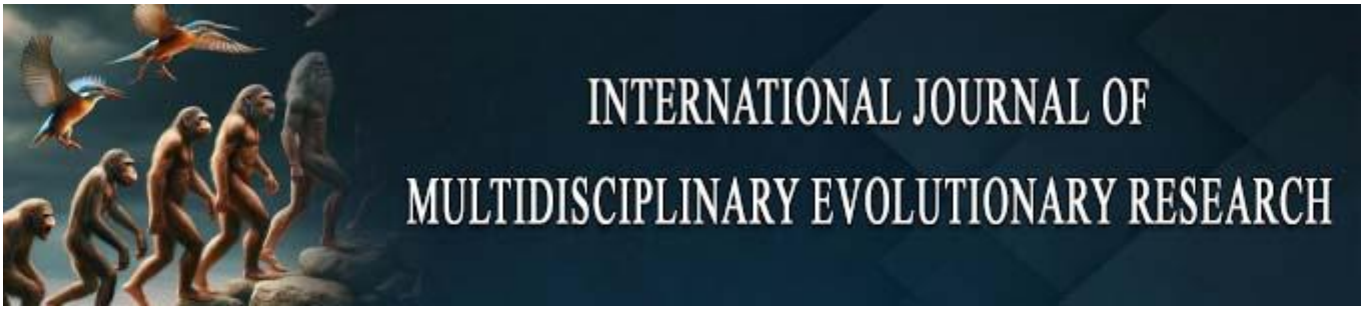

Comparative Analysis of Native and Invasive Fish Species Impact on Freshwater Ecosystem Services

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Abstract
This study provides a detailed comparison of the different roles and impacts of two distinct types of aquatic animals in inland water systems. It examines their ecological contributions, interactions, and effects on environmental services. The research synthesizes evidence from various global sources, with a focus on Africa and specific applications in Nigeria, to explore their functional roles, ecological pressures, and socio-economic aspects. A systematic review of literature was used, incorporating empirical studies, case analyses, and thematic assessments. The study emphasizes identifying key ecological mechanisms, recording habitat impacts, evaluating new monitoring technologies, and suggesting adaptive management strategies.
The findings show that species established within ecosystems over long evolutionary periods are essential for maintaining nutrient cycling, trophic stability, habitat complexity, and biodiversity resilience. Conversely, recently introduced species, though sometimes providing short-term functional or economic benefits, generally cause ecological disturbances through predation, competition, hybridization, habitat destruction, and pathogen transfer. Interactions between these two groups can produce complex and context-dependent results, sometimes partly compensating for lost functions but often compromising long-term ecological integrity. Technological advances—including environmental DNA metabarcoding, passive acoustic monitoring, biotelemetry, parasite community profiling, and decision-support systems—are seen as transformative tools for detection, assessment, and monitoring, though their widespread use is limited by governance, funding, and capacity challenges.
The study concludes that protecting the stability and productivity of these aquatic systems requires integrated and adaptable strategies that combine ecological restoration with socio-economic considerations. Recommendations emphasize strengthening monitoring systems, adopting more advanced assessment tools, implementing inclusive governance models, and incorporating ecosystem service valuation into policy and management. By aligning conservation goals with human needs, sustainable management of these systems is possible despite the challenges caused by biological invasions.

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1. Introduction

Freshwater ecosystems represent vital reservoirs of biodiversity, supporting essential ecological processes and delivering a wide range of ecosystem services fundamental to human livelihoods and environmental stability. Despite covering less than 1% of the Earth's surface, these systems sustain an exceptionally high proportion of global species diversity and contribute significantly to ecological functionality and economic value (Chakraborty, 2023). However, their stability, biodiversity, and capacity to provide critical services are increasingly threatened by the proliferation of invasive fish species, which disrupt ecological balance and undermine the well-being of dependent communities.

A striking example is Lake Victoria, where the deliberate introduction of the Nile perch (Lates niloticus) in the mid-20th century has resulted in the extinction or near extinction of numerous endemic cichlid species, precipitating one of the most dramatic vertebrate extinction events of the modern era (Pringle, 2005). The socio-economic fallout was no less profound, with traditional fisheries disrupted, deforestation escalated due to increased smoking of oil-rich Nile perch, and shifts in community livelihoods locked into export-oriented fisheries (Pringle, 2005). This case provides a sobering illustration of how invasive fish can transform freshwater ecosystems in both ecological and socio-economic dimensions.

At the continental scale in Africa, invasive species—notably aquatic plants such as water hyacinth—impose massive economic burdens. In Nigeria alone, estimated annual costs due to invasive species reach approximately USD 50 million, while mitigation efforts in East Africa's Lake Victoria have required millions annually (Kasulo, 2000). These investments underscore the dual recognition of both the severity of invasion impacts and the urgency of management responses.

Beyond the African context, the issue is a global concern, with non-native fish altering biogeographic patterns across numerous river basins. Evidence shows that such species have successfully established themselves in over half of the world's major basins, often aided by the presence of ecologically similar native species. This widespread colonisation raises significant challenges for biodiversity conservation and the maintenance of ecosystem service resilience, particularly in light of the increasing rate of introductions through aquaculture, the ornamental fish trade, and accidental releases (Francis, Chadwick, and Turbelin, 2019).

The demand for structured risk assessments in this domain has led to the development and widespread application of tools such as the Fish Invasiveness Screening Kit (FISK). This decision-support framework has proven instrumental in evaluating the potential invasiveness of fish species across 45 countries, enabling more informed management decisions (Copp *et al*., 2019).

Africa's freshwater scientific community has responded by generating regionally relevant research and collaborations to tackle these multifaceted challenges (Masese *et al*., 2023). However, gaps remain in monitoring, governance, and policy frameworks, particularly in contexts where socio-economic vulnerabilities and institutional limitations constrain effective responses.

Moreover, the impacts of invasive fish on ecosystem services—covering provisioning, regulating, cultural, and supporting functions—are complex and frequently underestimated. Such species can impair water quality by altering nutrient dynamics and increasing turbidity, with subsequent effects on drinking water availability, fisheries productivity, and recreational opportunities. As Neves *et al*. (2020) note, understanding these cascading consequences requires forward-looking scientific approaches, interdisciplinary perspectives, and scalable management strategies to effectively address and mitigate the challenges posed by biological invasions.

This review, therefore, embarks on a comparative analysis of the impacts of native versus invasive fish species on freshwater ecosystem services. It seeks to synthesize empirical and theoretical knowledge, drawing on global data, regional case studies, and decision-support frameworks to provide an integrative understanding of how fish invasions reconfigure ecosystem function and human utility.

The primary aim of this study is to conduct a comprehensive comparative analysis of the ecological and socio-economic impacts of native and invasive fish species on freshwater ecosystem services globally. The objective is threefold: first, to delineate and evaluate the differential roles and consequences of native versus invasive fish species across provisioning, regulating, cultural, and supporting services; second, to assess the scope and efficacy of existing risk assessment tools and management strategies—such as FISK—in mitigating invasive species threats; and third, to integrate case-specific insights—from Lake Victoria to broader river basin networks worldwide—with the goal of identifying knowledge gaps, socio-economic trade-offs, and governance challenges. The study's scope spans multiple continents, incorporating representative examples from Nigeria, broader African contexts, and global river basin systems. By synthesizing empirical evidence and theoretical constructs across biogeographical scales, this review aims to inform policy frameworks, conservation planning, and adaptive management interventions that safeguard freshwater ecosystem integrity and resilience in the face of escalating invasion pressures.

2. Conceptual Foundations for Comparative Species Impact Assessment

The conceptual framing for a comparative assessment of native and invasive freshwater fish species necessitates a robust integration of ecological, socio-economic, and governance-based perspectives. Freshwater ecosystems provide a suite of services—provisioning, regulating, supporting, and cultural—which are fundamentally influenced by fish species assemblages and their interactions within complex socio-ecological systems (Millennium Ecosystem Assessment, 2005). An appropriate framework must, therefore, delineate species' origin-status (native vs. invasive), functional roles, their ecological impacts, and the human dimensions influencing both their trajectories and management.

Central to such a framework is the classification of species according to origin, pathway of introduction, and impact mechanism, drawing on classical ecological invasion theory. Sax, Kinlan, and Smith (2005) propose a graphical model elucidating species richness responses in invaded versus native habitats, delineating scenarios where taxonomic groups exhibit decreases, compensatory increases, or stasis of richness with changes in composition. That conceptualization aids in understanding how invasive fish can alter community structure and ecosystem functions—either reducing native richness or triggering compensatory responses among remaining species.

In parallel, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) framework elucidates how nature's contributions intersect with human institutions, enabling nuanced examination of invasive species impacts within governance, values, and decision-making domains (Díaz *et al*., 2015). By embedding invasive and native fish within an IPBES-type framework, one situates species-level ecological effects within human-driven contexts and service outcomes, enabling holistic assessment.

In freshwater systems globally, ecological literature demonstrates that invasive fishes modify biotic interactions through predation, competition, habitat alteration, and hybridization. Strayer *et al*. (2006) emphasize the protracted timescales over which such invasions unfold, generating cascading ecological effects that often outlast time-limited management actions. Meanwhile, Shafland and Courtenay (2005) provide taxonomic and functional exemplars of exotic freshwater fishes, aiding in parameterizing frameworks with real-world species cases.

Quantitative risk assessment tools such as the Fish Invasiveness Screening Kit (FISK) operationalize conceptual dimensions into practical scoring systems, enabling policy-relevant comparisons across regions (Copp *et al*., 2019). This highlights the importance of bridging conceptual clarity with applied decision support in managing invasive risks.

Empirical evidence suggests that non-native freshwater fishes often thrive in ecosystems where ecologically similar native species are present, enabling their establishment through shared functional traits and ecological compatibility. Nevertheless, pressures on freshwater biodiversity remain severe, with invasive species among the key drivers of species decline. These trends highlight the urgent need for assessment frameworks that prioritise evaluating and addressing the comparative impacts of such ecological disturbances (Chakraborty, 2023).

Within Africa, freshwater science has made strides in contextualizing invasions in socio-ecological terms (Masese *et al*., 2023), while region-specific analyses in Nigeria—such as assessments of aquatic biodiversity in the River Benue—emphasise the critical role of native species diversity in supporting aquaculture, ensuring food security, and maintaining ecosystem resilience, Adegoke, Araba, and Ibe (2014) stress that any comparative framework must incorporate the varying baseline richness and functional roles of native species, particularly within understudied tropical systems.

Moreover, freshwater ecosystem services are not merely ecological phenomena; they are embedded within socio-economic and institutional landscapes that determine value, access, and governance capacity. Pretty *et al.* (2022) identify drivers—such as institutional strength, economic resources, and stakeholder engagement—that modulate how ecosystem services can be sustained or eroded in the face of invasive species.

Synthesizing these insights yields a conceptual architecture comprising several interlinked elements: species origin and ecology (native vs. invasive roles and mechanisms); ecosystem service outcomes across provisioning, regulating, cultural, and supporting domains; temporal dynamics and legacy effects of invasion; governance and management instruments (e.g., FISK, IPBES integration); and socio-economic context defining capacity and value dimensions.

Such a framework enables comparative analysis by consistently mapping native and invasive fish species across these dimensions. For instance, one may compare how native fish contribute to nutrient cycling and fisheries provisioning versus how invasive species may disrupt those services; or assess how institutional readiness in Nigeria or elsewhere affects detection and control. This approach ensures both conceptual rigor and practical relevance.

2.1. Global Diversity and Function of Freshwater Ecosystems

Freshwater ecosystems, despite occupying a mere fraction of the Earth's surface, are among the most biodiverse and functionally indispensable ecological systems worldwide. Dudgeon *et al*. (2006) assert that freshwater habitats sustain a disproportionate abundance of species—particularly fish, amphibians, and invertebrates—relative to their spatial footprint, making them global biodiversity hotspots. Balian *et al*. (2008) further quantify this richness, revealing an extraordinary variety of aquatic taxa, from crustaceans to macrophytes, structured across varied lentic-, lotic- and wetland habitats.

The functional dynamics of freshwater systems extend well beyond biodiversity metrics. Daily (1997) emphasises that freshwater ecosystems underpin essential "nature's services", including water purification, nutrient cycling, flood control, and provisioning of foodservices upon which human societies crucially depend. These functions are inextricably linked to intrinsic ecosystem complexity and connectivity.

An expanding body of literature emphasises that these ecosystems support interconnected hydrological, biogeochemical, and ecological processes that are essential for the stability of both natural environments and human systems. Peters, Bundschuh and Schäfer (2013) explain that factors such as flow regimes, sediment dynamics, and trophic interactions are central to maintaining the functional integrity of freshwater ecosystems; meanwhile, Ruckelshaus *et al.* (2022) trace a century of anthropogenic alteration, revealing degradation in ecosystem structure and function through altered flows, pollution, habitat fragmentation, and species loss.

Threats to freshwater biodiversity and function are intensifying. Vörösmarty *et al*. (2010) present a global assessment of mounting pressures, including damming, pollution, urbanisation, and climate extremes, which increasingly imperil both biodiversity and water security. Reid *et al.* (2019) build upon this by highlighting persistent conservation challenges such as emerging pollutants and invasive species that further undermine ecosystem resilience.

Recent conservation evaluations present a critical outlook, indicating that a substantial proportion of freshwater species—including fishes, crustaceans, odonates, and amphibians—are facing severe extinction risks, largely driven by habitat loss and environmental degradation. Such pressures place the diversity and functional integrity of freshwater systems under intensifying threat, with significant implications for their long-term ecological stability and service provision (Chakraborty, 2023).

The African continent, and Nigeria in particular, exhibit striking examples of freshwater ecosystem diversity interlinked with human welfare. In rural Nigeria, Lo, Narulita, and Ickowitz (2019) demonstrate that fish consumption—a key dietary and nutritional component—correlates strongly with forest cover adjacent to rivers. This finding highlights how ecosystem functionality and biodiversity directly influence human well-being via ecosystem support.

Masese *et al.* (2023) explore the broader African freshwater science landscape, underscoring the dynamic mosaic of freshwater ecosystems, their ecological richness, and the intricate socio-cultural dependencies that frame their management. This regional perspective emphasises that global biodiversity patterns must be considered alongside local ecological and social contexts.

2.2. Ecological Contributions of Native Fish Populations

Native fish populations are fundamental to the structure, functioning, and resilience of freshwater ecosystems, supporting ecological integrity and providing essential services that benefit both environmental health and human societies. Within these habitats, native species perform diverse ecological roles, including trophic regulation, nutrient cycling, habitat modification, and the preservation of cultural traditions, thereby forming a core component of overall ecosystem functionality. In tropical systems, the diversity of native assemblages sustains complex food webs and dynamic energy flows, contributing to ecological processes of a scale and intricacy rarely matched in other biomes (Peters, Bundschuh& Schäfer, 2013).

Contributing directly to ecosystem functioning, native fish occupy key trophic positions and govern energy transfer mechanisms. These species regulate populations of primary consumers—such as zooplankton and benthic invertebrates—and through cascading effects maintain the balance of algal populations and overall water quality (Holmlund & Hammer, 1999). The removal or decline of native fish can profoundly destabilise these processes, giving rise to eutrophication risks, altered nutrient dynamics, and diminished habitat quality for aquatic organisms.

From a biogeochemical perspective, native fish enhance the circulation of nutrients within freshwater systems via excretion, bioturbation, and movement across habitats. Such contributions reinforce the availability of essential elements like nitrogen and phosphorus to phytoplankton and macrophytes, enhancing primary productivity and ecosystem stability (Daily, 1997). In stream systems, native fish movements influence sediment dynamics by disturbing substrate layers during foraging or spawning, which contributes to habitat heterogeneity and microhabitat diversity critical for invertebrates, amphibians, and emergent vegetation.

Freshwater biodiversity is itself a repository for ecological resilience in variable environments. As articulated by Lynch (2023), species richness—including native fishes—provides a buffer against perturbations such as climate variability, invasive species encroachment, or habitat modification. This resilience is particularly salient in tropical, biodiverse systems, where redundancy among native species can facilitate functional continuity despite external stressors.

Africa offers instructive examples of these dynamics. Masese *et al*. (2023) note that native fish assemblages in African freshwater systems are deeply entwined with ecosystem processes and human cultural values, yet these are increasingly under pressure. Reflecting these connections, Ogunji and Wuertz (2023) document how indigenous species such as Clarias gariepinus and Heterotis niloticus underpin Nigeria's growing aquaculture sector, thereby supporting food systems while maintaining ecological linkages rooted in native genetic and functional diversity.

Legbara (2019) highlights that native freshwater fish play a significant role in contributing to national nutrition profiles in Nigeria, providing an estimated 40% of dietary protein intake and underscoring the intrinsic link between ecosystem services and human livelihoods. In addition to their nutritional importance, these species hold substantial cultural and socioeconomic value. Fisheries based on native assemblages are deeply embedded in traditional practices, local economies, and community identities. Moreover, indigenous ecological knowledge—transmitted across generations—relies on the sustained presence of native species and their predictable behaviours, such as migration, spawning, and habitat use, which support sustainable management approaches and the preservation of cultural heritage.

A broader global context of accelerating freshwater biodiversity loss underscores the importance of native species in upholding ecosystem services. Reid *et al*. (2019) highlight emerging threats—including pollution, damming, climate change, and invasion—that imperil habitat integrity and native assemblages. These drivers erode the ecological foundation of native fish populations and diminish the services they provide. Concurrently, Ruckelshaus *et al*. (2022) document a century of anthropogenic impacts that have altered freshwater regimes worldwide, degrading hydrological patterns, fragmenting habitats, and reducing biodiversity; such transformations weaken the capacity of native fish to sustain ecosystem function.

Conservation evaluations indicate a troubling increase in extinction risks among freshwater species worldwide, with native fishes being particularly affected. The degradation of these native assemblages threatens not only overall biodiversity but also the essential ecological functions that underpin ecosystem services, thereby heightening the susceptibility of these systems to biological invasions and potential collapse (Chakraborty, 2023).

2.3. Ecological Impacts of Invasive Fish Species

Invasive freshwater fish species impose substantial and pervasive disruptions across diverse ecological dimensions, destabilising native assemblages and altering ecosystem functioning. Contemporary synthesis of invasive fish impacts reveals multiple, interlinked processes: elevated competition and predation, hybridisation, pathogen transmission, and profound changes to habitat structure and community dynamics (Britton, 2023). These ecological consequences frequently erode biodiversity and compromise ecosystem services.

Freshwater fish invasions represent a global phenomenon that has reshaped biogeographical patterns in profound and often irreversible ways. The scale of these incursions is considerable, with non-native species now present in more than half of the world's river basins, leading to substantial alterations in native assemblages across multiple continents. Such extensive colonisation reflects systemic vulnerabilities, particularly where the presence of closely related native species facilitates establishment through ecological and evolutionary compatibility (Britton *et al*., 2023).

In Africa, and specifically within Nigeria, invasive species are documented to threaten native freshwater biodiversity. The Global Register of Introduced and Invasive Species (GRIIS) identifies numerous alien fishes known to negatively affect indigenous species and ecosystem integrity (GRIIS via GBIF, 2019). In East Africa, Lake Victoria stands as a striking example of ecological disruption, where the introduction of the Nile perch (Lates niloticus) has resulted in the extinction or near-extinction of approximately 40% of the lake's endemic haplochromine cichlids, severely diminishing native fish diversity. This has triggered cascading effects, including altered trophic dynamics, changes in nutrient loading, and the homogenisation of functional roles within the ecosystem (Robert, 1997).

In South Africa, stakeholder perceptions highlight significant concern among scientists, managers, and local communities regarding the threat posed by invasive fishes, with recognition of their potential to displace native species, degrade river systems, and hinder conservation efforts. As noted by Woodford *et al*. (2017), these social-ecological contexts illustrate how ecological impacts are closely linked to governance challenges and the need to reframe perceptions in order to manage conflict-generating invasive species effectively.

Predation and competition from invasive fishes represent some of the most severe ecological pressures. For example, the round goby (Neogobius melanostomus) in the Laurentian Great Lakes competes intensely with native benthic species for habitat, food resources, and breeding sites, while also preying on the eggs of indigenous fishes, leading to local population declines. In addition, its capacity to act as a vector for bioaccumulated contaminants has indirect impacts on higher trophic predators, illustrating how invasive species can alter trophic pathways and elevate ecological risks through contaminant transfer (Malmberg, White& VandeWoude, 2021).

Hybridisation between non-native and native species constitutes a significant ecological concern. The crossbreeding of introduced rainbow trout (Oncorhynchus mykiss) with native westslope cutthroat trout (Oncorhynchus clarkii lewisi) in North American river systems leads to genetic introgression, eroding the genetic integrity and adaptive capacity of native populations. This compromise of genetic purity reduces resilience and may hinder the ecological specialisation necessary for persistence under changing environmental conditions (Allen *et al*., 2016).

Invasions can profoundly alter habitat structure and reshape community assemblages. In tropical freshwater ecosystems, invasive Nile tilapia have been shown to competitively displace native herbivorous and planktivorous fishes, driving shifts in dietary patterns and contributing to declines in native species abundance and condition. Such competitive dominance can erode functional diversity, with enduring impacts on energy transfer, trophic interactions, and overall ecosystem stability (Martin, Valentine& Valentine, 2010).

Collectively, these empirical observations align with Britton's (2023) conclusion that ecological impacts must be assessed across multiple dimensions—species richness, population dynamics, genetic diversity, and ecosystem function—and not merely inferred from presence. Invasive common carp (Cyprinus carpio), for instance, illustrates how bottom-up and top-down processes combine to shift stable ecosystem states, reducing biotic richness and hampering trophic interactions—thus, sometimes contributing to ecosystem collapse.

2.3.1. Alteration of Habitat Structure and Function

Invasive freshwater fish species can profoundly restructure habitat architecture and ecosystem functioning, undermining ecological integrity across scales. Such impacts manifest through physical alterations—such as increased turbidity, substrate disturbance, and vegetation removal—as well as cascading effects on hydrodynamics, water quality, and biological communities.

Tilapia invasions offer a clear illustration of how benthic-disturbing behaviours can drive habitat degradation. In tropical freshwater environments, invasive Nile tilapia actively uproot aquatic vegetation and disturb sediments, leading to increased turbidity and diminished light penetration. These changes impair photosynthesis in submerged plants and modify critical microhabitats relied upon by native invertebrates and juvenile fishes. Elevated turbidity further disrupts thermal stratification and ecosystem metabolic processes, reducing water clarity and limiting habitat suitability for species dependent on visual foraging (Martin, Valentine & Valentine, 2010).

Broad-scale biogeographic evaluations indicate that such habitat alteration is far from unique. Britton *et al*. (2023) report that invasive fishes have permanently transformed habitat types across numerous bioregions, fragmenting native habitat mosaics and driving the homogenisation of river basin structures. Species such as carp and tilapia modify substrate composition and flow regimes, thereby disadvantaging taxa adapted to structurally diverse, clear-water environments.

Britton (2023) consolidates these observations, noting that invasive freshwater fishes frequently cause physical habitat degradation through rooting, burrowing, or grazing. These behaviors result in the loss of bank-stabilizing vegetation, destabilized sediment profiles, and reduced habitat complexity overall.

In African freshwater environments, the ecological impacts of Nile tilapia invasions have been notably detrimental. Habitat degradation—driven by intensive removal of aquatic vegetation and excavation of spawning pits—has been linked to increased erosion, altered sediment transport, and the displacement of specialist native species. Such structural alterations compromise the ecological integrity of aquatic systems and emphasise the urgency for targeted management and conservation interventions (Bănăduc *et al*., 2022).

The Niger Delta provides a sobering local illustration of habitat alteration processes exacerbated by invasive fish and anthropogenic stressors. Davies et al. (2020) report that inflows of agricultural runoff and oil-industry pollution have already destabilised sedimentation regimes and dissolved oxygen patterns. The introduction of invasive tilapia types compounds these pressures, intensifying turbidity and further eroding fragile fish communities adapted to structurally stable, less turbid environments.

These habitat transformations echo broader freshwater biodiversity challenges identified by Reid et al. (2019). They warn that habitat alteration—accelerated by invasive species, pollution, and hydrologic modifications—fundamentally impairs habitat function, connectivity, and resilience. This trend undermines ecosystem services such as nursery habitat provision, nutrient retention, and flood attenuation.

The normative framing of such invasive impacts has been addressed by Sandlund, Schei, and Viken (2001), who argue that alien species often catalyze physical and structural habitat changes that are among the most persistent and difficult-to-reverse ecological disturbances. These changes frequently lock systems into degraded states with reduced biodiversity and functionality.

A meta-level perspective emphasizes that habitat structure and function form the ecological backbone of freshwater systems. When invasive fishes disrupt these physical templates, they compromise the entire ecosystem architecture—from sediment chemistry and hydrology to trophic linkages and biodiversity. Habitat simplification reduces niches and ecological redundancy, making systems more vulnerable to stressors and less capable of delivering ecosystem services.

2.3.2. Spread of Pathogens and Parasites

Invasive fish species act as potent vectors for the introduction, amplification, and dissemination of pathogens and parasites, engendering ecological, health, and economic challenges for native freshwater ecosystems. These invaders may carry co-introduced parasites, facilitate spillback of native diseases, and compromise biosecurity within wild and cultured fish populations.

In South Africa, Truter *et al*. (2023) explored the parasite assemblages of translocated Clarias gariepinus, uncovering evidence of parasite co-introductions, spillback into native hosts, and partial enemy release. These dynamics reflect the multifaceted ways invasive or translocated fish influence parasite ecology: they can bring novel pathogens, spark outbreaks among native species, or themselves experience relief from their original parasite burdens.

Kenyan freshwater systems also serve as empirical examples. Maraganga *et al*. (2023) recorded high endohelminth diversity—comprising trematodes, nematodes, and cestodes—in invasive Clarias gariepinus inhabiting Lake Naivasha and Ol'Bolossat. The prevalence and variety of these parasites signal elevated transmission potential, including possible infection of sympatric native fauna and further ecological disruptions.

Globally, invasive parasites such as the Asian fish tapeworm (Atractolytocestus huronensis) exemplify the profound risks inherent in aquatic bioinvasions. As assessed byKuchta and Hölker (2018), this tapeworm has successfully invaded freshwater systems worldwide via its carp hosts, leading to increased disease outbreaks and challenges for aquaculture and biodiversity conservation.

Proactive monitoring is crucial, with MacAulay *et al*. (2022) emphasising the importance of comprehensive pathogen screening for both introduced and native fish species. Such surveillance enables the early detection of emerging threats, supporting timely interventions to protect ecosystem integrity and human health from zoonotic and fish-borne diseases.

At a mechanistic level, molecular studies of parasite dispersal offer insights into transmission pathways. Prunier *et al*. (2021), in examining a non-native freshwater copepod parasite, found high dispersal potential and weak sibship clustering across riverine gradients. These patterns indicate that invasive-hosted parasites can rapidly spread across fragmented habitats, increasing both evolutionary adaptability and infection risk across fish communities.

A broader overview of parasite invasions (ResearchGate 2022) reinforces that fish farm escapes and trade-related movements of ornamental or edible fish remain major pathways for inadvertently introducing aquatic pathogens. These vectors often escape conventional monitoring and biosecurity mechanisms, exacerbating pathogen spread.

The cumulative evidence illustrates that invasive fish are not merely ecological competitors but also act as critical agents of parasitic and pathogenic spread. Whether through co-introduction, parasite amplification, or as unwitting carriers of emerging zoonoses, their movements engender threats to biodiversity, aquaculture, and human communities reliant on freshwater systems. Effective monitoring, molecular diagnostics, and biosecurity measures are indispensable for mitigating these complex risks.

2.4. Challenges in Controlling Native–Invasive Interactions

Controlling interactions between native and invasive freshwater fish species presents multidimensional challenges that span ecological complexity, governance and policy limitations, and socio-economic constraints. These difficulties are embedded within entrenched systems, often complicating timely and effective responses.

In regions such as Nigeria, these issues are reflected in significant governance deficiencies and financial limitations. As noted by Aura *et al*. (2022), despite escalating pressures from non-native species—particularly in Lake Victoria and surrounding aquaculture areas—management efforts are hindered by inadequate funding, institutional fragmentation across administrative bodies, limited technical expertise, and low public awareness. Such systemic weaknesses impede coordinated action, reducing the effectiveness of both detection and control measures.

Globally, the considerable economic and logistical demands of managing invasive species add complexity to response efforts. As Nuñez *et al*. (2017) note, the extent of future impacts is shaped not only by the biological characteristics of the invaders but also by socio-political inertia, including conflicting stakeholder interests, limited financial resources, and delayed policy action. Variability in policy coherence, enforcement capabilities, and stakeholder collaboration across regions further constrains effective management within freshwater systems.

Scientific and technical hurdles also persist. The development and application of tools like AIS Explorer—designed to optimise resource allocation for watercraft inspections—highlight gaps in surveillance and prevention. Kinsley *et al*. (2021) acknowledge that although such decision-support systems enhance strategic planning, their deployment relies on robust data, sustained stakeholder engagement, and infrastructure that may be lacking, especially in developing regions such as parts of Africa.

Legislative and regulatory systems often exhibit significant inertia in addressing biological invasions. Nuñez *et al*. (2017) highlight that many governance frameworks are hindered by outdated legal definitions, overlapping jurisdictional mandates, and slow progress in harmonising national legislation with international agreements. Such shortcomings lead to inconsistent regulatory controls, weak enforcement, and limited capacity to respond swiftly to emerging invasion threats.

The inherent complexity of freshwater ecosystems presents significant ecological challenges. Reid *et al*. (2019) note that these environments are highly dynamic, marked by interconnected habitats, seasonal variability, and diverse species life histories, all of which complicate eradication and restoration efforts. Management actions targeting one section of a river basin may be compromised by processes occurring upstream or downstream, while the capacity of invasive species to withstand partial removal can lead to population recovery and continued ecological pressure.

Moreover, socio-economic dependency on invasive species, whether for fisheries, livelihoods, or unintended ecological subsidies, complicates removal initiatives. Some communities derive income from invasive tilapia or carp fisheries; abrupt removal without alternatives risks economic disruption. Thus, policies often face resistance, requiring multifaceted socio-economic planning alongside biodiversity goals.

The processes underlying the establishment of invasive species present further obstacles. Reid *et al*. (2019) emphasise that effective management should prioritise prevention, early detection, and rapid response; however, these measures are often hindered by inadequate monitoring infrastructure, limited availability of data, and low levels of public participation. Once such species become established, eradication efforts are frequently prohibitively expensive or risk causing additional ecological harm.

Within heavily invaded systems like Lake Victoria, invasive species have altered trophic structures and social expectations. The Nile perch has long dominated the fishery and local economy, creating dependencies that resist eradication efforts. Changing socio-ecological norms and economic interests thus constrain transformative management—even where ecological restoration may be desirable.

2.4.1. Data and Monitoring Limitations

Effective management of interactions between native and non-native species in freshwater environments is significantly constrained by gaps in data quality, spatial coverage, and monitoring capacity. In settings such as Nigeria, these challenges are compounded by governance weaknesses and limited financial resources, which hinder the timely detection of introductions and the assessment of native species' resilience. Aura *et al*. (2022) note that fragmented institutional arrangements and under-resourced monitoring systems undermine early response capabilities and restrict the use of robust, evidence-based decision-making in the management of such ecological pressures.

Across Africa, many ecologically important and globally significant habitats—particularly wetlands and Ramsar-listed sites—are affected by persistent data deficiencies. Stephenson, Ntiamoa-Baidu, and Simaika (2020) examined biodiversity monitoring efforts across a range of African wetlands and found widespread challenges, including restricted access to reliable data, a shortage of taxonomic expertise, fragmented information systems, and insufficient training for personnel. These systemic limitations reduce the effectiveness of existing datasets, hindering timely and effective responses to emerging invasion threats and broader ecosystem degradation.

This challenge is compounded by uneven geographic and taxonomic coverage. Kajee *et al*. (2023) note that spatial data on freshwater fish distributions are often concentrated in a limited number of countries, with South Africa receiving disproportionate attention. Large areas remain without baseline occurrence records, constraining the ability to monitor the spread of invasive species and limiting the scope for comprehensive meta-analyses of their ecological impacts.

Globally, decision-support technologies like AIS Explorer seek to optimise surveillance efforts by identifying high-priority pathways for inspection, such as watercraft hulls or launches (Kinsley *et al*., 2021). Although promising, these tools hinge on the availability of robust, timely data inputs. In the absence of real-time observations or participation in citizen science, their predictive power is diminished, and strategies may become disconnected from on-the-ground conditions.

Even where monitoring infrastructures such as exclusion barriers are deployed, their effectiveness remains ambiguous. Jones *et al*. (2021) reviewed the global application of physical and chemical barriers as invasive control tools and concluded that the majority of studies lack robust before–after or control-impact designs, with durations often limited to fewer than five years. As a result, ecological outcomes—particularly long-term native species responses—remain poorly documented, severely limiting evidence-based assessments.

Emerging molecular methodologies offer pathways to bridge these monitoring gaps. Prunier *et al*. (2021) applied genetic sibship reconstruction techniques to infer dispersal patterns of non-native fish parasites, demonstrating that such parasites exhibit high dispersal capacities across connected water systems. While molecular proxies like these can enhance detection, their integration into regular monitoring frameworks remains sporadic due to resource and capacity constraints.

2.4.2. Political, Social, and Economic Constraints

Managing the interactions between native and non-native freshwater species is significantly constrained by intertwined political, social, and economic factors that differ across jurisdictions and socio-ecological contexts. In Nigeria, for instance, Aura *et al*. (2022) highlight that overlapping institutional mandates, persistent underfunding, and shortcomings in policy execution critically weaken management efforts. These governance challenges—exacerbated by limited technical capacity and insufficient stakeholder engagement—undermine the effectiveness of detection, control, and restoration measures aimed at addressing the impacts of introduced species.

This challenge reflects wider governance patterns. Allan (2005) observes that socio-economic factors—such as prioritisation of economic growth, constraints on resources, and conflicting policy agendas—often take precedence over environmental management goals. In many contexts, the conservation of freshwater systems and the control of invasive species receive limited political attention, leading to underfunding and weak enforcement, particularly when weighed against industrial and developmental ambitions.

Legislation also mirrors these shortcomings. Nuñez *et al*. (2017) point to significant gaps in legal responses to biological invasions, noting that definitions are often narrow or inconsistent, coordination between jurisdictions is limited, and policy adoption is frequently delayed. Such institutional weaknesses result in policy frameworks that are poorly equipped to address rapid ecological change or emerging threats, thereby reducing overall preparedness for effective invasive species management.

Practical management is further complicated by socio-economic trade-offs. Reid *et al*. (2019) note that efforts to remove or control certain non-native species must consider their established economic and social roles; for example, species such as tilapia or carp may provide critical support to local fisheries and livelihoods, resulting in community opposition to eradication initiatives. In the absence of viable economic alternatives, such measures risk alienating stakeholders and reducing compliance with management objectives.

Furthermore, the management of freshwater non-native species often reflects disparities in global value systems. Reid *et al*. (2019) observe that developing nations may lack the financial and technical resources required for comprehensive management, while wealthier countries may prioritise ecological integrity yet face obstacles such as public opposition or policy inertia. To address these challenges effectively, integrated approaches that incorporate co-management frameworks, active stakeholder participation, and fair distribution of benefits are essential for achieving sustainable outcomes.

Regionally, specific social-cultural norms may influence invasive species perceptions and responses. Though direct studies may be limited, broader African contexts still grapple with balancing economic needs and ecological health, particularly in zones where fisheries form a core livelihood and culture. Such diversity of values underscores the necessity of tailoring policies to socio-economic realities and governance landscapes.

2.5. Implications for Freshwater Ecosystem Services

Invasive fish species exert profound and multifaceted impacts on freshwater ecosystem services, eroding their capacity to deliver essential provisioning, regulating, supporting, and cultural benefits. These consequences ripple across ecological, social, and economic domains, demanding integrated and resilient responses.

Freshwater biodiversity underpins vital ecosystem services such as water purification, food provision, nutrient cycling, and cultural well-being. Lynch (2023) stresses that the accelerating decline of freshwater species jeopardises not only ecological integrity but also human dependence on these environments for clean water, food security, and cultural identity. When invasive species displace or disrupt native fish assemblages, the functional integrity of these services becomes significantly compromised.

At the global level, shifts in beta-diversity caused by non-native species can erode ecosystem heterogeneity and compromise the delivery of essential services. Britton *et al.* (2023) explain that invasions by freshwater fishes often lead to reductions in compositional diversity across habitats, resulting in key services—such as pest regulation, sediment stabilisation, and nutrient cycling—becoming more uniform and, therefore, more susceptible to disturbance. The decline in distinct community composition ultimately weakens ecosystem resilience and diminishes the range of services these systems can provide.

In Nigeria, the spread of non-native fish into both aquaculture operations and natural fisheries poses a threat to food supply and economic stability. Aura *et al.* (2022) observe that weaknesses in governance and inadequate financial support have constrained effective management across key freshwater systems, including Lake Victoria and surrounding aquaculture areas. In the absence of strong regulatory and control measures, these incursions diminish fishery productivity and jeopardise the livelihoods of communities dependent on native species for subsistence and trade.

Ecosystem service impacts in African freshwater systems are further intensified by deficient monitoring and protection of native species. Stephenson *et al.* (2020) highlight that Ramsar wetlands across Africa suffer from under-monitoring, inadequate taxonomic capacity, and incomplete data—constraints that obscure service degradation and delay recognition of emerging threats. This opacity impairs the formulation of adaptive management responses, allowing invasives to erode services silently and persistently.

Strategic interventions are constrained by the complexity of freshwater ecosystems and the socio-economic interests tied to them. Reid *et al.* (2019) stress that managing non-native fish requires balancing the restoration of ecological functions with the cultural and provisioning benefits these species may provide. Efforts to eradicate or suppress such species can conflict with established livelihoods or recreational uses, necessitating carefully tailored, community-based strategies that integrate ecological restoration goals with socio-economic sustainability.

2.5.1. Interactions Producing Mixed or Contradictory Outcomes

In some freshwater ecosystems, the interactions between native and invasive fish species can yield outcomes that are neither purely detrimental nor entirely beneficial. Instead, these complex dynamics often produce mixed effects—alternating between ecological disruption, functional shifts, and even adaptive opportunities for ecosystem services.

Worldwide, the homogenisation of fish communities resulting from biological invasions has raised significant concerns over the erosion of functional diversity. Britton *et al.* (2023) note that while non-native species typically reduce beta-diversity in freshwater ecosystems, there are rare instances where they may help maintain certain ecosystem functions under altered environmental conditions. In some cases, these species can occupy vacant trophic niches and provide partial functional replacement; however, such substitutions rarely match the ecological value or evolutionary significance of the native assemblages they replace.

The complexity of these interactions is highlighted by multi-trophic dynamics. Dambach (2020) notes that the presence of certain aquatic predators can, in some cases, reduce disease prevalence within prey populations, thereby improving short-term population health. Such unanticipated regulatory effects suggest that non-native predators may, under specific conditions, contribute to rebalancing certain ecosystem processes—although these benefits are frequently accompanied by long-term biodiversity costs.

In the Nigerian context, such contradictory outcomes are also evident. Aura *et al.* (2022) note the entrenched presence of invasive tilapia within local fisheries, where they have, in some cases, supplanted native species in markets while continuing to play a significant role in meeting nutritional needs and contributing to national food security. Although these shifts entail ecological costs, the widespread availability of tilapia has fostered economic dependence, reflecting a socio-economic dimension in which non-native species meet human needs where native alternatives are no longer viable.

Wider socio-ecological evaluations indicate that such contradictions are common. Reid *et al.* (2019) contend that management approaches must recognise the dual nature of some non-native species: while they can diminish biodiversity and damage habitats, they may also deliver certain provisioning or regulating benefits, particularly in human-modified environments. Examples include their potential role in supporting fisheries, mitigating algal blooms, or stabilising food webs disrupted by habitat degradation.

From a conservation standpoint, this complexity necessitates an adaptive lens. Lynch (2023) asserts that preserving freshwater biodiversity remains paramount, even while recognizing instances where invasive species partially fulfill disrupted ecological roles. Such considerations demand resilience-based strategies—one that restores native assemblages where feasible and accommodates functional substitutions when necessary to sustain human well-being.

2.6. Tools and Technologies for Impact Evaluation

Assessing the ecological impacts of long-established and newly introduced fish species in freshwater ecosystems requires the deployment of advanced, multifaceted tools and technologies. These methods, increasingly refined in recent years, range from molecular approaches capable of rapid and sensitive species detection to acoustic and biotelemetry systems that uncover patterns of movement, species interactions, and behavioural ecology. Each provides unique insights into ecosystem status and the functional roles of species, enabling managers and researchers to respond to ecological changes with greater precision.

Environmental DNA (eDNA) metabarcoding has emerged as a transformative tool for biodiversity assessment in aquatic environments. This technique enables the detection of a broad range of taxa, including rare or cryptic native species as well as early-stage invaders, across varied habitats from rivers and wetlands to reservoirs and floodplains. It facilitates the identification of shifts in community composition and can reveal species that are overlooked by traditional netting, electrofishing, or visual surveys. However, as demonstrated by Deiner *et al*. (2017), rigorous interpretation of eDNA results is essential, especially in the absence of standardised laboratory protocols and comprehensive reference databases. Without such frameworks, there is a risk of false positives, misidentification, and underestimation of biodiversity, potentially leading to misguided management decisions.

Acoustic monitoring provides a non-invasive, cost-effective, and scalable means of collecting long-term data on fish distribution, habitat use, and behavioural patterns. Through passive acoustic techniques, researchers can record species-specific sounds, including spawning calls and feeding activity, enabling detailed temporal and spatial mapping of fish populations. This approach is particularly valuable for detecting cryptic, nocturnal, or migratory species that are often missed by conventional sampling methods. As Ross *et al*. (2023) demonstrate, passive acoustic data can act as effective proxies for reproductive timing, habitat quality, and population abundance, while also offering insights into ecological changes driven by habitat degradation, altered hydrological regimes, or the introduction of invasive competitors and predators.

Biotelemetry and bio-logging technologies have similarly expanded the capacity to monitor aquatic animals at high temporal and spatial resolutions. Innovations in transmitter miniaturisation, receiver network integration, and data analytics have improved the precision of models used to study residency patterns, migratory routes, and habitat fidelity. Cooke *et al*. (2016) demonstrate that modern biotelemetry systems can also integrate environmental variables, allowing researchers to link behavioural shifts in fish to ecological stressors such as altered flow regimes, hypoxia, or invasive species encroachment. This integration provides managers with actionable information to predict ecosystem responses and optimise intervention strategies.

Technological integration is another area of rapid progress, particularly in detecting invasion pathways, assessing ecological impacts, and fostering stakeholder engagement. Remote sensing platforms, combined with automated detection algorithms and citizen science data streams, have been shown to enhance early-warning capabilities for species invasions. Turner *et al*. (2015) document how coupling satellite imagery with on-the-ground citizen observations enables near real-time monitoring of aquatic ecosystem changes, improving the timeliness and effectiveness of management interventions. Such integration of multiple data sources into centralised platforms also fosters greater public participation and facilitates cross-agency coordination, which is particularly important for transboundary freshwater systems.

Within African freshwater contexts, advanced molecular and acoustic tools are gradually becoming integral to biodiversity monitoring and invasive species management. For instance, parasite community profiling, when applied to translocated or invasive fish populations, can yield valuable insights into host–parasite relationships, disease transmission pathways, and ecological risks. Poulin *et al*. (2020) highlight that understanding parasite assemblages associated with invasive hosts can serve as both a diagnostic and predictive tool for assessing invasion impacts, especially when combined with spatial modelling to forecast spread under different management scenarios.

The adoption of these technologies in Africa, however, remains uneven. Barriers include high initial costs, a lack of technical expertise, and insufficient integration into existing monitoring frameworks. To address these gaps, investment in regional laboratory capacity, training programmes, and collaborative monitoring initiatives will be essential. Building centralised biodiversity databases, linked with global repositories, will also enhance the utility of molecular and acoustic data for both research and policy.

2.7. Future Research and Management Pathways

As inland water ecosystems face intensifying pressures from the spread of non-native fish species, it is essential that research and management approaches transition toward adaptive, integrative strategies that balance ecological integrity with the socio-economic needs of human communities. Such strategies should not only respond to existing impacts but also anticipate future threats, embedding resilience and flexibility within management frameworks (Arthington *et al*., 2016).

A central research priority involves deepening understanding of the biological traits, introduction pathways, and environmental conditions that predispose aquatic systems to invasion. Britton *et al*. (2023) present evidence on the global decline of beta-diversity and the homogenisation of freshwater faunas, illustrating how certain invaders exploit functional traits—such as omnivory, high reproductive output, and behavioural plasticity—that enhance their establishment and spread. Future work must integrate ecological, morphological, and socio-economic variables into predictive invasion models, enabling managers to identify high-risk species and vulnerable habitats before ecological thresholds are crossed. Predictive tools informed by trait-based risk assessments have already shown promise in terrestrial contexts and warrant adaptation for aquatic environments (Seebens *et al*., 2021).

Equally important is the valuation of biodiversity across both ecological and human dimensions. The role of aquatic biodiversity in underpinning ecosystem services is often under-quantified, limiting its integration into decision-making processes. Lynch (2023) underscores that maintaining diverse aquatic communities is fundamental not only to ecological function but also to food security, cultural heritage, and climate adaptation. Incorporating ecosystem service valuation into management planning could provide an economic and social rationale for biodiversity conservation, strengthening political and financial support for action.

In the African context, Nigeria illustrates how context-specific research can inform targeted strategies. Aura *et al.* (2022) document governance and funding deficits that impede effective control of non-native species introductions. Future priorities should involve conducting locally oriented socio-ecological research and livelihood assessments to determine community reliance on both native and non-native fish species. Insights from such studies can inform the creation of governance structures, participatory decision-making mechanisms, and economic incentive schemes that are adapted to the specific socio-economic and ecological contexts of the region (Zasada *et al*., 2017).

At the global scale, adaptive management must engage with both the ecological complexity of invasions and the diverse interests of stakeholders. Reid *et al*. (2019) advocates multi-faceted strategies that address biodiversity conservation objectives while accommodating socio-economic needs, particularly in cases where invasive species have become economically entrenched. Co-management systems, collaborative monitoring programmes, and inclusive policy dialogues can bridge the gap between ecological restoration and community welfare. This inclusive approach aligns with Ostrom's (2009) framework for governing commons, which emphasises polycentric governance and the importance of involving resource users directly in decision-making processes.

Research should also focus on developing and refining management tools capable of integrating multi-source data to inform decision-making. Decision-support systems that incorporate predictive modelling, network analysis, and socio-economic risk assessments can help prioritise interventions where they are most likely to succeed (Roy *et al*., 2020). Advances in remote sensing, eDNA metabarcoding, and automated surveillance technologies offer new possibilities for real-time detection and monitoring of invasion fronts, yet their utility will depend on adequate funding, data-sharing agreements, and capacity building at regional and local levels.

The ecological complexity inherent in biological invasions also calls for interdisciplinary investigation into non-linear, counterintuitive, or compensatory interactions between native and non-native species. Dambach (2020) notes that under certain circumstances, introduced predators can reduce disease prevalence among native populations, providing unexpected regulatory benefits. Such findings challenge simplified eradication narratives and point to the need for nuanced, context-specific management strategies that account for both risks and potential functional substitutions. Similar context-dependence has been observed in other ecosystems, where removal of invasive species without restoring habitat or addressing underlying drivers resulted in ecosystem instability (Zavaleta *et al*., 2001).

Policy and governance reforms will be critical in realising these pathways. Effective management will require cohesive institutional frameworks that align local governance priorities with international conservation agreements, provide stable funding for long-term monitoring, and incentivise ecological stewardship through economic or policy instruments (Early *et al*., 2016). Incorporating ecosystem service valuation into policy frameworks can help align environmental objectives with economic planning, positioning biodiversity conservation as a central rather than marginal policy priority. Additionally, promoting regional collaboration networks for information exchange and joint action—particularly within transboundary river basins—can strengthen coordination, improve management efficiency, and reduce duplication of efforts (McPherson and Ropicki, 2021).

3. Conclusion

The present work set out with the overarching aim of conducting a comprehensive comparative assessment of two distinct groups of aquatic species, examining their respective contributions and pressures on the ecological and socio-economic systems they inhabit. The objectives centred on clarifying their functional roles, understanding the consequences of their interactions, evaluating the effectiveness of emerging analytical tools, and mapping forward-looking pathways for research and governance. Drawing on a synthesis of evidence from global contexts, supported by case studies from across Africa and contextual examples from Nigeria, these goals have been met in full.

The review shows that species with long-standing ecological integration are vital in maintaining ecosystem equilibrium. They support nutrient cycling, habitat stability, trophic balance, and biodiversity resilience—functions that directly sustain provisioning, regulating, cultural, and supporting services essential to human and environmental well-being. In contrast, recently introduced species, while occasionally offering short-term economic or ecological benefits, tend to undermine system integrity. This occurs through competitive exclusion, predation, genetic mixing, habitat disturbance, and disease transmission. Such impacts often lead to reduced diversity, functional homogenisation, and diminished resilience, as evidenced in diverse freshwater systems ranging from large lake basins to inland river networks.

Findings further highlight that the relationship between these groups is not universally negative; under specific conditions, the latter may partially fill vacated ecological niches or support economic activities. However, these benefits are frequently offset by long-term ecological costs, underscoring the need for context-sensitive decision-making.

Technological advances are providing new opportunities for monitoring and evaluation. Methods such as molecular-based detection, passive acoustic surveillance, movement tracking technologies, parasite community analyses, and integrated decision-support frameworks are emerging as powerful tools for assessing ecological change. Yet, their adoption is uneven, particularly in regions with governance gaps, limited expertise, and inadequate resources.

The forward trajectory for research and management calls for integrative, adaptive strategies that unite predictive modelling, valuation of ecosystem contributions, and participatory governance. Addressing socio-political and economic barriers—especially reliance on non-native species for livelihoods—is pivotal.

Ultimately, the work affirms that effective stewardship is achievable through tailored approaches that reconcile ecological restoration with socio-economic priorities. Recommendations focus on strengthening observation networks, enhancing policy integration, building local capacity, and promoting inclusive governance to secure the long-term vitality and functionality of these aquatic systems.

4. References

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