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EDITED BY
Abdulwakil Saba,
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REVIEWED BY
Fernando Rubino,
National Research Council (CNR), Italy
Rohit Jha,
Louisiana State University, United States

*CORRESPONDENCE
Sylvester Chibueze Izah
chivestizah@gmail.com;
sylvester.izah@bmu.edu.ng

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# Invasive species as threat multipliers in freshwater ecosystems: biodiversity loss, interacting stressors, and management responses in the Anthropocene

Sylvester Chibueze Izah[1,2*], Matthew Chidozie Ogwu[3], Vivian Ibienebakabobo Promise[4], Esther Ugo Alum[5], Wisdom Richard Poyeri[2], Ayebapreye Kari[2] and Morufu Olalekan Raimi[6]

[1]Department of Community Medicine, Faculty of Clinical Sciences, Bayelsa Medical University, Yenagoa, Bayelsa State, Nigeria, [2]Department of Microbiology, Faculty of Science, Bayelsa Medical University, Yenagoa, Bayelsa State, Nigeria, [3]Goodnight Family Department of Sustainable Development, Appalachian State University, Boone, NC, United States, [4]Department of Public Health, Faculty of Health Sciences, Bayelsa Medical University, Yenagoa, Bayelsa State, Nigeria, [5]Department of Research and Publications, Kampala International University, Kampala, Uganda, [6]Niger-Delta Institute for Emerging and Re-emerging Infectious Diseases, Federal University, Otuoke, Bayelsa State, Nigeria

Freshwater ecosystems occupy a small proportion of the Earth's surface yet support exceptionally high biodiversity and essential ecosystem services. In the Anthropocene, these systems are increasingly threatened by interacting pressures, including hydrological alteration, land-use change, pollution, climate warming, and biological invasions. This review examines invasive species as a major driver of freshwater biodiversity loss between 2015 and 2026, while situating invasions within the broader multi-stressor context emphasized in recent freshwater studies. Importantly, this review advances the concept of invasive species as *"threat multipliers"*, defined here as ecological agents that not only exert direct impacts but also amplify, reinforce, and prolong the effects of co-occurring stressors such as climate change, eutrophication, and hydrological disruption. This framing extends beyond traditional invasion ecology by explicitly linking invasion processes to multi-stressor interaction theory. Evidence shows that invasive fishes, macrophytes, decapods, and other ecosystem engineers reduce native biodiversity through competition, predation, habitat modification, food-web disruption, pathogen transfer, and biotic homogenization. Their impacts are often intensified by warming, nutrient enrichment, altered flow regimes, and other disturbances that facilitate establishment, spread, and ecological dominance. Where available, quantitative evidence demonstrates substantial ecological and socio-economic consequences, including reductions in biodiversity indices, declines in ecosystem functioning, and measurable economic losses associated with degraded ecosystem services. In addition, invasions impair ecosystem functioning and weaken ecosystem services by altering water clarity, nutrient cycling, habitat structure, fisheries productivity, and biomonitoring reliability. The review also highlights emerging responses, including eDNA-based early detection, prioritization frameworks, integrated control strategies, and the concept of functional eradication where complete removal is unrealistic. Major knowledge gaps remain in understanding multi-invader interactions, seasonal detectability, cross-ecosystem spillovers, long-term ecological change, and climate-ready management, especially in underrepresented regions such as Africa. This review provides both generalizable insights and region-specific implications for biodiversity conservation and management in the Anthropocene.

KEYWORDS

**Anthropocene, climate change, ecosystem services, freshwater biodiversity, freshwater management, invasive species**

## 1 Introduction

Freshwater ecosystems occupy a very small fraction of the Earth's surface, yet they support disproportionately high biodiversity and provide essential ecosystem services, including fisheries, water supply, nutrient processing, and livelihood support. At the same time, they are among the most threatened ecosystems globally because biodiversity loss in fresh waters is driven by interacting pressures rather than by any single stressor. Dudgeon (2019) emphasizes that freshwater biodiversity in the Anthropocene is jeopardized by a "panoply" of interacting threats, including climate change, habitat degradation, pollution, flow modification, and biological invasions, with direct consequences for ecosystem functioning and human well-being. Presently, many global freshwater ecosystems as undergoing major physical, chemical, and biological change. Janse et al. (2015) model broad human impacts on inland aquatic biodiversity at the global scale.

Among these pressures, invasive alien species have emerged as a major and persistent driver of freshwater ecological change. Freshwater systems appear especially vulnerable to invasion because they are heavily connected to human transport, water management, trade, and intentional species introductions. Havel et al. (2015) note that aquatic ecosystems are particularly at risk from invasive species because threats to biodiversity intersect directly with human dependence on water resources. In the same vein, Moorhouse and Macdonald (2015) argue that freshwater environments are highly invasible, and often more susceptible than terrestrial systems to negative biodiversity, physical-ecosystem, and socioeconomic impacts when invasions occur. At the global scale, Gallardo et al. (2016) synthesized 151 publications and 733 cases and showed that invasive species in aquatic ecosystems generate ecological effects that propagate through food webs and affect biodiversity, abundance, and habitat properties across taxa and habitats. Recent syntheses further reinforce that invasive species represent one of the dominant drivers of biodiversity loss globally, interacting strongly with climate change and land-use change (Bhat et al., 2024; Seletlo et al., 2024; Sesay et al., 2024).

The mechanisms through which invasive species alter freshwater ecosystems are diverse and often mutually reinforcing. Freshwater invasions show recurring impacts through competition, predation, habitat modification, pathogen transmission, trophic disruption, and ecological homogenization. Britton (2023) reports that invasive freshwater fishes can alter recipient ecosystems through increased competition and predation pressure, genetic introgression, and the transmission of non-native pathogens. Emery-Butcher et al. (2020) further show that when invasive species act as ecosystem engineers, their effects can be especially severe because they modify habitat structure and resource availability for many other organisms. Evidence also suggests that these impacts intensify where several invaders co-occur: Guareschi et al. (2021) found that, in rivers, the richness of co-occurring alien invaders was more important than abundance in negatively affecting aquatic macroinvertebrate biodiversity. In addition, global meta-analyses indicate that invasive ecosystem engineers can significantly alter biodiversity and ecosystem functioning across aquatic systems (Guy-Haim et al., 2018), reinforcing their systemic ecological influence.

Invasive species can also erode ecosystem services. Walsh et al. (2016) demonstrated that an invasion-driven trophic cascade caused substantial declines in water clarity, highlighting how ecological change can translate into major service losses and economic costs.

A key insight is that freshwater invasions rarely act alone. Instead, their establishment, spread, and impacts are shaped by broader Anthropocene change. Kernan (2015) stresses that aquatic ecosystems are subject to multiple simultaneous stresses and that the effects of invasive species are compounded by complex interactions among these pressures. Climate change is especially important in this regard because warming, altered hydrology, disturbance, and changing habitat suitability can facilitate invasion success and magnify impacts (Iyiola et al., 2024; Izah et al., 2023a; Ogwu and Izah, 2026). Experimental evidence supports this concern: Salis et al. (2023) report that successful invasions into freshwater systems double under climate warming. More broadly, global assessments of biodiversity and ecosystem services highlight biological invasions as a key driver of ecosystem transformation alongside climate change and land-use change (Díaz et al., 2019).

These issues are particularly important in African freshwater ecosystems, where invasions interact with existing pressures such as catchment degradation, eutrophication, altered flows, overexploitation, and weak monitoring capacity. Fouchy et al. (2019) describe African fresh waters as subject to multiple, overlapping stressors, while Egoh et al. (2020) show that invasive alien species in Africa threaten key ecosystem services and that priority-setting is needed to make management more effective. Shackleton et al. (2019) further demonstrate that invasive alien species shape local livelihoods and human well-being, underscoring that invasion impacts in Africa are simultaneously ecological and social. Given this, Africa is treated in this review as a related system rather than an exclusive focus—used to illustrate how global invasion dynamics manifest under conditions of limited monitoring capacity, high socio-ecological dependence, and overlapping stressors.

Specific freshwater cases illustrate this clearly. Omondi and Merceline (2023) identify invasive species as an important driver of ecological change in Lake Victoria, while Hill et al. (2020) show that South Africa has a long history of invasive alien aquatic plant management and that biological and integrated control programs have achieved widespread control in many degraded systems. Despite this growing body of work, important gaps remain in understanding how invasive species interact with other drivers of freshwater biodiversity decline, especially in African systems where long-term monitoring and accessible biodiversity data are still limited.

Against this background, this review adopts a multi-stressor perspective to examine invasive species as threat multipliers in freshwater ecosystems between 2015 and 2026. Specifically, it (i) synthesizes key ecological mechanisms through which invasive species drive biodiversity loss, (ii) evaluates how climate change and other stressors interact with invasion dynamics, (iii) assesses consequences for ecosystem functioning and ecosystem services, and (iv) reviews emerging monitoring and management responses, with particular attention to African freshwater systems.

## 2 Freshwater biodiversity in the Anthropocene

Freshwater ecosystems are among the most biologically diverse yet highly threatened ecosystems on Earth (Figure 1). Although they occupy less than 1% of the global surface area, they support a disproportionately large share of global biodiversity, including a significant fraction of vertebrate species and an even greater diversity of invertebrates and microorganisms. Despite this ecological importance, freshwater biodiversity is declining at rates that exceed those observed in terrestrial and marine systems, largely due to the cumulative and interacting effects of human activities (Dudgeon, 2019; Cazzolla Gatti, 2016). Table 1 provide the ecological impacts of invasive species in freshwater ecosystem. Recent global syntheses confirm that freshwater biodiversity decline is among the most rapid across all biomes, driven by a combination of habitat degradation, climate change, and biological invasions (Ogwu et al., 2022, 2023; Bhat et al., 2024; Seletlo et al., 2024).

The Anthropocene has intensified pressures on freshwater systems through rapid population growth, land-use change, industrialization, and climate change. These pressures manifest in multiple forms, including hydrological alteration (e.g., dams and water abstraction), pollution, habitat degradation, and biological invasions (Izah, 2022). Importantly, these drivers do not operate independently; rather, they interact in complex ways that amplify their combined impacts on biodiversity and ecosystem functioning (Dudgeon, 2019; Fouchy et al., 2019). For example, nutrient enrichment and eutrophication can create conditions that favor invasive aquatic plants, while altered flow regimes can facilitate the establishment and spread of non-native species.

While fishes and plants are well-covered, microbial invasions and cryptic invasions are equally important but frequently overlooked. Microorganisms, including bacteria, fungi, and viruses, can significantly alter ecological balances, particularly in freshwater systems, where they can function as silent invaders. These microbial invasions may not be immediately apparent but can lead to severe disruptions in water quality, nutrient cycling, and pathogen dynamics. Microbial invasions, although often cryptic, can significantly impact ecosystem functioning, especially through the introduction of non-native pathogens or the alteration of native microbial communities (Litchman, 2010; Thakur et al., 2019). These microorganisms can act as *hidden drivers* of biodiversity loss, influencing food webs, disease transmission, and nutrient dynamics in ways that are difficult to detect but no less impactful. For example, the introduction of non-native bacterial strains can shift the microbial community structure, thereby altering nitrogen cycling and eutrophication rates in freshwater systems (Chen et al., 2026; Tait et al., 2020).

At the global scale, models such as GLOBIO-Aquatic highlight the extensive human footprint on inland waters, demonstrating that biodiversity loss in freshwater systems is closely linked to land-use intensity, infrastructure development, and climate-related changes (Janse et al., 2015). Similarly, broader syntheses indicate that freshwater ecosystems are undergoing significant physical, chemical, and biological transformations, with invasive species representing a key biological component of these changes (Reid et al., 2019). Additional macroecological assessments show that invasion patterns are strongly influenced by environmental drivers such as climate, connectivity, and human activity, reinforcing the global-scale predictability of invasion processes (Colangelo et al., 2017).

In recent years, the understanding of freshwater biodiversity loss has shifted from single-driver explanations to multi-stressor frameworks. Heino et al. (2021) emphasize that lakes and other freshwater systems must be viewed as components of larger, interconnected landscapes, where regional and global processes influence local biodiversity patterns. This perspective is particularly relevant in the Anthropocene, where local ecosystems are increasingly shaped by global drivers such as climate warming, species introductions, and long-distance dispersal mechanisms (Peller and Altermatt, 2024). Furthermore, global biodiversity assessments highlight that multiple drivers) including invasive species, climate change, and land-use change (interact to accelerate ecosystem degradation, often producing non-linear and difficult-to-reverse impacts (Díaz et al., 2019; Hald-Mortensen, 2023).

Biological invasions represent a central element within this multi-stressor context. Aquatic ecosystems are especially vulnerable to invasive species due to their connectivity and exposure to human-mediated dispersal pathways, including shipping, aquaculture, and water transfer schemes (Havel et al., 2015; Izah et al., 2023b). Once established, invasive species can alter community composition, disrupt trophic interactions, and modify habitat structure, often leading to declines in native biodiversity (Ricciardi and MacIsaac, 2011; Gallardo et al., 2016). These impacts are further exacerbated when multiple invaders co-occur, as demonstrated by studies showing that combined invasion pressure can constrain both taxonomic and functional diversity in freshwater

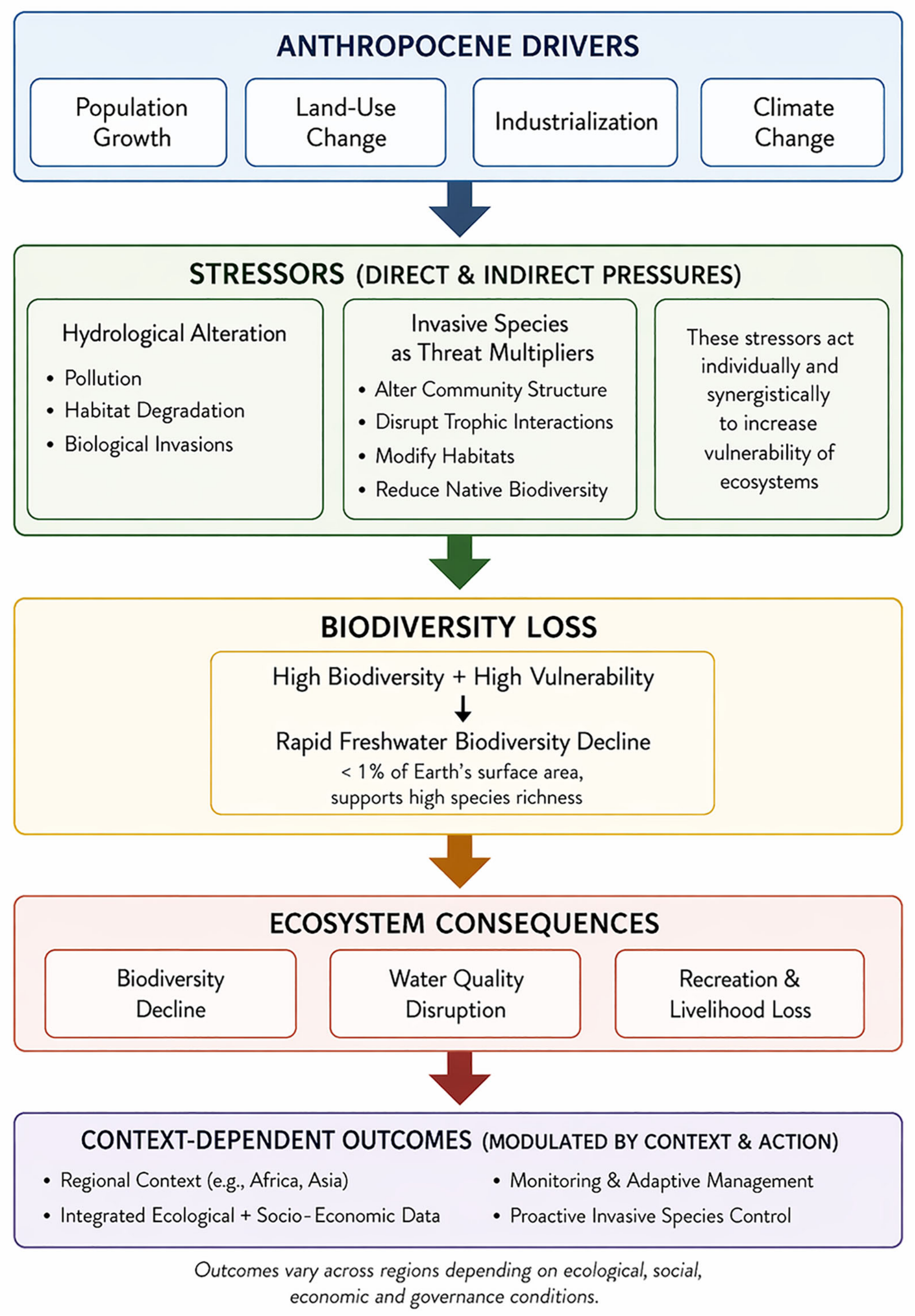


FIGURE 1
Drivers and consequences of freshwater biodiversity loss in the Anthropocene.

systems (Guareschi et al., 2021). Recent reviews further confirm that invasive alien species act as major drivers of biodiversity loss across aquatic systems, with consequences extending to ecosystem stability and resilience (Bir et al., 2022; Saidova et al., 2024).

Within this broader Anthropocene perspective, invasive species are not simply additional stressors but interact dynamically with hydrological alteration, pollution, and climate change to accelerate biodiversity loss. For example, nutrient enrichment and warming can increase the growth and competitive advantage of invasive macrophytes, while habitat fragmentation and altered flow regimes can facilitate the establishment of non-native fishes. These interactions reinforce the concept of invasive species as threat multipliers, particularly where stressors combine synergistically to produce amplified ecological impacts.

TABLE 1 Synthesized ecological impacts of invasive species in freshwater ecosystems.

| Study type | System/scale | Key quantified/qualitative impact | Impact category | Reference |
|---|---|---|---|---|
| Global meta-analysis | Global aquatic systems | 151 studies, 733 cases → consistent biodiversity decline, altered abundance, habitat modification | Multi-trophic ecological impacts | Gallardo et al. (2016) |
| Long-term empirical study | Rivers (England) | Invader richness significantly reduces biodiversity indices (WHPT, taxa richness) | Biodiversity reduction (quantitative) | Guareschi et al. (2021) |
| Ecosystem services study | Lake Mendota (USA) | Approximately 1 m clarity loss; 60% zooplankton decline; US$86–163M restoration cost | Ecosystem services + economic loss | Walsh et al. (2016) |
| Review (fish invasions) | Freshwater fish systems | Competition, predation, genetic introgression, pathogen spread | Direct biotic interactions | Britton (2023) |
| Review (ecosystem engineers) | Global freshwater | Habitat restructuring, resource modification | Habitat modification | Emery-Butcher et al. (2020) |
| Regional case study | Lake Victoria (Africa) | Large-scale food web alteration, biodiversity decline | Regional ecological transformation | Omondi and Merceline (2023) |
| Economic field assessment | Kenya lakes | Fish catch decline (90 → 10–15 kg/day); US $150–350M losses | Socio-economic impacts | Komu (2025) |
| Regional management review | South Africa | Spread linked to eutrophication and nutrient enrichment | Stressor interaction (eutrophication–invasion) | Hill et al. (2020) |

WHPT, Walley–Hawkes–Paisley–Trigg index.

The consequences of freshwater biodiversity loss extend beyond ecological integrity to affect ecosystem services that are critical for human societies (Izah and Aigberua, 2023). For instance, invasive species can trigger trophic cascades that reduce water quality and clarity, thereby affecting drinking water supply, recreation, and fisheries productivity (Walsh et al., 2016). In addition, changes in species composition can impair nutrient cycling, carbon sequestration, and other key ecosystem processes (Cantonati et al., 2020). Experimental and applied studies further demonstrate that invasive species can reduce ecosystem-service reliability, including nitrogen removal and water purification functions (Alldred et al., 2016), thereby linking biodiversity loss directly to ecosystem functionality.

In the African perspective, freshwater biodiversity faces particularly acute threats due to the convergence of rapid development, climate variability, and limited management capacity. Studies indicate that African freshwater systems are subject to multiple co-occurring stressors, including land-use change, pollution, and invasive species, which together drive ecosystem degradation (Fouchy et al., 2019; Egoh et al., 2020). Moreover, invasive species in Africa have been shown to impact biodiversity, ecosystem services, and local livelihoods, reinforcing the importance of integrated management approaches (Izah and Ogwu, 2023; Shackleton et al., 2019; Makhabu et al., 2024). Emerging regional studies also highlight the rapid spread of invasive aquatic plants and associated demographic dynamics, emphasizing the urgency of management interventions in sub-Saharan Africa (Ncube et al., 2025).

Importantly, these regional dynamics illustrate that the severity of invasion impacts is often context-dependent, shaped by governance capacity, monitoring availability, and socio-economic conditions. In many African systems, limited long-term data and constrained management resources may further amplify the role of invasive species as drivers of ecological change, highlighting the need for regionally tailored and data-informed approaches.

Given the complexity of these interacting drivers, there is a growing recognition that effective conservation of freshwater biodiversity in the Anthropocene requires holistic, system-level approaches. This includes improved monitoring, better integration of ecological and socio-economic data, and adaptive management strategies that can respond to changing environmental conditions (Bogardi et al., 2020; Stefanidis and Papastergiadou, 2024). In particular, recent advances in biodiversity prioritization tools and decision-support frameworks offer promising pathways for integrating invasive species management into broader conservation planning (Kingsbury et al., 2024).

Furthermore, freshwater biodiversity loss in the Anthropocene is driven by a network of interacting ecological and anthropogenic pressures, within which invasive species play a central and amplifying role. By interacting with climate change, pollution, and hydrological alteration, invasive species contribute disproportionately to ecosystem degradation, reinforcing their role as threat multipliers.

## 3 Invasive species as a major driver of freshwater biodiversity loss

Biological invasions are widely recognized as one of the most significant drivers of biodiversity change in freshwater ecosystems, particularly within the broader context of Anthropocene environmental change (Table 2). Freshwater systems are especially susceptible to invasion due to their connectivity, frequent disturbance, and strong linkage with human activities such as aquaculture, trade, water transfer, and transportation networks (Havel et al., 2015; Moorhouse and Macdonald, 2015). As a result, the introduction, establishment, and spread of non-native species have accelerated in recent decades, with substantial ecological consequences. Recent global syntheses confirm that invasive species are among the dominant drivers of biodiversity loss across aquatic ecosystems, often interacting with other stressors such as climate change and land-use change to produce compounded ecological impacts (Mayfield et al., 2021; Bir et al., 2022; Sesay et al., 2024).

TABLE 2 Interacting Anthropocene stressors: invasive species, climate change, and multiple threats.

| Study type | Focus | Major findings | Interaction type | Reference |
|---|---|---|---|---|
| Perspective | Freshwater biodiversity under multiple threats | Biodiversity loss driven by interacting pressures including climate change, dams, habitat degradation, and pollution | Additive and synergistic | Dudgeon (2019) |
| Review | Climate change and invasive species | Multiple stresses affect aquatic ecosystems and are compounded by invasive species interactions | Synergistic | Kernan (2015) |
| Experimental study | Climate warming and invasion success | Successful invasions into freshwater systems increase under warming conditions | Synergistic | Salis et al. (2023) |
| Review | Lakes under global change | Emphasizes system-level conservation beyond isolated ecosystems | Cross-scale interaction | Heino et al. (2021) |
| Regional synthesis | West African freshwater systems | Multiple stressors (pollution, deforestation, hydrological alteration) act simultaneously | Synergistic | Fouchy et al. (2019) |
| Data-driven program | Africa-wide | Freshwater degradation linked to habitat destruction, climate change, and invasions | Additive and synergistic | Freshwater Research Centre (2026) |

## 3.1 Mechanisms of biodiversity loss

The impacts of invasive species on freshwater biodiversity occur through multiple, often overlapping mechanisms (Figure 2). These include competition with native species, predation, hybridization, disease transmission, and habitat modification. Early foundational work highlighted that invasive species can fundamentally restructure freshwater communities and drive native species declines (Ricciardi and MacIsaac, 2011). More recent syntheses confirm that these effects are widespread and operate across multiple trophic levels. For example, Gallardo et al. (2016) demonstrated, through a global meta-analysis of 151 studies and 733 impact cases, that invasive species in aquatic ecosystems produce cascading ecological effects that influence biodiversity, species abundance, and ecosystem properties. Additional evidence indicates that invasive freshwater species affect multiple taxonomic groups, including fishes, macroinvertebrates, and aquatic plants, contributing to widespread ecological disruption across freshwater systems (Singh, 2021; Esmaeili et al., 2014).

The mechanisms through which invasive species influence biodiversity can be grouped into three broad and interacting pathways:

### 3.1.1 Direct biotic interactions

These include competition for resources, predation on native species, hybridization, and pathogen transmission. Invasive freshwater fishes, for example, can exert strong predatory and competitive pressures, often leading to declines or local extirpation of native species (Britton, 2023).

### 3.1.2 Habitat and ecosystem modification

Invasive organisms can act as ecosystem engineers, modifying physical habitats in ways that affect entire biological communities. These changes may include alterations in sediment structure, hydrology, nutrient availability, and habitat complexity. Such modifications often persist even after management interventions, making ecosystem recovery difficult (Emery-Butcher et al., 2020).

### 3.1.3 Food-web and system-level restructuring

Invasive species can trigger trophic cascades, alter energy flow, and promote biotic homogenization. These processes can restructure entire ecosystems, affecting biodiversity patterns and ecosystem functioning at multiple trophic levels (Gallardo et al., 2016).

## 3.2 Multi-invader dynamics and cumulative impacts

The impacts of invasive species are often intensified when multiple invaders co-occur within the same ecosystem. This phenomenon, often described as "invasional meltdown", can result in synergistic effects that exceed the impact of individual species (Ricciardi and Simberloff, 2025). Guareschi et al. (2021) provide strong empirical evidence for this in river ecosystems, showing that invader richness significantly constrains macroinvertebrate biodiversity and ecosystem functioning. Global analyses further indicate that multi-invader systems can generate disproportionately large ecological impacts, reinforcing the importance of considering cumulative invasion pressure rather than single-species effects (Guy-Haim et al., 2018; Thomaz et al., 2015).

These findings highlight that biodiversity loss in freshwater systems is frequently driven by the combined effects of multiple invasive species, rather than isolated invasion events. Consequently, management strategies must account for interactions among invaders and their cumulative ecological impacts.

## 3.3 Impacts on ecosystem functioning and services

Invasive species have profound effects on biodiversity, ecosystem functioning and ecosystem services. For example, Walsh et al. (2016) documented how an invasive species triggered a trophic cascade that led to significant reductions in water clarity, illustrating how ecological disruption can translate into declines in ecosystem services such as water quality and recreation.

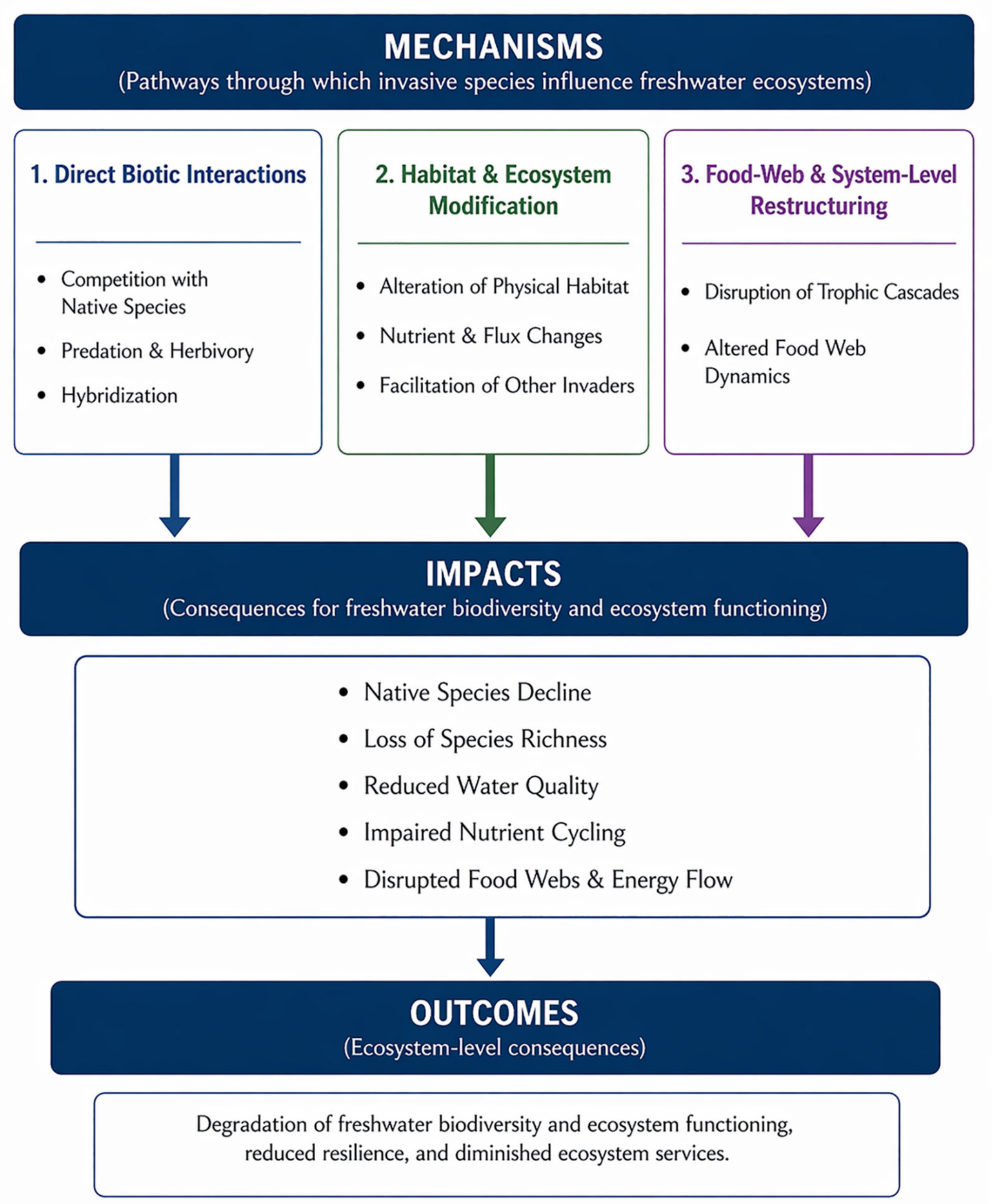


FIGURE 2
Mechanisms and ecosystem impacts of invasive species in freshwater systems.

Similarly, invasive aquatic plants can alter nutrient cycling, reduce oxygen availability, and disrupt aquatic food webs, thereby affecting fisheries productivity and water use. Experimental studies further demonstrate that invasive species can impair key ecosystem processes such as nitrogen removal and primary productivity, thereby reducing ecosystem resilience and service provision (Alldred et al., 2016). These impacts highlight that invasive species influence ecosystem functioning at multiple levels, from primary production to nutrient dynamics and energy transfer, ultimately affecting the capacity of freshwater systems to support human well-being.

## 3.4 Regional perspective: African freshwater systems

In African freshwater systems, invasive species have caused widespread ecological and socio-economic impacts. Invasive aquatic plants such as *Eichhornia crassipes* have led to reduced light penetration, oxygen depletion, and habitat loss, significantly altering aquatic environments (Hill et al., 2020).

In large lake systems such as Lake Victoria, invasive species have disrupted food webs and contributed to biodiversity declines (Omondi and Merceline, 2023). These ecological impacts are closely linked to socio-economic consequences, including reduced fisheries productivity, impaired water access, and negative effects on local livelihoods (Shackleton et al., 2019). Recent studies further highlight the rapid spread and demographic expansion of invasive aquatic species in African freshwater systems, emphasizing the increasing ecological and management challenges they pose (Ncube et al., 2025; Seletlo et al., 2024). These examples demonstrate that invasion impacts in African freshwater systems are strongly influenced by socio-ecological conditions, including dependence on aquatic resources and limited management capacity.

### 3.5 Invasive species as threat multipliers

In freshwater ecosystems, invasive species function as threat multipliers by amplifying the effects of other environmental stressors. This amplification occurs through three primary pathways:

- ✓ Enhancement of stressor intensity, such as increased eutrophication effects due to invasive macrophytes
- ✓ Expansion of spatial and temporal impacts, facilitated by the spread of invasive species across connected water systems
- ✓ Reduction of ecosystem resilience, through altered food webs and habitat degradation

These mechanisms explain why invasion impacts are often disproportionately severe in ecosystems already affected by climate change, pollution, or hydrological alteration.

### 3.6 Section synthesis

Invasive species affect freshwater biodiversity through interconnected mechanisms operating across biological, habitat, and ecosystem levels. These include direct species interactions, habitat modification, and system-level restructuring, all of which contribute to biodiversity loss and altered ecosystem functioning. By interacting with other environmental stressors, invasive species play a central and amplifying role in freshwater ecosystem degradation, reinforcing their characterization as threat multipliers within the Anthropocene.

## 4 Climate change and other interacting stressors

A defining feature of freshwater biodiversity loss in the Anthropocene is the interaction between multiple environmental stressors, among which climate change and biological invasions play particularly important and mutually reinforcing roles. Increasing evidence shows that invasive species do not act in isolation; rather, their establishment, spread, and ecological impacts are strongly mediated by climatic and environmental conditions. As a result, understanding freshwater biodiversity loss requires an integrated perspective that accounts for these interactions (Dudgeon, 2019; Kernan, 2015). Recent global assessments further emphasize that climate change, biological invasions, land-use change, and pollution act together as primary drivers of biodiversity decline, often producing non-linear and compounding ecological effects (Díaz et al., 2019; Hald-Mortensen, 2023). Figure 3 shows climate change and other interacting stressors in freshwater systems.

### 4.1 Climate change as a driver of invasion dynamics

Climate change influences freshwater ecosystems through rising temperatures, altered precipitation patterns, increased frequency of extreme events, and changes in hydrological regimes. These changes can directly affect species distributions, life-history traits, and ecosystem processes, while also indirectly facilitating biological invasions.

For instance, warming temperatures can expand the suitable habitat range for many invasive species, allowing them to establish in regions that were previously climatically unsuitable (Koncki and Aronson, 2015). Similarly, altered flow regimes and increased disturbance can create ecological niches that favor opportunistic invaders over native species (Hassan et al., 2019). Climate-driven shifts in thermal regimes and hydrological variability can alter competitive balances, often favoring invasive species with broad ecological tolerances, rapid growth rates, and high dispersal capacity.

Experimental and empirical evidence increasingly supports the role of climate change in enhancing invasion success. Salis et al. (2023) demonstrated that successful invasions into freshwater systems can increase significantly under warming conditions, providing strong evidence that climate change may accelerate invasion dynamics. Additional studies indicate that climate change can increase both the probability of invasion establishment and the magnitude of ecological impacts once invasions occur (Liu et al., 2024; Finnsson et al., 2025).

### 4.2 Interaction types: additive, synergistic, and antagonistic effects

The interaction between invasive species and other stressors can be broadly categorized into three types:

#### 4.2.1 Additive interactions

In additive interactions, the effects of multiple stressors accumulate without modifying each other. For example, habitat degradation and invasive species may independently reduce biodiversity, with total impact reflecting the sum of individual effects.

#### 4.2.2 Synergistic interactions

In synergistic interactions, the combined effects of stressors exceed the sum of their individual impacts. This is particularly common in freshwater systems, where climate change and eutrophication can enhance the growth and spread of invasive species, leading to amplified ecological consequences. For example, nutrient enrichment combined with invasive macrophytes can accelerate eutrophication, resulting in rapid declines in oxygen levels and biodiversity.

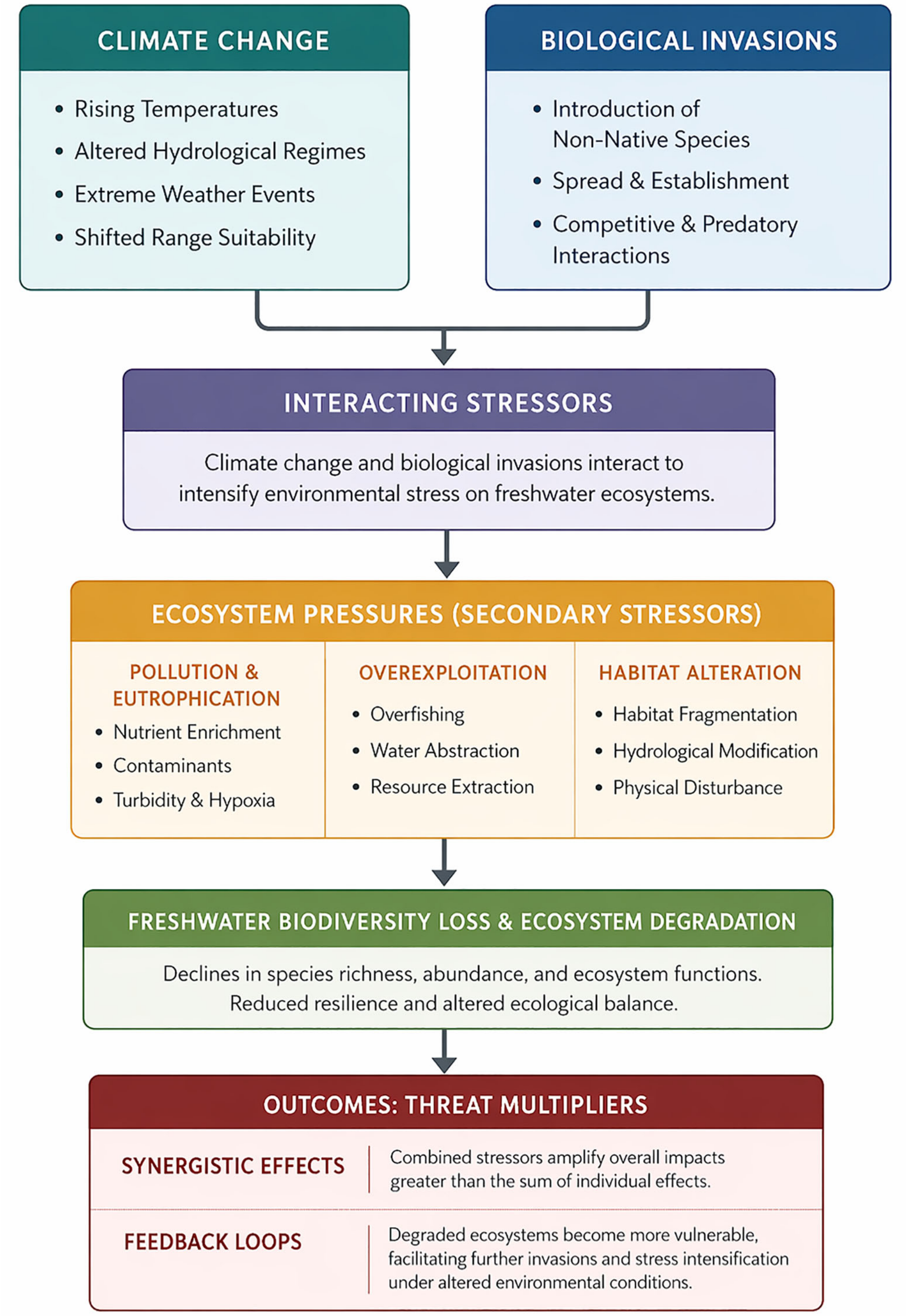


FIGURE 3
Climate change and other interacting stressors in freshwater systems.

### 4.2.3 Antagonistic interactions

In antagonistic interactions, one stressor reduces or modifies the effect of another. Although less commonly reported, such interactions may occur when environmental conditions limit the establishment or impact of invasive species.

## 4.3 Climate–invasion feedback mechanisms

The interaction between climate change and invasive species is not limited to establishment success but also extends to impact intensity and ecosystem feedbacks. Under changing environmental conditions, invasive species may exert stronger ecological effects by increasing metabolic rates, altering trophic interactions, or modifying habitat structure more rapidly.

Studies on aquatic invasive plants indicate that climate change can enhance both their growth and spread, thereby amplifying their ecological impacts on native biodiversity and ecosystem functioning (Hassan and Nawchoo, 2020). Similarly, invasive ecosystem engineers may respond to environmental change in ways that further modify habitat conditions, creating feedback loops that reinforce invasion success (Emery-Butcher et al., 2020). These feedback mechanisms create self-reinforcing cycles in which climate change facilitates invasion, and established invaders further reduce ecosystem resilience, increasing vulnerability to subsequent climatic stress. Figure 3 provide an overview of the climate change and other interacting stressors in freshwater systems.

## 4.4 Interactions with other anthropogenic stressors

In addition to climate change, freshwater ecosystems are influenced by a range of anthropogenic stressors, including pollution, eutrophication, habitat fragmentation, and overexploitation. These stressors often interact with biological invasions in complex ways. For example, nutrient enrichment from agricultural runoff can promote the growth of invasive macrophytes such as *Eichhornia crassipes*, while dam construction and flow regulation can facilitate the establishment of non-native fish species by altering habitat conditions.

Hydrological alteration, particularly through damming and water abstraction, can reduce flow variability and create stable environments that favor invasive species over native taxa adapted to dynamic conditions (Cantonati et al., 2020). Pollution, including heavy metals and organic contaminants, can further weaken native species and increase susceptibility to invasion, thereby enhancing the competitive advantage of tolerant invasive species (Izah et al., 2022). Importantly, these stressor interactions are often multiplicative, meaning that their combined effects exceed the sum of their individual impacts. This helps explain why invasion impacts are often disproportionately large in highly modified freshwater systems.

## 4.5 Cross-ecosystem linkages and spatial dynamics

Freshwater ecosystems are not isolated systems but are embedded within broader landscape and catchment-scale processes. As a result, invasion dynamics are often influenced by cross-ecosystem linkages, including the movement of organisms, nutrients, and energy across ecosystem boundaries. Recent studies highlight that invasive species can generate spillover effects that extend beyond the initial site of invasion, influencing adjacent aquatic and terrestrial systems (Peller and Altermatt, 2024).

These cross-system interactions complicate management efforts, as controlling invasive species in one location may not prevent reinvasion from connected systems. Dispersal pathways such as waterbirds, human transport, and hydrological connectivity play important roles in facilitating the spread of invasive species across freshwater networks (Reynolds et al., 2015).

## 4.6 Regional perspective: African freshwater systems under multiple stressors

In African freshwater systems, the interaction between invasive species and other stressors is particularly pronounced. These systems are subject to overlapping pressures, including land-use change, pollution, hydrological alteration, and climate variability, which together exacerbate biodiversity loss (Fouchy et al., 2019; Egoh et al., 2020). Limited monitoring capacity, rapid population growth, and strong dependence on freshwater resources further intensify the impacts of these interacting stressors in many African regions. In many cases, these stressors create environmental conditions that favor invasive species, leading to reinforcing cycles of ecosystem degradation. For example, nutrient enrichment and hydrological alteration can promote the expansion of invasive aquatic plants, which in turn degrade water quality and reduce ecosystem resilience.

## 4.7 Implications for monitoring and management

The interaction between climate change and other stressors has important implications for monitoring and management. As environmental conditions become more variable and unpredictable, traditional management approaches based on static assumptions may become less effective. Recent studies demonstrate that the detectability of aquatic invasive species can vary seasonally due to environmental conditions, highlighting the need for adaptive and dynamic monitoring strategies (Rounds et al., 2024). Similarly, long-term ecological monitoring is essential for understanding invasion dynamics and informing management decisions under changing environmental conditions. Integrated management approaches that simultaneously address invasive species and underlying stressors such as nutrient loading, habitat degradation, and climate vulnerability are increasingly recognized as essential for achieving sustainable outcomes.

## 4.8 Section synthesis

Climate change and other anthropogenic stressors interact with invasive species in complex and often synergistic ways, shaping invasion dynamics and amplifying ecological impacts. By enhancing invasion success, increasing impact intensity, and reducing ecosystem resilience, climate change reinforces the role of invasive species as threat multipliers in freshwater ecosystems. These interactions highlight the importance of adopting integrated, multi-stressor approaches to understanding and managing freshwater biodiversity loss in the Anthropocene.

## 5 Consequences for ecosystem functioning, ecosystem services, and public health

The consequences of freshwater biodiversity loss extend well beyond changes in species composition (Figure 4). In the Anthropocene, degradation of freshwater ecosystems increasingly translates into impaired ecosystem functioning, declining ecosystem services, and direct and indirect risks to human health (Izah, 2018; Izah et al., 2018; Izah and Seiyaboh, 2018a, b). Freshwater systems regulate water quality, nutrient cycling, habitat provision, food production, and cultural benefits, and thus biodiversity loss can destabilize ecological processes that societies depend on. Dudgeon (2019) emphasizes that the cumulative effects of multiple threats to freshwater biodiversity ultimately reduce ecosystem-service provision and negatively affect human well-being. Global assessments further indicate that biodiversity loss in freshwater ecosystems directly undermines ecosystem stability, resilience, and the capacity to sustain essential services such as water purification, fisheries productivity, and climate regulation (Díaz et al., 2019; Bhat et al., 2024).

### 5.1 Ecosystem functioning: from biodiversity change to process disruption

Freshwater biodiversity underpins key ecosystem processes, including primary production, nutrient cycling, decomposition, and energy transfer across trophic levels. Changes in species composition caused by invasive species and other stressors can disrupt these processes, leading to altered ecosystem functioning.

For example, invasive species can modify trophic interactions and energy pathways, often resulting in simplified food webs and reduced functional diversity. These changes can impair ecosystem stability and reduce the ability of systems to recover from disturbances. Invasive ecosystem engineers are particularly influential in this regard, as they can alter habitat structure, sediment dynamics, and hydrological conditions, leading to long-term changes in ecosystem processes (Emery-Butcher et al., 2020; Guy-Haim et al., 2018). In addition, invasive species can influence biogeochemical cycles by altering nutrient uptake, retention, and release. Experimental evidence shows that invasive species can reduce nitrogen removal efficiency and alter nutrient cycling pathways, thereby affecting water quality regulation functions (Alldred et al., 2016). These process-level changes highlight that biodiversity loss affects not only species richness but also the functional integrity of freshwater ecosystems.

### 5.2 Impacts on ecosystem services

The degradation of freshwater ecosystems has direct implications for ecosystem services that support human societies. These services include provisioning services (e.g., fisheries, water supply), regulating services (e.g., water purification, flood control), and cultural services (e.g., recreation and tourism). Invasive species can significantly reduce the quality and reliability of these services.

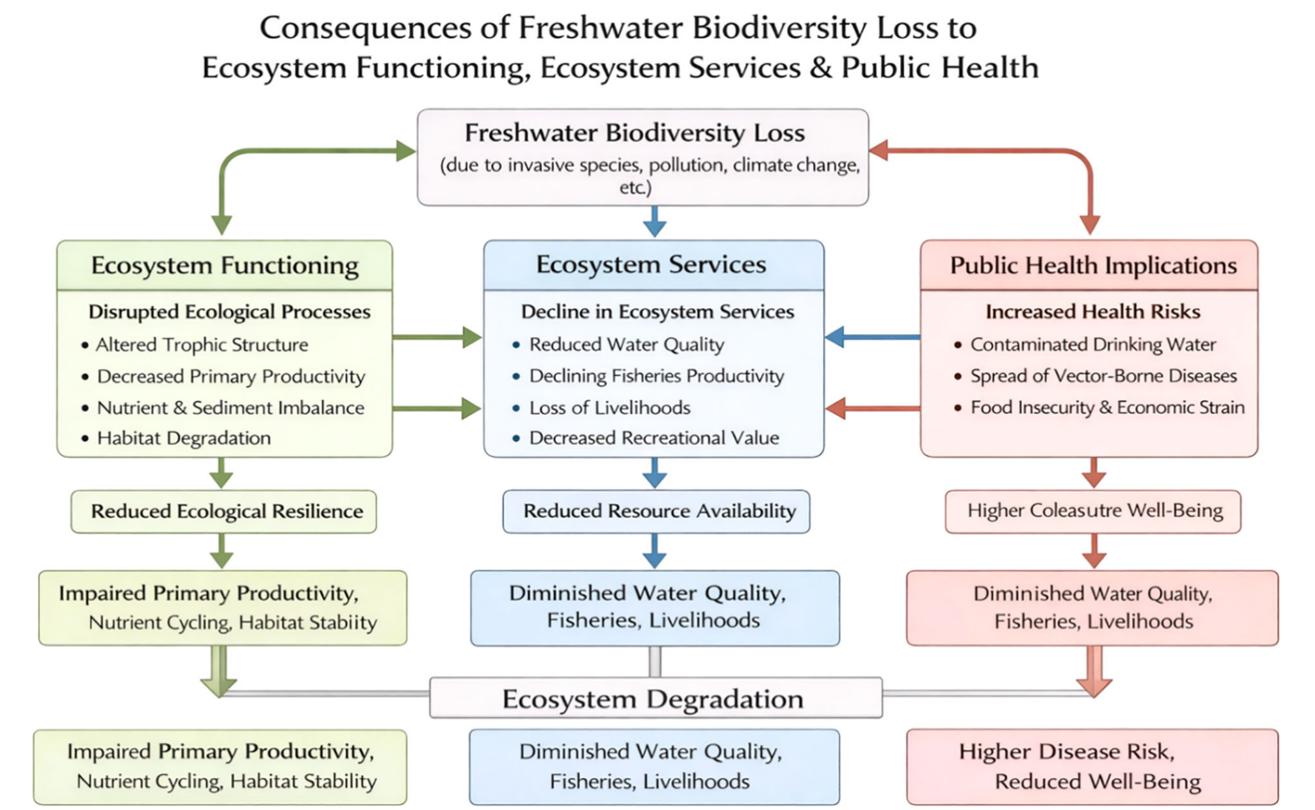


FIGURE 4
Consequences of freshwater biodiversity loss for ecosystem functioning, ecosystem services, and public health.

For example, invasion-driven trophic cascades can reduce water clarity and quality, affecting drinking water supplies and recreational use (Walsh et al., 2016). Economic assessments further demonstrate that invasive species can generate substantial financial losses through reduced fisheries productivity, increased water treatment costs, and impacts on tourism and recreation (Komu, 2025; Moore, 2025).

In freshwater fisheries, invasive species can alter species composition, reduce native fish populations, and disrupt food webs, leading to declines in fish yields and economic returns. Case studies from African freshwater systems show that invasive aquatic plants can significantly reduce fish catches and negatively affect livelihoods dependent on fisheries resources (Ncube et al., 2025; Seletlo et al., 2024). In addition, invasive species can affect water supply and quality by altering nutrient dynamics, increasing sedimentation, and promoting algal blooms. Such changes can increase the cost and complexity of water treatment and reduce access to safe drinking water, particularly in regions with limited infrastructure.

### 5.3 Public health implications

Freshwater ecosystem degradation also has important implications for public health. Changes in biodiversity and ecosystem functioning can influence the distribution and abundance of disease vectors, pathogens, and harmful organisms. For example, invasive species can alter habitat conditions in ways that favor disease vectors such as mosquitoes or snails, potentially increasing the risk of waterborne and vector-borne diseases. Alterations in water quality caused by invasive species and eutrophication can promote the proliferation of harmful algal blooms and pathogenic microorganisms, posing risks to human health through drinking water and recreational exposure. In addition, reduced water quality and availability can affect sanitation, hygiene, and overall health outcomes, particularly in vulnerable communities. These impacts are especially significant in developing regions, where reliance on freshwater resources is high and access to alternative water sources and treatment systems may be limited.

### 5.4 Socio-ecological consequences

The impacts of freshwater biodiversity loss extend beyond ecological and health dimensions to include broader socio-economic and cultural effects. Many communities depend directly on freshwater ecosystems for food, income, and cultural practices. Invasive species can disrupt these socio-ecological systems by reducing resource availability, increasing management costs, and altering ecosystem dynamics. Studies indicate that invasive species can significantly affect local livelihoods, particularly in regions where communities rely heavily on fisheries, agriculture, and water resources (Shackleton et al., 2019; Seletlo et al., 2024). In addition, the loss of biodiversity and ecosystem services can reduce resilience to environmental change, making communities more vulnerable to climate variability and extreme events. This highlights the importance of integrating ecological, social, and economic considerations in freshwater management and conservation strategies.

### 5.5 Feedbacks between ecosystem degradation and human systems

The relationship between freshwater ecosystem degradation and human systems is characterized by feedback loops. Human activities contribute to biodiversity loss and ecosystem degradation, while the resulting decline in ecosystem services further affects human well-being and economic development. Invasive species play a key role in these feedbacks by reinforcing ecosystem degradation and reducing the capacity of freshwater systems to recover from disturbances. For example, reduced water quality can lead to increased reliance on alternative water sources, which may further stress freshwater systems. Similarly, declining fisheries can lead to increased exploitation of remaining resources, exacerbating ecological pressures. These feedback mechanisms illustrate the interconnected nature of ecological and human systems and underscore the need for integrated management approaches.

### 5.6 Section synthesis

Freshwater biodiversity loss has far-reaching consequences for ecosystem functioning, ecosystem services, and public health. By disrupting ecological processes, reducing service provision, and increasing risks to human health and livelihoods, invasive species contribute significantly to the socio-ecological impacts of freshwater ecosystem degradation. These impacts reinforce the role of invasive species as threat multipliers, linking ecological change to human well-being and highlighting the need for integrated, system-level management strategies.

## 6 Monitoring, control, and management responses

Effective management of invasive species in freshwater ecosystems requires integrated approaches that account for the complexity of multi-stressor interactions and the dynamic nature of Anthropocene environmental change. Traditional management strategies that focus on single species or isolated ecosystems are often insufficient to address the scale and interconnectedness of invasion processes. Accordingly, there is increasing recognition that invasive species management must be embedded within broader ecosystem-based and multi-stressor frameworks to achieve long-term ecological outcomes.

In this perspective, invasive species management should be understood as part of a wider effort to address interacting stressors, reinforcing the view of invasive species as threat multipliers whose impacts cannot be effectively mitigated in isolation. Figure 5 shows the overview of monitoring, control and management responses to invasive species in freshwater ecosystems.

### 6.1 Monitoring and early detection

Early detection is a critical component of invasive species management, as it increases the likelihood of successful

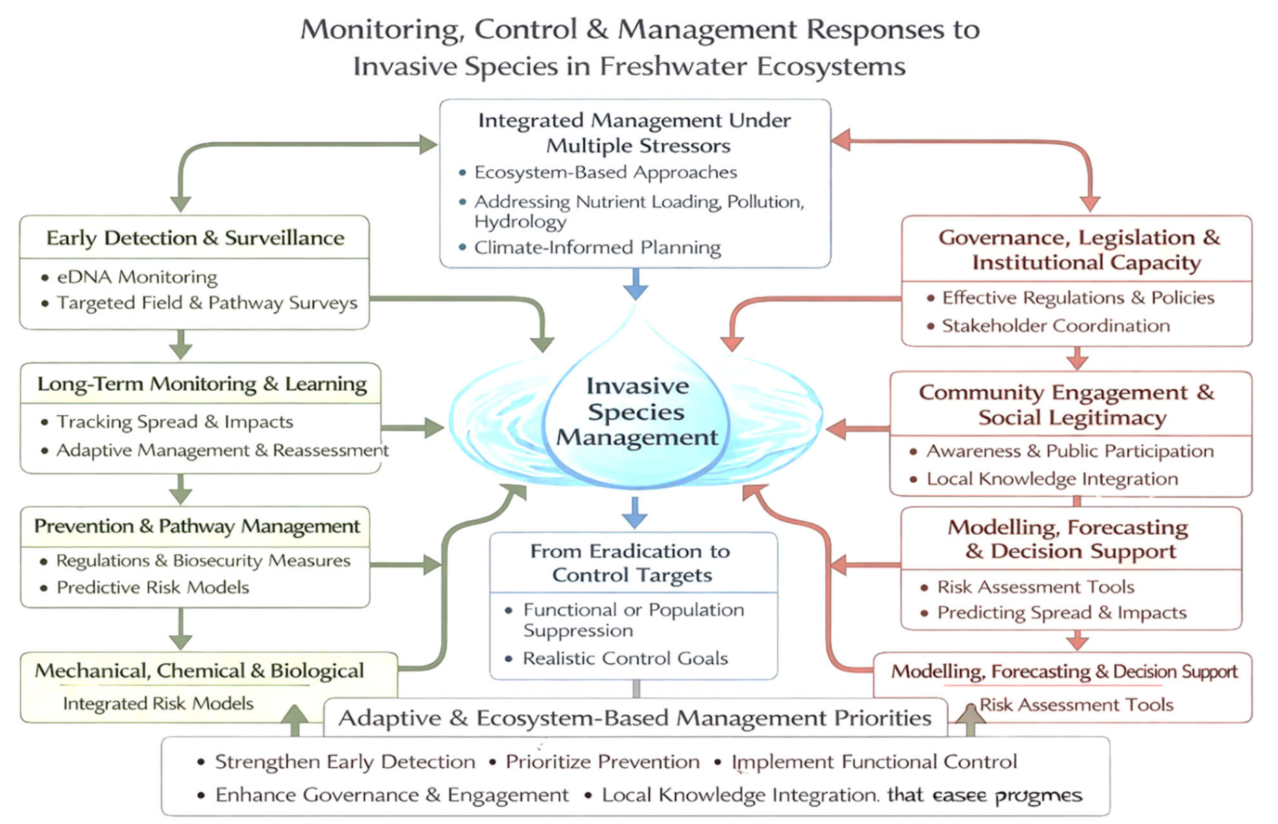


FIGURE 5
Monitoring, control and management responses to invasive species in freshwarer ecosystems.

intervention before species become widely established. Traditional monitoring methods, such as field surveys and taxonomic identification, remain important but can be time-consuming and limited in spatial and temporal coverage. Recent studies indicate that detectability of aquatic invasive species can vary depending on environmental conditions and seasonal dynamics, highlighting the need for adaptive monitoring approaches (Rounds et al., 2024).

Emerging technologies such as environmental DNA (eDNA) analysis provide powerful tools for detecting invasive species at low abundances, enabling more rapid and sensitive monitoring across freshwater systems. eDNA-based approaches allow for the identification of species presence through genetic material in water samples, making it possible to detect invasive species even when they are not directly observable.

Vander Zanden et al. (2024) emphasize that long-term ecological monitoring combined with emerging detection tools can significantly improve understanding of invasion dynamics and support evidence-based management decisions. In addition, integrating eDNA with conventional monitoring and spatial tools such as GIS can improve detection efficiency and provide early warning signals for invasion spread.

## 6.2 Prevention and biosecurity measures

Prevention remains the most cost-effective strategy for managing invasive species. Once established, invasive species are often difficult or impossible to eradicate, making it essential to reduce the risk of introduction and spread. Key pathways for the introduction of invasive species include aquaculture, shipping, trade, and water transfer systems. Strengthening biosecurity along these pathways, including regulation of species introductions and improved monitoring of high-risk vectors, is essential for reducing invasion risks. Policy frameworks at national and international levels play a critical role in prevention. Given the connectivity of freshwater systems, coordinated policies across regions and transboundary cooperation are necessary to effectively manage invasion pathways and limit spread.

## 6.3 Control and management strategies

Where invasive species are already established, a range of control and management strategies can be employed. These include mechanical removal, chemical control, biological control, and integrated management approaches. Mechanical methods, such as harvesting or physical removal, can be effective for managing invasive plants but may be labor-intensive and costly. Chemical control can provide rapid results but may have unintended ecological impacts if not carefully managed. Biological control, which involves the introduction of natural enemies to control invasive species populations, has been successfully applied in some freshwater systems, particularly for invasive aquatic plants (Hill et al., 2020). Integrated management approaches that combine multiple control methods are increasingly recognized as more effective because they address different stages of invasion and reduce reliance on any single method.

### 6.4 Functional eradication and long-term management

Complete eradication of invasive species is often unrealistic, particularly in large or highly connected freshwater systems. As a result, the concept of functional eradication has gained increasing attention. Functional eradication refers to reducing invasive species populations to levels where their ecological impacts are minimal, even if complete removal is not achieved. This approach aligns with ecosystem-based management by prioritizing ecological outcomes and system recovery rather than total species elimination. Functional eradication is particularly relevant in systems where invasive species have become deeply integrated into ecosystem processes, requiring sustained and adaptive management over time.

### 6.5 Climate-aware and multi-stressor management

Given the strong interactions between invasive species and other stressors, effective management must address underlying environmental drivers in addition to invasion processes. Kernan (2015) emphasizes that aquatic ecosystems are subject to multiple interacting stresses, and that addressing these interactions is critical for effective management. Climate change can further complicates management by altering environmental conditions, species distributions, and invasion dynamics, necessitating climate-aware management strategies. For example, reducing nutrient loading and restoring natural flow regimes can help limit the spread and impact of invasive species by improving ecosystem resilience (Cantonati et al., 2020). Addressing co-occurring stressors such as eutrophication, pollution, and hydrological alteration is therefore essential for achieving long-term success in invasive species management.

### 6.6 Regional perspective: management in African freshwater systems

In African freshwater systems, management of invasive species faces additional challenges, including limited financial resources, insufficient monitoring capacity, and competing socio-economic priorities. Fouchy et al. (2019) and Egoh et al. (2020) highlight that freshwater systems in Africa are subject to multiple overlapping stressors, which complicate management efforts. Despite these challenges, successful management initiatives demonstrate that integrated approaches combining biological control, policy support, and stakeholder engagement can achieve meaningful outcomes (Hill et al., 2020). Shackleton et al. (2019) further show that invasive species management in Africa must consider socio-economic dimensions, particularly the dependence of local communities on freshwater resources. Community-based approaches that involve local stakeholders in monitoring and management can improve effectiveness and sustainability of interventions. In addition, improving access to biodiversity data and strengthening institutional capacity are critical for supporting evidence-based decision-making across the region.

### 6.7 Policy and governance considerations

Effective governance is essential for managing invasive species and addressing freshwater biodiversity loss. This includes the development and implementation of policies that regulate species introductions, support monitoring and control efforts, and promote sustainable resource use. Woodford et al. (2017) demonstrate that management of invasive freshwater species is closely linked to legislative and governance frameworks, particularly in systems where policy and enforcement capacity influence outcomes. Adaptive governance approaches that integrate scientific knowledge, stakeholder participation, and flexible decision-making are increasingly necessary for managing complex freshwater systems. Transboundary cooperation is particularly important in freshwater systems, where rivers and lakes often span multiple jurisdictions. Coordinated governance frameworks can enhance management effectiveness by aligning policies and facilitating shared responses to invasion threats.

### 6.8 Section synthesis

Monitoring, management, and policy responses to invasive species in freshwater ecosystems must account for the complexity of multi-stressor interactions and the dynamic nature of environmental change. By integrating early detection, prevention, control strategies, and climate-aware management, it is possible to reduce the impacts of invasive species while enhancing ecosystem resilience. These approaches highlight the importance of holistic, system-level strategies that address both invasive species and the broader environmental drivers of freshwater biodiversity loss.

## 7 Knowledge gaps and future directions

Despite the growing body of research on invasive species and freshwater biodiversity loss, several important knowledge gaps remain. Addressing these gaps is essential for improving understanding of invasion dynamics and for developing more effective management strategies in the Anthropocene. Figure 6 summarizes the major knowledge gaps and future research priorities in freshwater invasion ecology, highlighting key areas where further investigation is required to improve both scientific understanding and management outcomes.

### 7.1 Multi-invader interactions and cumulative impacts

Although the impacts of individual invasive species are relatively well documented, less is known about how multiple invasive species interact within the same ecosystem. Evidence suggests that co-occurring invaders can produce synergistic effects, often leading to greater ecological impacts than single-species invasions (Guareschi et al., 2021). Typically, multi-invader interactions

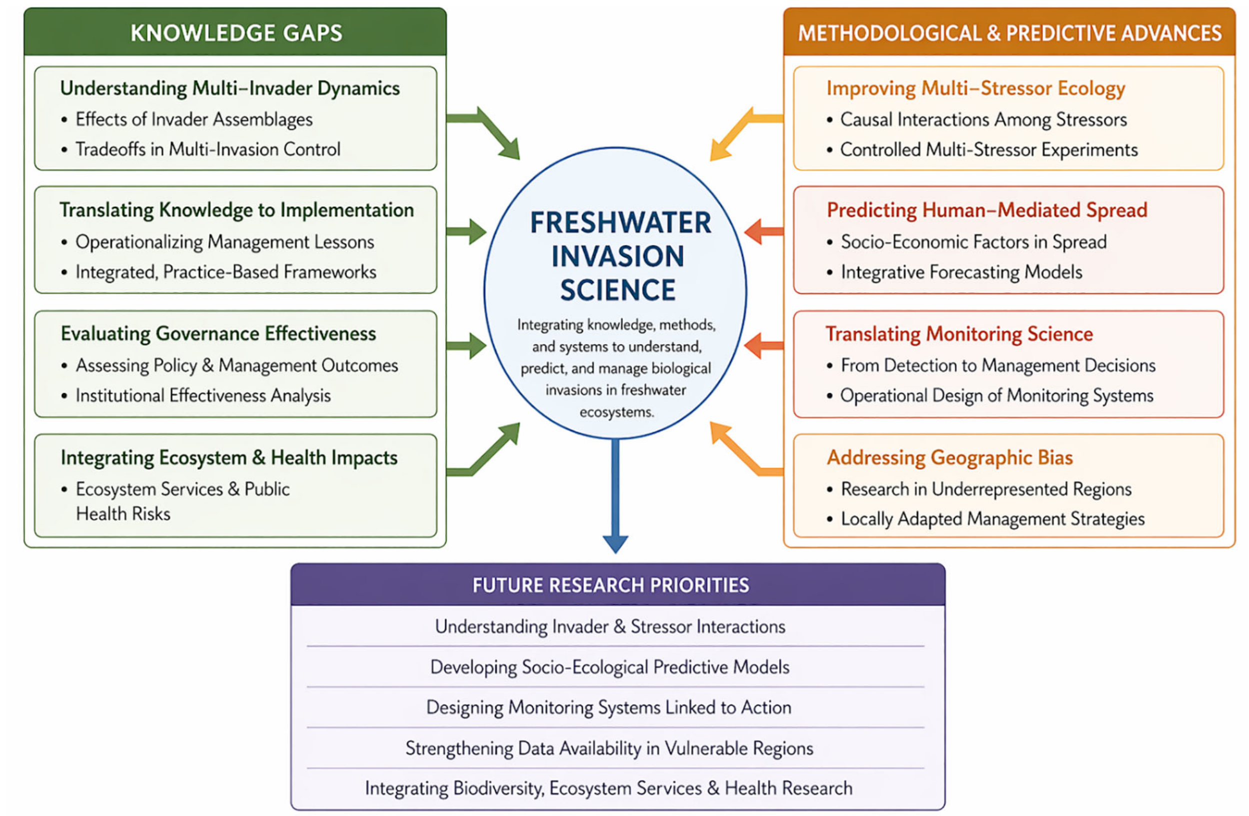


FIGURE 6
Key knowledge gaps and future research directions in freshwater invasion ecology.

represent a central knowledge gap, particularly in understanding how cumulative invasion pressure alters ecosystem stability and biodiversity outcomes. However, there is still limited understanding of the mechanisms underlying these interactions, including how species traits, environmental conditions, and community structure influence cumulative impacts.

Therefore, future research should focus on:

✓ Quantifying combined effects of multiple invaders,
✓ Identifying thresholds where invasion impacts become non-linear, and
✓ Understanding how multi-invader systems influence ecosystem resilience

## 7.2 Interaction with climate change and other stressors

The interaction between invasive species and other environmental stressors, particularly climate change, remains an area of active research. While studies show that warming can facilitate invasion success (Salis et al., 2023), the long-term consequences of these interactions are not fully understood. This highlights the need to better integrate invasion ecology with climate and multi-stressor frameworks, particularly in quantifying additive, synergistic, and antagonistic interactions (Kernan, 2015).

Therefore, future work should:

✓ Develop predictive models linking climate scenarios to invasion risk,
✓ Assess how environmental variability affects invasion outcomes, and
✓ Examine feedback mechanisms between stressors and invasion processes

## 7.3 Seasonal dynamics and detectability

Monitoring invasive species in freshwater systems is complicated by temporal variability, including seasonal changes in species abundance and detectability. Rounds et al. (2024) highlight that detection probability can vary significantly depending on environmental conditions, which can lead to underestimation of invasion extent. Basically, seasonal variability in detectability represents a key methodological gap that can influence monitoring accuracy and management decisions.

Therefore, future research should:

✓ Optimize monitoring protocols across seasons,
✓ Integrate eDNA and conventional sampling approaches, and
✓ Develop standardized detection frameworks for freshwater systems

## 7.4 Cross-ecosystem linkages and spatial scaling

Freshwater ecosystems are embedded within broader landscape and catchment-scale processes, yet many studies still focus on isolated systems. Recent work suggests that invasive species can generate cross-ecosystem effects, influencing adjacent aquatic and terrestrial systems (Peller and Altermatt, 2024). This suggests the importance of cross-ecosystem linkages, particularly in understanding how invasion processes operate across spatial scales and connected freshwater networks.

Therefore, future research should:

✓ Investigate dispersal pathways across connected ecosystems,
✓ Quantify spillover effects between aquatic and terrestrial systems, and
✓ Incorporate landscape-scale perspectives into invasion ecology

## 7.5 Long-term ecological change and legacy effects

Many studies on invasive species focus on short-term impacts, while long-term ecological changes and legacy effects remain less well understood. Invasive species can produce persistent changes in ecosystem structure and function, even after their populations decline or are controlled. Furthermore, long-term ecological change and legacy effects represent a critical gap in current research, particularly in understanding recovery trajectories and irreversible ecosystem shifts.

Therefore, future research should:

✓ Conduct long-term monitoring of invaded systems,
✓ Assess recovery trajectories following control measures, and
✓ Evaluate irreversible ecosystem shifts caused by invasions

## 7.6 Data gaps and regional disparities

There are significant geographical disparities in freshwater invasion research, with many regions, particularly in Africa, underrepresented in global datasets. Fouchy et al. (2019) and Egoh et al. (2020) highlight the limited availability of long-term ecological data in African freshwater systems, which constrains understanding of invasion dynamics and impacts. Based on the regional data gaps as a major limitation, the need for improved biodiversity data coverage and monitoring capacity in underrepresented regions.

Therefore, future priorities should include:

✓ Expanding biodiversity databases in underrepresented regions,
✓ Enhancing collaboration across institutions and countries, and
✓ Supporting capacity building in freshwater research and monitoring

## 7.7 Climate-ready and adaptive management

As environmental conditions continue to change, there is a growing need for management strategies that are robust to uncertainty and adaptable to future conditions. Traditional static management approaches are often insufficient under dynamic climate and ecological conditions; this underscores the importance of developing climate-ready and adaptive management frameworks that integrate ecological monitoring, predictive modeling, and flexible decision-making. To enhance practical utility, the following climate-ready protocols are recommended for managers across sectors. In the context of fisheries, climate-ready protocols include adjusting harvest quotas seasonally based on predictive models of stock abundance and climate variability, and revising spatial management boundaries to account for shifts in species distributions due to warming ocean conditions. These approaches have been explored in adaptive fisheries literature that seeks proactive responses to climate impacts (Wilson et al., 2018). For water infrastructure, designing and operating systems that can withstand extremes such as floods and droughts includes building storage capacity, rehabilitating irrigation networks, and incorporating adaptive design standards for future climate variability (Jain et al., 2025). Brewington et al. (2024) recommended the incorporation of invasive species into U.S. climate change adaptation planning and policy, advocating for investments in climate-ready infrastructure and adaptation plans to ensure physical assets are protected through land management and wildfire prevention strategies. Other notable examples include the adoption of climate-ready seeds for agriculture, as suggested by Saab (2015), to enhance resilience and improve crop yields under changing environmental conditions.

Managing microbial invasions requires new detection tools, such as metagenomic sequencing or environmental DNA (eDNA) sampling (Morisette et al., 2021; McGaughran et al., 2024), which can identify microbial communities before visible impacts are felt. Early identification is vital for preventing outbreaks of invasive pathogens, such as aquatic bacteria that may exacerbate the effects of climate warming on local biodiversity. As environmental stressors, microbial invasions need to be considered within climate-ready management frameworks, especially because they can remain cryptic, evolving within the ecosystem unnoticed until the consequences are severe. Climate change may facilitate these invasions, making the identification of microbial threats a crucial component of adaptive management.

Therefore, future directions should include:

✓ Developing climate-ready management frameworks,
✓ Incorporating uncertainty into decision-making processes, and
✓ Linking ecological monitoring with adaptive management strategies

## 7.8 Section synthesis

Significant progress has been made in understanding the role of invasive species in freshwater ecosystems, but important gaps remain in knowledge of multi-invader interactions, stressor interactions, seasonal dynamics, spatial processes, and long-term ecological change. Addressing these gaps requires interdisciplinary approaches, improved data availability, and integration of ecological, climatic, and socio-economic perspectives. Also, advancing research in these areas will be essential for developing effective, climate-resilient strategies to manage invasive species and conserve freshwater biodiversity in the Anthropocene.

## 8 Conclusion

Freshwater ecosystems, although covering a small proportion of the Earth's surface, support exceptionally high biodiversity and provide critical ecosystem services. In the Anthropocene, these systems are increasingly threatened by interacting stressors, including climate change, pollution, habitat degradation, hydrological alteration, and biological invasions. This review highlights invasive species as a major driver of freshwater biodiversity loss, acting through mechanisms such as competition, predation, habitat modification, and food-web restructuring. A key contribution of this study is the conceptualization of invasive species as "threat multipliers", emphasizing their role in amplifying the intensity, spatial extent, and persistence of other environmental stressors. By interacting with factors such as warming, eutrophication, and altered flow regimes, invasive species accelerate ecosystem degradation, reduce ecological resilience, and produce disproportionately large impacts on biodiversity, ecosystem functioning, and ecosystem services, including water quality, fisheries, and public health.

The review further demonstrates that effective management of invasive species requires integrated, multi-stressor approaches that combine early detection, prevention, control strategies, and climate-aware management. Advances in monitoring tools, including eDNA and spatial analysis, provide new opportunities for improving detection and understanding invasion dynamics, while governance frameworks and stakeholder engagement remain essential for sustainable management. Despite these advances, significant knowledge gaps persist, particularly in multi-invader interactions, seasonal detectability, cross-ecosystem processes, long-term ecological change, and regional data disparities. Addressing these gaps through interdisciplinary research, improved data availability, and adaptive management will be critical for developing climate-resilient strategies. Recognizing invasive species as threat multipliers provides a unifying framework for understanding freshwater ecosystem degradation and for guiding more effective, system-level conservation efforts in the Anthropocene.

## Author contributions

SI: Writing – original draft, Project administration, Methodology, Data curation, Visualization, Validation, Conceptualization, Funding acquisition, Supervision, Writing – review & editing. MO: Writing – original draft, Visualization, Methodology, Validation, Conceptualization, Writing – review & editing. VP: Writing – review & editing, Writing – original draft. EA: Writing – review & editing, Writing – original draft. WP: Writing – review & editing, Writing – original draft. AK: Writing – review & editing, Writing – original draft. MR: Writing – review & editing, Writing – original draft.

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## Publisher's note

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