Space. *Ecological Applications*, 35(3): e70026. <https://doi-org.prox.lib.ncsu.edu/10.1002/eap.70026>

Emery-Butcher HE, Beatty SJ, Robson BJ. 2020. The impacts of invasive ecosystem engineers in freshwaters: A review. *Freshwater Biology*, 65:999–1015. <https://onlinelibrary.wiley.com/doi/10.1111/fwb.13479>

Escobar LE, Romero-Alvarez D, Larkin DJ, Phelps NB. 2019. Network analysis to inform invasive species spread among lakes. *Journal of Oceanography and Limnology*, 37:1037–1041. <https://www.proquest.com/asfa/docview/2917966906/14A8A51B04584E83PQ/12?accountid=12725&sourcetype=Scholarly%20Journals>

Escobar LE, Mallez S, McCartney M, Lee C, Zielinski DP, Ghosal R, Bajer PG, Wagner C, Nash B, Tomamichel M, et al. 2018. Aquatic Invasive Species in the Great Lakes Region: An Overview. *Reviews in Fisheries Science & Aquaculture*, 26:121–138. <https://research-ebSCO-com.prox.lib.ncsu.edu/c/oivr5p/viewer/pdf/bw4zcdliq5?route=details&auth-callid=768c8edc-06ca-43ce-b91b-6029fa281a73>

Fadlovich R, Landom K, Walsworth TE. 2025. Selectivity of invasive species suppression efforts influences control efficacy. *Journal of Applied Ecology*, 62:280–289. <https://besjournals-onlinelibrary-wiley-com.prox.lib.ncsu.edu/doi/10.1111/1365-2664.14856>

Gutierrez JB and Teem JL. 2006. A model describing the effect of sex-reversed YY fish in an established wild population: The use of a Trojan Y chromosome to cause extinction of an introduced exotic species. *Journal of Theoretical Biology*, 241:333–341. <https://www-sciencedirect-com.prox.lib.ncsu.edu/science/article/pii/S0022519305005242>

Haase P, Bowler DE, Baker NJ, Bonada N, Domisch S, Garcia Marquez JR, Heino J, Hering D, Jahnig SC, Schmidt-Kloiber A, et al. 2023. The recovery of European freshwater biodiversity has come to a halt. *Nature*, 620:582–588.

<https://www.proquest.com/docview/2848844944?parentSessionId=dgL7J8SojIlt5NNTZ3RhKaFgfB3iKOUemCzRgKCZks%3D&sourcetype=Scholarly%20Journals>

Harvey-Samuel T, Ant T, Alphey L. 2017. Towards the genetic control of invasive species.

Biological Invasions, 19:1683–1703. <https://link-springer-com.prox.lib.ncsu.edu/article/10.1007/s10530-017-1384-6>

<https://link-springer-com.prox.lib.ncsu.edu/article/10.1007/s10530-017-1384-6>

Havel JE, Kovalenko KE, Thomaz SM, Amalfitano S, Kats LB. 2015. Aquatic invasive species: challenges for the future. *Hydrobiologia*, 750:147–170.

<https://www.proquest.com/asfa/docview/1657499278/14A8A51B04584E83PQ/5?accountid=12725&sourcetype=Scholarly%20Journals>

Hernández Elizárraga V, Ballantyne S, O'Brien LG, Americo JA, Suhr ST, Senut MC, Minerich B, Merkes CM. 2023. Toward invasive mussel genetic biocontrol: Approaches, challenges, and perspectives." *iScience*, 26(1). doi:10.1016/j.isci.2023.108027

Hesselschwerdt J and Wantzen KM. 2018. Global warming may lower thermal barriers against invasive species in freshwater ecosystems – A study from Lake Constance. *Science of The Total Environment*, 645:44–50. <https://www-sciencedirect-com.prox.lib.ncsu.edu/science/article/pii/S0048969718325634>

Kim J and Mandrak NE. 2017. Effects of vertical electric barrier on the behaviour of common carp. *Management of Biological Invasions*, 8(4), 497-505.
<https://proxying.lib.ncsu.edu/index.php?url=https://www.proquest.com/scholarly-journals/effects-vertical-electric-barrier-on-behaviour/docview/2287043579/se-2>

Kopf RK, Boutier, Finlayson CM, Hodges K, Humphries P, King A, Kingsford RT, Marshall J, McGinness HM, Thresher R, Vanderplasschen A. 2019. Biocontrol in Australia: Can a carp herpesvirus (CyHV-3) deliver safe and effective ecological restoration?. *Biological Invasions*: 21, 1857–1870. <https://doi-org.prox.lib.ncsu.edu/10.1007/s10530-019-01967-1>

Levers L and Pradhananga A. 2021. Recreationist willingness to pay for aquatic invasive species management. *PLoS One*. 16. <https://pmc.ncbi.nlm.nih.gov/articles/PMC8046257/>

Mintram KS, van Oosterhout C, Lighten J. 2021. Genetic variation in resistance and high fecundity impede viral biocontrol of invasive fish. *Journal of Applied Ecology*. 58: 148–157. <https://doi.org/10.1111/1365-2664.13762>

Perrin SW, Bærum KM, Helland IP, Finstad AG. 2021. Forecasting the future establishment of invasive alien freshwater fish species. *Journal of Applied Ecology*, 58, 2404–2414. <https://doi.org/10.1111/1365-2664.13993>

Pfitzner, C. 2023. GENETIC BIOCONTROL OF INVASIVE FISH VIA SELF-STOCKING INCOMPATIBLE MALE SYSTEM. *Proceedings of the Royal Society of Victoria*, 135(1-2), 97. <https://proxying.lib.ncsu.edu/index.php?url=https://www.proquest.com/scholarly-journals/genetic-biocontrol-invasive-fish-via-self/docview/2921228731/se-2>

Rodriguez-Rey M, Consuegra S, Borger L, Garcia de Leaniz C. 2019. Improving Species Distribution Modelling of freshwater invasive species for management applications. *PLoS One*. <https://pmc.ncbi.nlm.nih.gov/articles/PMC6576753/>

Rydell N, Gehri R, VanDeHey J, Dembkowski D, Gauthier K, Van Egeren S, Kubisiak J, Nault M, Isermann D. 2025. Responses of larval fish and zooplankton to whole-lake 2,4-D herbicide treatments used to control Eurasian watermilfoil in northern Wisconsin lakes. *Hydrobiologia*, 852, 2769–2786. <https://doi-org.prox.lib.ncsu.edu/10.1007/s10750-024-05698-w>

Shelton J, Weyl O, Van Der Walt J, Marr S, Impson D, Maciejewski K, Tye D, Dallas H, Esler K. 2017. Effect of an intensive mechanical removal effort on a population of non-native rainbow trout *Oncorhynchus mykiss* in a South African headwater stream. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27:1051–1055. <https://onlinelibrary-wiley-com.prox.lib.ncsu.edu/doi/full/10.1002/aqc.2752>

Simberloff D. 2021. Maintenance management and eradication of established aquatic invaders. *Hydrobiologia*, 848:2399–2420. <https://pubmed.ncbi.nlm.nih.gov/32836349/>

Sunarto A and McKoll KA. 2020. Biocontrol of the common carp (*cyprinus carpio*) in australia: A review and future directions. *Fishes*, 5(2), 17. <https://doi.org/10.3390/fishes5020017>

Sunarto A, Grimm J, McColl KA, Ariel E, Nair KK, Corbeil S, Hardaker T, Tizard M, Strive T, Holmes B. 2022. Bioprospecting for biological control agents for invasive tilapia in Australia. *Biological Control*, Volume 174, ISSN 1049-9644, <https://doi.org/10.1016/j.biocontrol.2022.105020>.

Tamayo M and Olden JD. 2014. Forecasting the Vulnerability of Lakes to Aquatic Plant Invasions. *Invasive Plant Science and Management*, 7:32–45. <https://www.proquest.com/asfa/docview/1515640462/14A8A51B04584E83PQ/18?accountid=12725&sourcetype=Scholarly%20Journals>

Thomaz SM, Fauvelot C, Kats LB, Kotta J, Pelicice FM. 2025. Preface: Aquatic Invasive Species IV. *Hydrobiologia*, 852:1987–1995. <https://link-springer-com.prox.lib.ncsu.edu/article/10.1007/s10750-025-05833-1>

Towne K, Huber E, Lajovic J, Wright G. 2024. Increasing broad-spectrum aquatic invasive species early detection program efficiency through biased site selection and gear allocation. *Biological Invasions*, 26:2217–2236. <https://link-springer-com.prox.lib.ncsu.edu/article/10.1007/s10530-024-03306-5>

Waller DL, Bartsch MR, Fredricks KT, Bartsch LA, Schleis SM, Lee SH. 2016. Effects of carbon dioxide on juveniles of the freshwater mussel (*Lampsilis siliquoidea* [Unionidae]). *Environmental Toxicology and Chemistry*, 36(3), 671-681. <https://doi-org.prox.lib.ncsu.edu/10.1002/etc.3567>

Walsh JR, Carpenter SR, Zanden JV. 2016. Invasive species triggers a massive loss of ecosystem services through a trophic cascade. *Proceedings of the National Academy of Sciences*, 113:4081–4085. <https://pmc.ncbi.nlm.nih.gov/articles/PMC4839401/>