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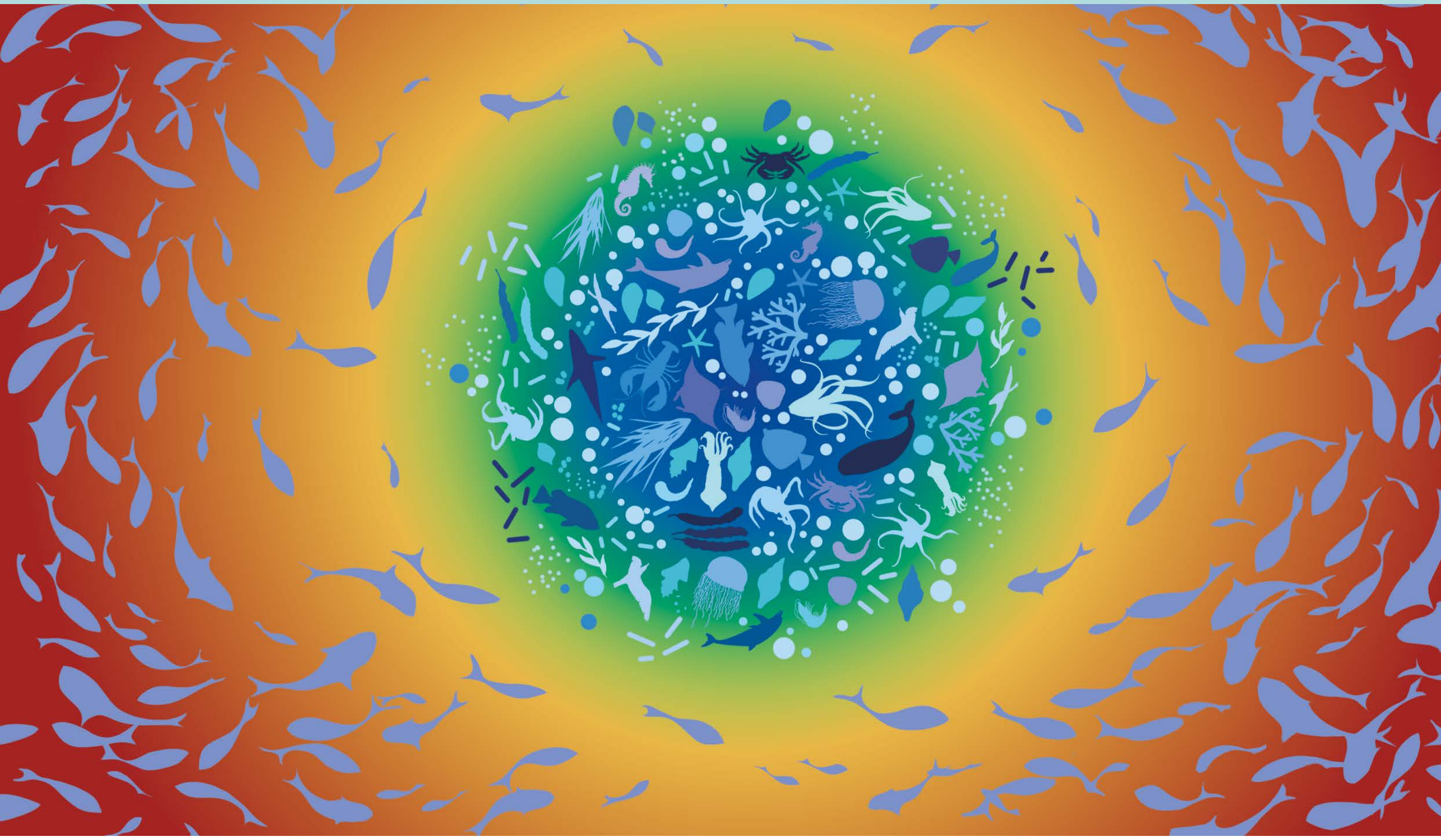

Fisheries responses to invasive species in a changing climate

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Preparation of this document

This technical paper was developed under the framework of a collaboration between the Food and Agriculture Organization (FAO) and the National Research Council – Istituto per le Risorse Biologiche e le Biotecnologie Marine (CNR-IRBIM) in Italy. This work responds to the mounting evidence that biological invasions are increasingly impacting aquatic systems and living resources around the world, a situation which in many cases is fostered by the effects of climate change. The development of this technical paper involved three main steps: (i) case studies commissioned from experts around the world; (ii) a global survey; and (iii) a workshop that drew out lessons learned and good practices. The results presented in this technical paper were discussed at the workshop "Compilation and analysis of fisheries management responses to aquatic invasive species (AIS) in the context of climate change", hereafter referred to as the "AIS workshop". During this two-day meeting, held online on 8–9 May 2023, 11 scientists from around the world (the "expert team") presented their case studies and discussed guidance on effective management, based on their personal experience. Additional opinions and views were elicited with an online survey, which involved 101 scientists from 44 countries. The resulting information, together with a comprehensive literature review, provided the basis to identify nine management measures, which were drafted by the FAO-CNR team and then analysed and discussed by the expert team during the AIS workshop. Hence, management advice was discussed from a broad spectrum of experiences, legal, political, social and ecological settings, drawing lessons learned for the design of coping strategies aimed to either minimize the negative effects of AIS or to take advantage of potential opportunities.

Taking action on AIS complies with international and regional conventions for the conservation of biodiversity such as the Convention on Biological Diversity (Rio Convention, Article 8h: "Prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species") and the Aichi targets (especially Target 9); and it supports the implementation of principles provided by the Code of Conduct for Responsible Fisheries (FAO, 1995). Articles 7 and 9, among others, apply to introduced species: Article 9.3.1 calls on states to conserve genetic diversity and maintain the integrity of aquatic communities and ecosystems by appropriate management, which requires cooperation and harmonized procedures between countries that share water resources in which the transboundary movements of aquatic animals take place. The publication of this document will also contribute to the FAO organizational objective of Better Production (BP), and more particularly BP2 – Blue Transformation – more efficient, inclusive, resilient and sustainable blue food systems.

The views expressed in this report aim to provide a comprehensive overview of the subject matter, based on collective insights and analyses that led to a consensus among the participating experts. The contents of this technical paper were reviewed and edited by Ernesto Azzurro with contributions from Tarûb Bahri, John Valbo-Jørgensen, Xuechan Ma, Pierluigi Strafella and Marcelo Vasconcellos. Data analysis was carried out by Claudio Vasapollo (CNR-IRBIM). Part 1 was authored by Ernesto Azzurro (lead author; CNR-IRBIM), Tarûb Bahri (FAO), John Valbo-Jørgensen (FAO), Xuechan Ma (FAO), Pierluigi Strafella (CNR-IRBIM), Marcelo Vasconcellos (FAO), Jane W. Behrens (Technical University of Denmark), Jannike Falk-Andersson (Norwegian Institute for Water Research), Sylvaine Giakoumi (Stazione Zoologica Anton Dohrn), Edwin D. Grosholz (University of California, Davis), Holden E. Harris (National Ocean and Atmospheric Administration Southeast Fisheries Science Center; University of Miami), Jason Hall-Spencer (University of Plymouth; University of Tsukuba),

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Abstract

Due to the increasing pressure of a globalized economy and under the effects of a changing climate, biological invasions have become a frequent feature of marine and freshwater environments. Global fisheries and aquaculture are therefore required to adjust to these changes, with the dual aim of reducing the negative ecological consequences caused by these species and making the most of the advantages they might bring.

Here, capitalizing on a wide spectrum of management actions which can be implemented to control and/or adapt to aquatic invasions, nine measures are presented; they can be grouped under environmental, social or socioeconomic strategies, exploring their potential, main challenges and enabling factors. The nine measures, provided with key recommendations, are:

#1: Develop and manage a commercial fishery
#2: Encourage recreational harvesting
#3: Explore market opportunities
#4: Implement outreach programmes
#5: Foster stakeholder engagement
#6: Implement spatial control
#7: Implement biological control
#8: Restore ecosystems
#9: Do nothing

These suggestions, discussed among a group of international experts and presented in a synthetic form, may be used as a practical resource (though not an exhaustive one), to aid in the evaluation and identification of appropriate fisheries management responses to aquatic invasive species in the context of climate change. While it may not address all the complexities of the subject, it provides a starting point for adaptation strategies, recognizing the diverse legal, cultural and socioeconomic conditions in different fishery contexts, offering valuable insights for policymakers, fisheries managers, and practitioners who have to deal with aquatic invasions.

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Introduction

Aquatic invasive species (AIS) are a growing threat for aquatic ecosystems and related fisheries systems in both marine (Giakoumi *et al.*, 2016) and freshwater (Bernery *et al.*, 2022) environments. Ecological impacts caused by AIS are recognized on a global scale (Gallardo et al., 2016) and are extensively documented (Strayer, 2010; Britton *et al.*, 2011; Cuthbert *et al.*, 2021). Concurrently, the economic consequences associated with AIS showcase both negative and positive outcomes, particularly within the realm of fisheries (Lovel *et al.*, 2006; Haubrock *et al.*, 2022; Tsirintanis *et al.*, 2023; IPBES, 2023). This phenomenon, which has rapidly increased in recent decades (Bailey *et al.*, 2020), is closely related to the rates at which humans translocate species beyond their native ranges around the world (Seebens *et al.*, 2017; Pyšek *et al.*, 2020; Seebens *et al.*, 2021), and thus reflects the increased globalization of our economies (Meyerson and Mooney, 2007).

Many aquatic invasions are being exacerbated by global warming, which is modifying the likelihood and routes through which non-native species enter aquatic systems (Rahel and Olden, 2008; Kernan 2015). Additionally, climate warming is enhancing the ability of established AIS to disperse within their new environments, consequently promoting the widespread establishment of warm-water invaders (Rahel and Olden, 2008). This phenomenon not only increases the vulnerability of aquatic resources but also poses a growing threat to related production systems (Barange *et al.*, 2018; D'Amen and Azzurro, 2020; Bahri *et al.*, 2021). The complex interaction between climate change and AIS holds implications for fishery management responses, whose effectiveness can be significantly influenced by climate interactions. This is also relevant to the ongoing shifts in species distributions, where increased connectivity between habitats may facilitate the expansion of species into new areas (Rahel and Olden, 2008). For instance, climate change is driving the range extension of the long-spined sea urchin (*Centrostephanus rodgersii*), posing a significant threat to the kelp-dominated reef ecosystems and consequently to the abalone fisheries in Tasmania (Keane *et al*., this volume). In Japan, ocean warming has also caused the component species of sargassum to shift from temperate to tropical species (e.g. *Sargassum ilicifolium*) that have shorter flourishing seasons, raising concern about declining fish populations that use temperate sargassum (*Sargassum yamamotoi* and *S. piluliferum*) beds as nurseries (Nakamura, this volume).

Shifts in distribution frequently result from the species responding to changing environmental conditions and may not necessarily entail the introduction of non-indigenous species. Nevertheless, AIS which are already established may gain dominance as they are more adapted to warmer temperatures than native species (Le Hen et al., 2023). One notable example is the African catfish (*Clarias gariepinus*) and common carp (*Cyprinus carpio*) in India, thriving in changing climatic conditions that adversely affect native species (Singh, this volume). Moreover, as showcased in several other case studies in this report, rising water temperatures are expected to favour the survival, establishment, or further expansion of certain AIS such as Nile perch (*Lates niloticus*) in Lake Victoria (Natugonza, this volume), the blue swimming crab (*Portunus segnis*) in Tunisian waters (Ben Souissi *et al.*, this volume), the common lionfish (*Pterois miles*) in the Eastern Mediterranean Sea and the *P. volitans/P. miles* complex in the Western Atlantic (Harris, Kleitou and Hall-Spencer, this volume), the paiche (*Arapaima gigas*) in the Bolivian Amazon (Van Damme, Macnaughton and Carvajal-Vallejos, this volume), and the European green crab (*Carcinus maenas*) in North America (Grosholz, this volume). The accelerating impacts of climate change, coupled with other anthropogenic pressures on natural resources such as overexploitation and pollution, are challenging fisheries management to adopt nuanced, adaptive approaches to address AIS (Carosi, Lorenzoni and Lorenzoni, 2023). For instance, climate-induced changes to the hydrology or flow of the Zambezi River are expected to have a significant long-term impact on the kapenta (*Limnothrissa miodon*) fisheries in Lake Kariba, and thus need to be considered in management responses (Marshall, this volume).

Prevention is an important first step to manage the risks of invasive species in aquatic environments. This measure was reflected in the hierarchy of Aichi Target 9 from the Convention for Biological Diversity (CBD), and reiterated in Target 6 of the Kunming-Montreal Global Biodiversity Framework, as well as in EU Regulation 1143/2014, where prevention should be first, then rapid eradication, and lastly containment and ongoing management.

However, despite a wide range of international instruments, regulations and mandates which are today in force to control the transfer of aquatic organisms and to prevent new introductions (e.g. Bartley and Minchin, 1997; Kolkolo, 2005; Singh, 2021; IMO, 2004; UNEP, 2011; EU Regulation 1143/2014), non-indigenous species (NIS) increasingly settle as enduring components of the environment (Havel *et al.*, 2015). Once established, the eradication of these species is almost always considered impracticable in aquatic environments (Ojaveer *et al.*, 2015; Simberloff, 2021; Green and Grosholz, 2021). Consequently, the irreversible nature of aquatic invasions explains their status as dominant and permanent features within aquatic ecosystems (Pinsky *et al.*, 2014), underscoring the imperative for adaptive management. While the presence of invasive species is, by definition, regarded as a threat to native ecosystems, a subset of these intruders become conducive to commercial exploitation in the fishing industry in both freshwater and marine environments. Moreover, in climate change hotspots, certain tropical AIS may paradoxically counterbalance the decline of indigenous species that are sensitive to temperature changes and share similar ecological traits (Katsanevakis *et al.*, 2023). Fisheries must adapt to these transformations, strategically working to manage their socioeconomic and ecological consequences, while simultaneously capitalizing on the potential benefits that established AIS, and more broadly NIS,[1] may provide. This dual approach underscores the importance of a comprehensive management strategy that acknowledges both the challenges and opportunities presented by any species introduced outside its native range.

One of the prominent aspects of this work pertains to those AIS that have become targets for local fisheries, and to the many NIS which have been deliberately introduced in response to demands from the fishing or aquaculture industries. FAO's review on inland fisheries (FAO, 2018) highlights the significance of NIS in fish production. The report provides a comprehensive summary of numerous deliberate introductions serving diverse purposes such as the improvement of aquaculture production (e.g. salmon, common carp, tilapia, whiteleg shrimp, pangasius, pacu, *Macrobrachium rosenbergii*), fisheries (e.g. icefish, Lake Tanganyika sardine, Nile perch, tilapia, common carp), biological control (e.g. black carp controlling snails, *Gambusia affinis* and *Poecilia reticulata* controlling mosquitos, grass carp controlling weeds, silver carp controlling plankton), and bait for recreational fisheries (e.g. *Carassius auratus*, *Gambusia holbrooki*, *Perca fluviatilis*, *Cyprinus carpio*) or angling (e.g. brown trout). Based on this review, the majority of recorded introductions have not undergone assessments. However, for those that have been assessed, the adverse ecological impacts have proven to be greater than the positive social and economic impacts (FAO, 2018).

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[1] Non-indigenous species (NIS) refers to non-native, alien or exotic organisms that have been introduced outside their natural range; they are not necessarily invasive species. Aquatic invasive species (AIS) are aquatic organisms that establish and reproduce rapidly outside their native range.

Today, the translocation of species into new environments continues to take place with limited or no regulations, particularly in developing nations (Britton *et al.*, 2011). Moreover, in most cases, there is no adherence to a precautionary approach for species introduction, including the application of codes of practice and comprehensive risk/benefit analysis (FAO, 2018). These measures, as advocated by the international community prior to any introduction (FAO, 1995; Bartley and Minchin, 1996; ICES, 2005), remain therefore underutilized.

Irrespective of whether their introduction was intentional or accidental, aquatic invaders have impacted aquatic ecosystems, caused the extirpation of many endemic species in freshwater habitats (Hulme, 2015; Natugonza, this volume), and transformed human landscapes (Díaz *et al.*, 2019) including local fisheries and the livelihoods that depend on them. At the same time, some of these species may provide an important contribution to local economies, making it difficult to set optimal management strategies for species that might represent both a threat and a source of income (Britton *et al.*, 2021; Caffrey *et al.*, 2015; Natugonza, this volume). Nevertheless, management choices may be challenged by the perspectives of different stakeholders, which can be difficult to reconcile (Woodford *et al.*, 2016).

This collection of management and research experiences from across the world provides information for policymakers, fisheries managers and practitioners seeking guidance on how to manage AIS in the context of climate change. It is not meant to be exhaustive, but rather a compilation of practical examples and suggestions which may be used as an aid in exploring, evaluating and identifying appropriate measures for AIS management. This volume can therefore serve as a starting point for adaptation thinking, notwithstanding the complexities that may arise from the varying legal, cultural and socioeconomic conditions in any given context.

The publication is divided into two parts.

- **Part 1. Identifying good management practices in response to aquatic invasions** presents a compendium of nine management measures. These measures were widely discussed and revised by the expert team during the AIS workshop (8–9 May 2023), enriched with the information elicited in Part 2, and informed by expert opinions collected through a global online survey (Appendix 1) as well as by literature review. Each measure was analysed according to its potential, main challenges and enabling factors, in order to provide a synthesis of key recommendations on AIS management in a fishery context.
- **Part 2. Case studies** illustrates a series of management experiences, opinions and visions from experts around the world. This section is divided into 11 chapters which provide a wide spectrum of management actions that were implemented to control or exploit aquatic invasions, as well as a box focusing on a single case of biological control (Table 1).

TABLE 1

Case studies addressed in Part 2 of the report. Reference is made to the main types of adaptation measures illustrated in the case studies, according to the numeration used in Part 1 of the report

	Location and Case study	Pathway	Impacts of the invasion	Climate interactions	Main adaptation measures undertaken	Pages
Marine	Barents Sea – Red king crab, *Paralithodes camtschaticus*	Deliberate introduction	Various impacts on ecosystem and habitats. Nuisance to local fisheries because of entanglement in gear and depredation of bait and catches. Additional fishing opportunities based on a highly valued species.	Potential sensitivity to ocean acidification, however, insufficient knowledge to predict the impact	#1, #6	129
Marine	Mediterranean Sea – Blue crab, *Portunus segnis*	Corridors (Suez Canal)	Socioeconomic consequences for small-scale fisheries, affecting fisher incomes, damaging fishing gears, and reducing catches.	Tropical invader favoured by warming conditions; climate-induced changes of native assemblages	#1	54
Marine	Ponto-Caspian Basin – Comb jelly *Mnemiopsis leydi*	Ballast waters/ ship transport	Cascading effects on ecosystem.	Increased sea surface temperatures in 2010 contributing to a decrease of the invasive *M. leidyi* population	#7	26
Marine	Atlantic and Pacific coasts of North America – European green crab, *Carcinus maenas*	Ballast waters/ ship transport	Predation causing impacts on ecosystem and commercial bivalve fisheries and aquaculture.	Green crab population growth and winter survival rate favoured by increased temperatures	#1, #6	109
Marine	Baltic Sea – Round goby, *Neogobius melanostomus*	Ballast waters/ ship transport	Trophic impacts on commercial species and benthic macrofauna due to predation and food availability.	No information	#1	45
Marine	Western Atlantic and Mediterranean Sea – Lionfish, *Pterois volitans* and *P. miles*	Escape from aquarium (Western Atlantic) and Corridors (Suez Canal)	Negative impacts on native species populations. Negative impacts on fisheries and tourism.	Higher growth rates of lionfish and expected further range expansion with increasing water temperatures	#1, #2, #3, #4, #5	116
Marine	Japan – seaweed beds and coral reefs	Unaided	Changes in species composition. Negative impacts on commercial fisheries, including lobster and abalone.	Climate-related shifts in the distribution of sargassum species and loss of kelp beds with subsequent impacts on fisheries	#2, #3, #4, #5, #8	139

	Location and Case study	Pathway	Impacts of the invasion	Climate interactions	Main adaptation measures undertaken	Pages
Marine	Australia – Sea urchin, *Centrostephanus rodgersii*	Unaided spread facilitated by climate change	Overgrazing of kelp reef ecosystems. Negative impacts on commercial abalone fisheries.	Climate-driven range extension of sea urchin, threatening kelp-dominated reef ecosystems and consequently affecting abalone fisheries	#1, #3, #4, #5, #6	147
Inland	Lake Kariba (Zimbabwe/ Zambia) – Sardine *Limnothrissa miodon*	Deliberate introduction	Increase in predators and changes in plankton composition and abundance.	Climate-induced changes in river flow expected to have a significant long-term impact on fisheries	#1	65
Inland	Bolivian Amazon – paiche, *Arapaima gigas*	Escape from aquaculture	Potential impacts on native fish fauna and subsistence fisheries dependent on them. Unequal distribution of benefits from the paiche fishery.	Tropical invader favoured by warming conditions; seasonal flooding and drought	#1, #3	78
Inland	India – African catfish *Clarias gariepinus* and common carp *Cyprinus carpio*	Escape from aquaculture	Catfish with high level of threat to fish biodiversity. Common carp moderate level of threat. Negative impacts on abundance and catches of native fish species.	Higher adaptability and survival rates of invasive species than native species in response to climate change impacts	#1, #4	93
Inland	Lake Victoria (East Africa) – Nile perch, *Lates niloticus*	Deliberate introduction	Negative impact on biodiversity and positive impact on fish production.	Warmer climate and eutrophication likely causing the haplochromine decline while favouring the establishment of Nile perch	#1	159

Part 1

Good practices

Chapter 1
Good practices to address aquatic invasions

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There is a large body of literature on the different actions, projects and methods used to manage the unwanted consequences of biological invasions. However, management experiences are mostly reported for terrestrial organisms, and relatively few cases are described for aquatic species in the specific context of fisheries. Fisheries management encounters challenges in addressing AIS within the context of climate change, given the distinctive features of aquatic environments. Under the changing climate, marine ecosystems, characterized by high connectivity across broad spatial scales, undergo significant alterations in species distribution and ecosystem functions. At the same time, isolated inland waters face even greater hurdles in adapting to these distributional changes, making them particularly vulnerable to severe impacts of global warming.

The diverse ecological, socioeconomic, political and technical characteristics of fishery systems across the world make it difficult to identify generally applicable approaches for dealing with AIS. While a general recommendation is to adopt risk analysis or a precautionary approach, the complexity of fishery systems necessitates context-specific strategies.

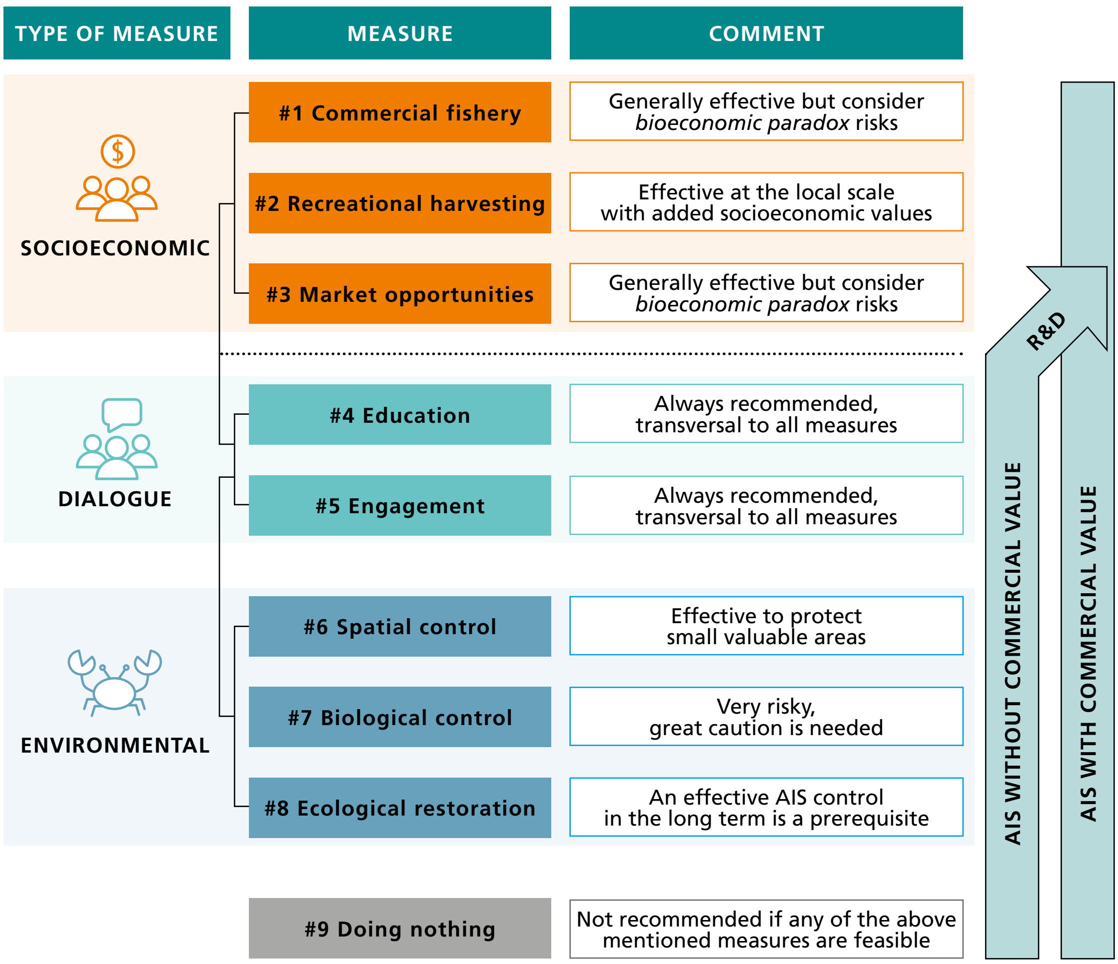
In this section we present a compendium of measures for managing established AIS in local fisheries, discussing their potential, main challenges and enabling factors for their implementation, and providing a synthesis of key recommendations. This compendium is based on the analysis of a series of case studies (Part 2) and a further expert consultation in the form of an online survey (Appendix 1). As a whole, this section summarizes experiences on a wide spectrum of management measures, which can be implemented to control and/or adapt to aquatic invasions within the complexity of each ecological and socioeconomic system.

Nine management measures were identified and grouped under socioeconomic strategies, communication strategies, and environmental interventions (Figure 1). A variable degree of overlap exists across the measures, as some of the good practices described can be considered relevant to several, if not all, measures. Moreover, some of the measures considered can be strongly interdependent. For instance, a commercial fishery cannot be developed on a given AIS (measure #1 *Develop and manage a commercial fishery*) without the existence of market opportunities for that species (measure #3 *Explore market opportunities*). Examples primarily deal with the management of established AIS, while other possible actions to be implemented prior to this stage – such as prevention, early detection and a priori risk/benefit analysis – were deliberately not covered in this volume, but should be considered as a cornerstone for the management of biological invasions, as widely recommended elsewhere (FAO, 1995; Ruesink *et al.*, 1995; Bartley and Minchin, 1996; Mack *et al.*, 2000; Simberloff, 2003; ICES, 2005; FAO, 2018).

The compendium of measures discussed below is not exhaustive and cannot be prescribed for every situation. As a good practice in fisheries management, the choice of the measure(s) to be implemented should be preceded by a thorough analysis of the risks, costs and benefits associated with the proposed measures, in line with the principles of an ecosystem approach to fisheries (FAO, 2003) and related management frameworks (Pikitch *et al.*, 2004; Arkema *et al.*, 2006). Considerable knowledge and consensual agreement among stakeholders is therefore needed to implement these strategies, taking into account the ecological impacts of AIS, the feasibility and costs of chosen measures, related socioeconomic opportunities and ecological risks, among other factors (de Carvalho-Souza *et al.*, 2024). Kleitou *et al.* (2021), for instance, conceptualized an ecosystem-based fishery management approach for AIS and proposed a decision-making framework to guide the choice of fishery management measures in the Mediterranean Sea. Based on a cost-benefit analysis, the authors provided initial guidance to determine whether a fishery targeting AIS, or NIS more broadly, should be implemented and in what manner (Figure 2). The development of similar approaches to guide the choice of management measures with regards to AIS in other contexts is encouraged.

FIGURE 1
Nine measures here considered for managing established AIS, organized by category

Each includes a main recommendation and a comment. Connecting lines on the left refer to the interdependence of the different measures. The term "bioeconomic paradox" refers to the dilemma of targeting and commercializing AIS. It entails the challenge of exploiting AIS for commercial purposes. While pursuing this strategy offers a chance to control their populations and mitigate their effects on ecosystems, it concurrently requires sustaining their viable populations to allow their market-driven harvest. In certain scenarios, AIS lacking commercial value can be transformed into species of commercial interest via innovative research and development (R&D). This shift extends management opportunities to new socioeconomic measures (above the dashed line).

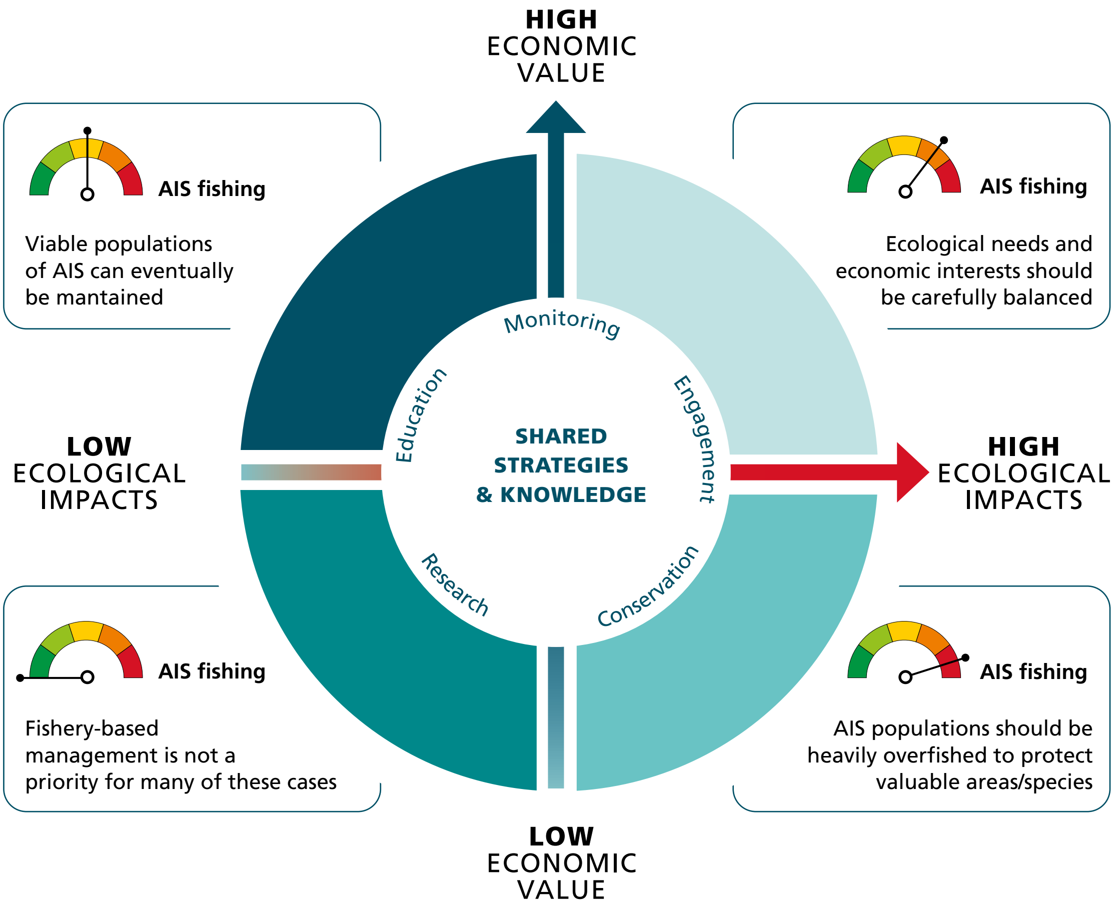


Source: Authors' own elaboration.

FIGURE 2

Example of decision diagram for fishery-based solutions to manage established AIS

The figure refers to four different situations, according to the commercial value and ecological impacts of the AIS under consideration. Each quadrant contains a general suggestion regarding the degree of fishing pressure to be applied on AIS populations, from no or little fishing (green) to sustainable fishing (yellow) up to moderate (orange) or heavy overfishing aimed at functional eradication (red). Measures in the centre of the diagram can be considered transversal to all cases and are always recommended, as well as the sharing of common management strategies and knowledge. Other important variables, such as timing and abundance of the AIS, are not considered in this conceptualization. Each management measure needs to be designed on the basis of appropriate knowledge and tailored to specific ecological and socioeconomic contexts.



Source: Authors' own elaboration.

1.1. SOCIOECONOMIC STRATEGIES

#1: Develop and manage a commercial fishery

About the measure

The management of economically valuable AIS predominantly revolves around the fisheries they sustain, and this measure may entail complex challenges and opportunities for all stakeholders of the social-ecological system (De Carvalho-Souza *et al.*, 2024; Kleitou *et al.*, 2021; Nuñez *et al.*, 2012; Kourantidou *et al.*, 2022; Meadows and Sims, 2023). In numerous instances, local communities have taken the initiative to exploit these new opportunities autonomously (Pecl *et al.*, 2019; Kleitou *et al.*, 2022; Gücü *et al.*, 2021; Falk-Andersson *et al.*, this volume). Management and adaptation processes can be facilitated and reinforced through guidance and support at various levels. In the case of invaders with commercial potential, many examples exist of national or international management experiences (reviewed by De Carvalho-Souza *et al.*, 2024) and this volume includes several examples in both marine and inland fisheries (Ben Souissi *et al.*, this volume; Behrens, Rozenfelde and Putnis, this volume; Van Damme, Macnaughton and Carvajal-Vallejos, this volume; Marshall, this volume; Singh, this volume; Natugonza, this volume). The development of a commercial fishery to remove AIS was among the most cited measures by the experts who were consulted (see Appendix 1 Table AII; Figure A9).

Technological adaptation – which may include the design of specific fishing gears such as gillnets and trap nets in the case of the round goby (Behrens, Rozenfelde and Putnis, this volume), or the development of new fishing traps such as for the blue crab (Ben Souissi *et al.*, this volume) – is often needed to help local fishers exploit a new resource. Actions that can be carried out to implement this measure include regional initiatives to establish a common management strategy, subsidies to fishers or to local industries (Keane *et al.*, this volume), scientific research for efficient exploitation of the AIS stocks, relocation of landing sites and new processing practices for AIS along the coast, and stakeholder training. The decision to develop a fishery for the AIS is also closely linked to measure #3 *Explore market opportunities*.

Positive outcomes and expectations

Supporting commercial fisheries in harvesting AIS creates opportunities to reduce their ecological impact while reducing the cost associated with control measures in both freshwater and marine systems (Appendix 1, Tab AII, Figure A7). Moreover, fishing for AIS can create new value chains and hence economic opportunities that compensate fishers for damages caused by these species. Economic benefits can lead to new local economies, such as in the case of Tunisian blue crabs (Ben Souissi *et al.*, this volume) and the red king crab (Falk-Andersson *et al.*, this volume), which are processed in local facilities and exported to several countries. In some cases, the AIS fishery can become the largest fishery of all, partially offsetting labour costs and economic losses from the harvest of the affected native species (Ben Souissi *et al.*, this volume; Keane *et al.*, this volume; Gücü *et al.*, 2021).

Challenges

Designing management for the commercial harvesting of AIS can be a powerful but yet challenging strategy as ecological impacts can be high and unwanted. Lowering populations of targeted AIS by fishery removals can fail if the effort is not sustained across large scales of time and space (Simberloff, 2021), and determining realistic and achievable management objectives (Keane *et al.*, this volume) is one of the first difficulties. Selective harvest by fishers (e.g. size-selective fishing of individuals of commercially viable sizes) may not lower abundance of the AIS below the levels needed to secure ecological benefits. This is also confirmed by the high percentage of neutral outcomes of this measure in both marine and freshwater systems, as highlighted by the expert survey regarding the strategy "species removal" (Appendix 1, Figure A6). Inadequate selectivity of removal methods targeting AIS can produce undesirable side effects in native fish species communities and habitats (Britton *et al.*, 2011). This challenge is well illustrated by the case of the rapa whelk in the Black Sea, whose intense harvest by beam trawl has caused significant damage to benthic habitats and other commercial species (Gücü *et al.*, 2021). Intensive targeting of AIS provides opportunities for controlling invasions and reducing their impacts on ecosystems, but at the same time creates a perverse incentive to maintain viable populations of the AIS to sustain its market-based harvest (Nuñez *et al.*, 2012, see also measure #3 *Explore market opportunities*; Behrens, Rozenfelde and Putnis, this volume; Ben Souissi *et al.*, this volume). High economic opportunities created by AIS may also result in stakeholders wanting to extend their spatial range of action, as in the case of the Barents Sea red king crab (Falk-Andersson *et al.*, this volume), or to introduce the AIS into previously uninvaded areas to benefit from its presence. Target AIS may become "conflict species", with competing management objectives and conflicts across jurisdictions, between fisheries groups and managers, among conservation managers, and among users.

Drastically reducing AIS populations can make their harvest uneconomical: this is the "bioeconomic paradox"[2] of market-based invasive species harvest (Harris, Kleitou and Hall-Spencer, this volume; Harris *et al.*, 2023). This brings in the challenge of trying to balance ecosystem-based management goals with the economic interest of fisheries. The former aims to limit the spread, and impacts of AIS and to maintain healthy ecosystems, while the latter requires maintaining viable AIS populations in the long term. This issue is widely represented in the case studies in this volume and in the broader literature. For example, lionfish fisheries can help control its invasion, however, their relatively small size and the labour-intensive process involved in harvesting present a challenge for profitable fishing (Harris, Kleitou and Hall-Spencer, this volume). When the AIS resource is shared among several countries, the lack of a common strategy may hamper its effective management or reduce viable management options, and generate conflicts (Falk-Andersson *et al.*, this volume; Marshall, this volume; Natugonza, this volume; Skonhoft and Kourantidou, 2021).

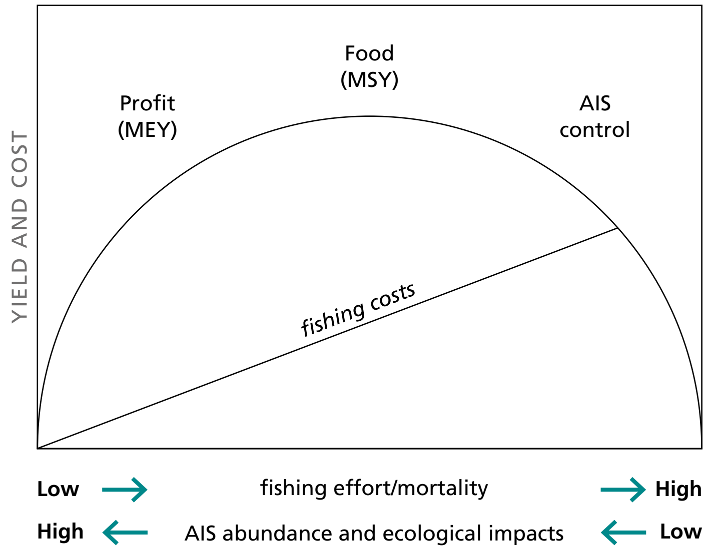
Effective management of commercial AIS can also be challenged by uncertainties on population dynamics, especially during the early phases of the invasion. Once a fishery has been established, drastic declines in AIS abundance negatively affect the fishery system (Marshall, this volume). In many cases aquatic invader populations have decreased spontaneously, after a growth phase, without human intervention ("boom and bust" dynamics; see also Falk-Andersson *et al.*, this volume).

Some authors proposed maintaining the commercial AIS stock under some controlled level of overfishing, which would enable some level of profitability while maintaining low biomass of invaders (Chagaris *et al.*, 2020; Bogdanoff *et al.*, 2021; Kleitou *et al.*, 2021) (Figure 3). Such a strategy should be based on the assessment of density-dependent effects on reproduction rates, as illustrated in the case of green crab (Grosholz, this volume). Thus, this strategy would include identifying new reference points occurring at progressively higher levels of fishing effort to guide decision-making in the appropriate management of AIS fisheries (Chagaris *et al.*, 2020; Bogdanoff *et al.*, 2021; Kleitou *et al.*, 2021). Crucially, these benchmarks should be dynamically adjusted over time to accommodate the evolving dynamics of marine ecosystems, especially in response to ocean acidification and climate change (Pinsky *et al.*, 2014, Bahri *et al.*, 2021; Kleitou *et al.*, 2021).

[2] The bioeconomic paradox (Harris *et al.,* 2023) entails the challenge of exploiting AIS for commercial purposes. While pursuing this strategy offers a chance to control their populations and mitigate their effects on ecosystems, it concurrently requires sustaining their viable populations to allow their market-driven harvest.

FIGURE 3
Conceptual representation of relative ranges of fishing mortality related to different AIS management objectives

The equilibrium production curve relating yield (or revenue) to fishing effort shows three reference points: maximum economic yield (MEY) where resource rent (the amount which is left over when all exploitation costs have been deducted from revenues) is maximized; maximum sustainable yield (MSY) where catch (food production) is sustainably maximized; and a hypothetical reference point where fishing mortality is high enough to balance economic and ecological needs (keep the AIS under control by fishing while maintaining a profitable fishery). The diagonal line represents the expected increase in exploitation costs with increasing fishing effort. These benchmarks must be continuously adjusted to accommodate the dynamics of marine ecosystems under evolving climatic conditions.



Source: Authors' own elaboration.

Enabling factors

Developing a commercial fishery on AIS may be feasible when the species is well-established, abundant and economically valuable if methods used to catch them are not environmentally damaging. Subsidies and external investments can accelerate the development of the AIS harvest industry, together with the effective engagement of local fishers (Keane *et al.*, this volume; Behrens, Rozenfelde and Putnis, this volume; Ben Souissi *et al.* , this volume). Wherever relevant, allocating AIS harvesting rights to marginalized groups can provide economic opportunities to small-scale fishers (Falk-Andersson *et al.*, this volume) although there is a drive to reduce fishery subsidies worldwide (Laffoley *et al.*, 2019). Intensification of AIS harvesting in priority areas, incentivized by subsidies specifically designed for that purpose, can be effective in controlling the invasion (See measure #6 *Implement spatial control*). Other enabling factors discussed in the case studies include the relocation of landing sites to facilitate new marketing strategies, the processing and export of AIS products (Beherens, this volume; Ben Souissi, personal communication), scientific work on the assessment of the AIS stock and the development of specific fishing techniques for its effective and selective harvesting (Ben Souissi *et al.*, this volume). Innovative harvest technologies may help decrease fishing costs and increase harvest capacity. For example, testing is underway to develop traps to allow commercial fishers to harvest deep-water lionfish in the western Atlantic (Harris *et al.*, 2020, 2023b; Harris, Kleitou and Hall-Spencer, this volume). The establishment of effective fishery management systems where management decisions (e.g. quotas, spatial measures) are based on scientific advice and on a dialogue with stakeholders can also facilitate timely interventions and reduce conflicts (Falk-Andersson *et al.*, this volume).

Key recommendations

- If used properly, the commercial harvest of AIS can help reduce the adverse effects of the invasion, while simultaneously creating alternative economic returns through the development of a new fishery.
- It cannot be assumed that any level of AIS removal will be beneficial to social, economic and/or ecological objectives; it is therefore recommended to identify, a priori, appropriate management targets and objectives.
- Managing AIS fishery necessitates conducting risk assessments and cost-benefit analyses to evaluate the ecological, social and economic risks involved. Consequently, determining the optimal level of AIS exploitation or stock size is recommended, a process involving both ecological conservation objectives and socioeconomic perspectives.
- Fishing regulations should be based on identified objectives and consider the unique features of each social and ecological context. For example, in some cases licences for AIS fishing could be established, but in other cases open access to keep the population down has to be preferred. Management objectives and regulations should be consistent across different countries sharing the same resource.
- Developing an AIS fishery may result in unregulated activities (such as illegal fishing and AIS translocations), which need to be properly prevented/contained.
- When targeting a new AIS resource, it is suggested to undertake scientific research on fishing and post-harvest technologies. There might be a need to develop appropriate fishing techniques/gears and processing methods to effectively and selectively exploit AIS to avoid bycatch or other impacts on native species and habitats.
- Investment by governments and industry in AIS harvest fisheries (e.g. economic incentives, grants) should be cost-effective in the long term and follow an adaptive management approach, to adjust management actions in response to changing conditions.
- The planning of this measure should consider possible effects of climate change, large variations ("boom and bust" dynamics) in the AIS stock size and related impacts, especially during the first phases of the invasion.
- The conception of a spatially explicit management system and/or fishery quotas should aim to prevent conflicts among different fisheries stakeholders, especially between fishers who get access and those who don't.
- An effective communication strategy including close dialogues with the different stakeholders is recommended as it might help to reduce stakeholder conflicts and concerns over time, and support adaptive management (see also measure #4 *Implement outreach programs*, and #5 *Foster stakeholder engagement*). Dialogue, cooperation and coordination among the different sectors and between fishery, research and management bodies should be empowered to set common objectives for the effective management of AIS using an adaptive and inclusive approach.
- Research and development may find ways to turn a non-commercial AIS into a commercial one, opening new potential for both mitigation and economic exploitation (see also measure #3 *Explore market opportunities*).
- Management actions that incentivize sustainable fishing of traditionally harvested native species may ensure that these resources continue to be valued in the future and that knowledge on their harvesting is maintained. This prevents dependence on a single AIS, and incentivizes the protection of native species and ecosystems (e.g. licences given conditional on harvesting native species), as in the case of the Barents Sea red king crab (Falk-Andersson *et al.*, this volume).

#2: Encourage recreational harvesting

About the measure
Recreational fisheries, defined here as a non-commercial fishing activity exploiting aquatic resources for recreation, tourism or sport, can represent a useful tool in controlling AIS. While it may not be the sole solution, when implemented as part of an integrated management approach, it can contribute to the overall control and mitigation of AIS populations. The best-known case is probably the one of the lionfish (*Pterois volitans* and *P. miles*) invasions (Harris, Kleitou and Hall-Spencer, this volume). Managers can encourage recreational harvesting of AIS in several different ways, such as by raising awareness (see also measure #4 *Implement outreach programmes*), by organizing fishing competitions and/or by making special regulations, e.g. more permissive rules for the AIS fishery (Fabrizio *et al.*, 2021; Kleitou *et al.*, 2021; Ulman *et al.*, 2022). Similar measures can be attempted in inland ecosystems (Li *et al.*, 2020) but with great caution, as recreational fishing, particularly angling, is a major pathway for the introduction of AIS (Cambray *et al.*, 2003; South *et al.*, 2002). Designing management for recreational harvesting of AIS is strictly linked to measure #5 *Foster stakeholder engagement* (see also Clements *et al.*, 2021; Quintana *et al.*, 2023). Finally, recreational fishers can contribute to attaining functional eradication (see measure #6 *Implement spatial control*) at vulnerable and/or valuable areas of limited extension.

Positive outcomes and expectations
Recreational fisheries can reach substantial scale and intensity (e.g. Mediterranean Sea: Agius and Vella, 2019; Michailidis *et al.*, 2020) and, in certain contexts, can act as an important activity in the control of AIS. This publication reports on experiences with the control of lionfish in the Caribbean and the Mediterranean (Harris, Kleitou and Hall-Spencer, this volume). It is possible to engage the public in the culling of AIS through awareness campaigns. However, the presence of AIS may also create new economic and leisure opportunities, for example for diving clubs or service providers in the tourism industry.

Challenges
National laws may limit the engagement of recreational fishers in culling activities (for example, spearfishing using scuba gear, including for lionfish, is not permitted in many countries). Moreover, the removal by recreational fishers may be of limited scope, providing potential refugia for the species; for example, scuba divers cannot operate below a certain depth (Harris, Kleitou and Hall-Spencer, this volume; Harris *et al.*, 2023b; Barbour *et al.*, 2011). Wide-scale control throughout the entire invasive range of an AIS is usually unattainable by recreational fishing (Harris, Kleitou and Hall-Spencer, this volume). Public perceptions might challenge the implementation of management actions, for instance when considering whether culling is acceptable, especially for vertebrates. In some cases, recreational fishing may come into conflict with professional fishers exploiting the same resource or with other commercial uses of the area.

Certain recreational fishing techniques, especially angling, may exhibit very low selectivity. Therefore, there might be a need for supplementary strategies or interventions to improve selectivity. This ensures the efficient removal of target species while minimizing adverse effects on non-target species and ecosystems.

Finally, if recreational harvesting of AIS generates incomes, such as in the tourism industry, a *bioeconomic paradox* can arise, as can happen in commercial fisheries (see measure #1 *Develop and manage a commercial fishery*).

Enabling factors

This measure is appropriate when the targeted AIS can be easily detected and removed by recreational fishers. Raised public awareness and the possibility of engaging motivated volunteers (also through bounty competitions) are also important enabling factors. Any potential use of the AIS, such as in local cuisine, may provide additional motivation for its recreational harvesting.

Synthesis of key recommendations

- Involve the tourism industry and recreational organizations, including angling and diving clubs, in the management of invasive species, ensuring their selectivity in targeting AIS.
- Once the selectivity of recreational fishing methods is assured, managers can promote this strategy by issuing specific licences or organizing carefully designed bounty competitions in conjunction with awareness campaigns.
- Encourage extensive collaboration among governments and stakeholders to implement coherent strategies across large geographical areas.
- Thoroughly evaluate each situation to prevent other possible risks, such as the possibility of intentional introductions by recreational fishers, particularly in freshwater systems.

#3: Explore market opportunities

About the measure

Marketing AIS products helps sustain AIS fisheries, and some AIS can be commercialized through a series of actions (e.g. Volden *et al.*, 2020; Pasko and Goldberg, 2014) which can be implemented at the local level but also at broader scales, seeking external markets. This option was highly prioritized by previous studies (e.g. Giakoumi *et al.*, 2019) and also ranked among the best practices mentioned in the expert survey, especially in marine systems (Figure A9). New market opportunities can also arise by processing the AIS in different forms, such as in the case of blue crab in Tunisia (*Portunus segnis*, Ben Souissi *et al.*, this volume), which is an edible crab currently processed in specialized manufacturing plants, rapidly established in the country after the blue crab invasion. The appeal of commercializing invaders is evident in invasive species cookbooks (Parks *et al.*, 2018; Nuñez *et al.*, 2012) and videos. Actions for value-adding, e.g. product traceability and utilization of byproducts such as skin, fins (Van Damme, Macnaughton and Carvajal-Vallejos, this volume; Harris, Kleitou and Hall-Spencer, this volume) and biomolecules, are also part of this measure.

Positive outcomes and expectations

Developing new market opportunities for the AIS helps the fishing industry develop an entire new value chain, with increasing prices and demand for the species. Local communities might start consuming the AIS (Ben Souissi *et al.*, this volume; Van Damme, Macnaughton and Carvajal-Vallejos, this volume), and integrating it in local culture and traditions. The AIS market sustains the fishery and also enhances its economic prospects, serving as a means to offset potential economic losses caused to the fishery economy by the species in question (see measure #1 *Develop and manage a commercial fishery*). In some cases, the fishery incomes generated by an invasion can be even higher than the pre-invasion ones (e.g. blue crab in Tunisia, Ben Souissi, personal communication); however, these increased incomes may not always find their way to the fishers and they may be damaging to the environment, as other stakeholders involved in the AIS business may invest or capitalize on these gains.

Challenges

In some instances, legislation may impose limits on the use or consumption of species. For example, under EU regulations, any food that was not consumed "significantly" prior to May 1997 is considered to be a novel food, which can be commercialized only after a specific risk assessment carried out by the European Food Safety Authority (EFSA). Indeed, some issues may arise in promoting invasive species for human consumption, when potential health risks exist (e.g. Cearnal, 2012; Annabi *et al.*, 2018). For example, some food safety challenges have been highlighted for the invasive rabbitfish in the Atlantic due to the risk of ciguatera toxin (e.g. Acosta *et al.*, 2015).

The higher value and commercial exploitation of AIS may provide management opportunities but at the same time create a bioeconomic paradox, i.e. incentives to maintain viable AIS populations to sustain the market-based AIS harvest (see also measure #1 *Develop and manage a commercial fishery*; Nuñez *et al.*, 2012). Thus, commercial AIS may create a valuable resource that stakeholders wish to keep or even spread. High market values for AIS may generate conflicts among fishers, such as in the case of red king crab (*Paralithodes camtschaticus*) in the Barents Sea (Falk-Andersson *et al*., this volume), or in the case of arapaima (*Arapaima gigas)* (Van Damme, Macnaughton and Carvajal-Vallejos, this volume). Market opportunities may promote unregulated growth of a fishery (Behrens, Rozenfelde and Putnis, this volume), including illegal fishing (Harris, Kleitou and Hall-Spencer, this volume). Fishery subsidies and AIS-related profits can be unevenly distributed along the value chain (Van Damme, Macnaughton and Carvajal-Vallejos, this volume), generating conflicts within the fishery system.

The absence of cultural traditions may initially challenge the local consumption of AIS (Ben Souissi *et al*., this volume). People are inherently conservative in food preferences, and they have a general tendency to dislike new foods (Nuñez *et al*., 2012). Neophobia and the negative image of AIS, and the associated concern about food safety, are common constraints in this kind of measure (Behrens, Rozenfelde and Putnis, this volume; Van Damme, Macnaughton and Carvajal-Vallejos, this volume; Harris, Kleitou and Hall-Spencer, this volume).

Inadequate infrastructure and the great distance between markets and landing points may, in some cases, limit the commercialization of large quantities of AIS (Van Damme, Macnaughton and Carvajal-Vallejos, this volume). The accumulation of waste in processing industries developed for AIS, if not managed, may also create the risk of contamination and pollution of local waterways, soil and air (Keane *et al*., this volume; Ben Souissi *et al*., this volume).

Enabling factors

The idea that AIS can be controlled by consuming/using them can gain popularity among the general public, government agencies, conservation groups and the media (Nuñez *et al.*, 2012). Existing AIS markets, including foreign markets (Behrens, Rozenfelde and Putnis, this volume) and established traditions, help consumers accept AIS as a food source. Other enabling factors may include the financial support of public administrations; the initiative of local communities; the interest of both internal and external investors; the diffusion of techniques and practices for processing the AIS; scientific research assessing the viability and possible use of new products; healthy business relationships across different countries (Voldnes *et al.*, 2012); and the existence of means of transportation and trade routes for the commercialization of AIS products to large markets (Van Damme, Macnaughton and Carvajal-Vallejos, this volume; Natugonza, this volume).

Key recommendations

- Promoting the commercial use of AIS products offers potential benefits but requires careful consideration of ecological and economic risks. Balancing these factors is crucial for informed decision-making.
- Consider risks of harvesting to the aquatic environment, human health and safety before encouraging harvest.
- Explore any possible use of AIS products compatible with current legislation.
- Take into account local traditions when promoting AIS products locally.
- Products related to AIS can leverage global market opportunities.
- Encourage dialogue and collaboration among multiple actors and stakeholders.
- Funds can be raised through national and international investments.
- Carefully consider the environmental impacts of processing industries and develop circular economy systems (for example, developing organic fertilizers using organic wastes from processing industries).
- Public education and awareness can overcome neophobia.
- Consider the branding of AIS products as an environmentally friendly choice but only if that is the case based on scientific information about the impact of the fishing technique.
- Engage stakeholders in the value chain and promote equitable distribution of profit margins.
- Techniques and practices to use/consume the invasive species can be disseminated through media, e.g. recipes shared through TV programmes, websites, social media, magazines and cookbooks.
- Develop national and regional programmes and policies to support this measure while avoiding an inequitable distribution of resources to prevent the possibility of conflicts.
- Research and development should explore any possible way to use AIS products, not only as a source of proteins. This strategy can turn non-commercial AIS into commercial AIS, opening new possibilities for their management (see #1 *Develop and manage a commercial fishery*).

1.2. COMMUNICATION STRATEGIES

#4: Implement outreach programmes

About the measure

Raising public awareness and educating the public about the occurrence, risks and potential uses of AIS is one of the most important measures for their management, and it can be applied across different ecological, legal, administrative, political and socioeconomic contexts (e.g. Giakoumi *et al.*, 2019). This is also confirmed by the results of the survey, where the lack of awareness, understanding, dialogue and acceptance among fishers represented the most cited challenge in the management of AIS (Appendix 1, Figure. A8). Similarly, education and awareness were the most cited best practices for the management of AIS in both freshwater and marine systems (Appendix 1, Figure. A9). Effective communication campaigns are a necessary ally for managing AIS and they can be carried out through a variety of means, from traditional printed materials displayed in appropriate locations (e.g. fishing harbours) to public meetings, TV shows, newspapers and social media.

Positive outcomes and expectations

Education and awareness among the general public and decision-makers will help them understand the threats posed by AIS, with a series of positive outcomes ranging from gaining the basic cultural values and assets needed to win support (including funding), to concrete action to manage AIS. Education also promotes behavioural changes and helps to engage local communities in management efforts (see measure #5 *Foster stakeholder engagement*).

Awareness is also crucial for securing the public acceptance of management interventions (Giakoumi *et al.*, 2019), the involvement of the fishery sector in those management interventions (Hart and Larson, 2014; Ben Souissi *et al*., this volume), and for reducing neophobia and the risks associated with aquatic invasions (e.g. Ben Souissi *et al.*, 2014).

Challenges

Negative or incomplete messages associated with AIS can amplify neophobia, hindering the commercial use of these species – for example, only advertising that the lionfish has poisonous spines without providing information about proper ways to handle and safely consume the fish can hinder its consumption (Harris, Kleitou and Hall-Spencer, this volume). Moreover, communication campaigns directed to the wrong target groups can result in limited effectiveness, or biased information that may down-play the environmental impact of a commercial AIS fishery.

Enabling factors

Interest and receptivity among national media on the issue of invasive species is of key importance. Campaigns based on social media can also facilitate reaching out to fishers and the general public. A good level of education among community groups is beneficial. Participatory actions, such as the elicitation of local ecological knowledge, help improve the dialogue with local communities, especially between local fishers and management bodies or researchers.

Key recommendations

- Identify priority audiences for awareness-raising programmes (e.g. general public, local fishers and other stakeholders, decision-makers, conservation groups).
- Ensure effective communication of simple messages which are easy to understand and catch the attention of community groups, primarily fishers. The language and communication tools should differ for different target audiences.
- Reiterate key messages regularly to ensure appropriate and effective responses.
- Encourage target groups to report sightings of NIS (see also measure # 5 *Foster stakeholder engagement*). Such initiatives, often carried out through social media, can be highly effective for "learning by doing", creating authentic and lasting alliances with fishers.
- Social media can be prioritized in some situations, but relevant information can be disseminated in a variety of ways, from printed materials and press releases to public events.
- Communication activities are also needed to support the branding of AIS products, where environmentally appropriate, to facilitate the opening of markets and increase the economic value of the AIS (see measure #3 *Explore market opportunities*).

#5: Foster stakeholder engagement

About the measure
Engagement of local fishers and volunteers is often cited as one of the key measures to deal with AIS, and this strategy is well represented in this report (Nakamura, this volume; Ben Souissi *et al*., this volume; Harris, Kleitou and Hall-Spencer, this volume). Local fishers can be engaged according to different goals and strategies (CIESM, 2018), from early detection of NIS to participatory monitoring and management. Actions may include elicitation of local ecological knowledge (LEK) (Azzurro *et al.*, 2019; Azzurro and Cerri, 2021), engagement of citizens in AIS monitoring (Martelo *et al.*, 2021), active AIS removal (see measure #2 *Encourage recreational harvesting* and Nakamura, this volume), and training (Ben Souissi *et al*., this volume).

Positive outcomes and expectations
The engagement of fishers and volunteers in the collection of information can facilitate early detection of AIS and enhance knowledge on the species distribution, population trends and behaviour. Working together with local communities also generates partnerships and awareness. Information provided by local fishers can substantially contribute to the early detection of new introductions and serve as a basis for key advice on how, where and when to address targeted removal (see measure #6 *Implement spatial control*).

Challenges
Challenges for this measure include conflicting management objectives among different fisheries (Natugonza, this volume; Falk-Andersson *et al*., this volume); mistrust, reluctance to cooperate, lack of dialogue and poor communication between fishers and management bodies (Appendix 1, Figure. A8); and difficulties in AIS identification by local communities (Ben Souissi *et al*., this volume). Quality checks on data are needed, as is funding to support volunteers in order to secure their buy-in and help them provide sound data.

Enabling factors
This measure is enabled by factors including pre-existing and long-lasting relationships between management bodies or researchers with local fishers; convergence of management objectives; a good level of education and awareness among local fishers; dialogue and partnership between stakeholders; and AIS that are easy to identify and strongly interact with fishing activities. Economic incentives can further enhance stakeholder engagement.

Key recommendations
- Be inclusive and build partnerships.
- Build trust through effective collaborations with motivated partners.
- When eliciting LEK information, consider local fishers as the experts.
- Be realistic and practical, start small with the “easy” targets, do not overload volunteers.
- Establish an appropriate communication strategy and common language to build bridges with local fishers.
- Act locally, but consider that this measure may extend to a larger geographical scope (for example involving different areas and countries) which can be achieved under proper coordination.

1.3. ENVIRONMENTAL INTERVENTIONS

#6: Implement spatial control

About the adaptation measure

It is rarely feasible to eradicate established AIS, i.e. the complete removal of all individuals of an entire population, in an aquatic system. The few documented cases have a very limited scope for fisheries development (Britton *et al.*, 2006) and concern only small and confined environments, with limited or no connection with other water bodies (Green and Grosholz, 2021; Simberloff, 2021; Rytwinski *et al.*, 2019). Spatially controlling AIS expansion in particularly vulnerable and valuable areas is considered a more realistic goal. Concepts behind this strategy are those of "maintenance management", i.e. keeping the population under levels that minimize adverse ecological and socioeconomic impacts (Simberloff, 2021), and "functional eradication", defined as suppressing invader populations below levels that cause unacceptable ecological effects (Grosholz, this volume; Green and Grosholz, 2021). In some cases, functional eradication has proved to be effective to protect specific conservation targets in high-priority locations with limited spatial extension, where very high exploitation rates can be obtained.

AIS control can be achieved by mechanical or physical means. In the case of European green crab (Grosholz, this volume; Green and Grosholz, 2021), the invasion was successfully controlled locally by using fences and mesh enclosures to exclude the unwanted AIS from beds of commercially important bivalves. Similar measures were undertaken to remove all visible AIS in productive abalone areas (Keane *et al.*, this volume). In some cases, recreational fishing can be involved in AIS removal with significant but temporary results (see measure #2 *Encourage recreational harvesting*; Harris, Kleitou and Hall-Spencer, this volume). Finally, maintenance management can be carried out by engaging professional fishers in AIS removal and providing financial incentives. Such "bounty programmes" can sometimes be the only means to control non-commercial AIS, such as in the case of the toxic pufferfish *(Lagocephalus sceleratus)* in Cyprus (Gücü *et al.*, 2021), although sustaining funding for such programmes can be uncertain. However, a thorough evaluation of the outcomes, efficiency and feasibility of each measure is essential, considering each case individually.

Positive outcomes and expectations

This measure is most useful for the control of AIS abundances at local levels and in spatially confined areas; to conserve biodiversity; and to protect native species and habitats of high conservation value and/or of commercial relevance.

Enabling factors

The measure is suitable when an invasion is restricted to a small and/or confined water body, or in the early stages of an invasion by easily detectable AIS. Its utility can be scaled up through collaboration with volunteers and scientists in harvesting programmes, hence a high level of public awareness and education is beneficial. Suppression activities are more likely to succeed when quantitative targets can be set (Green and Grosholz, 2021). The existence (and knowledge) of vulnerable life stages can offer opportunities for successful AIS removals. For example, during certain periods of the year, female blue crab (*Callinectes sapidus*) migrate from coastal lagoons to the open sea for reproduction: priority could be given to catching females during this critical phase of the life cycle of the species.

Challenges

As spatially restricted measures may have little or no effect on the overall population of an AIS, controlling measures may need to be periodically repeated (Grosholz, this volume; Harris, Kleitou and Hall-Spencer, this volume), resulting in a long-term commitment which can be demanding in terms of both effort and economic costs (Grosholz *et al.*, 2021). Keeping the AIS population below the carrying capacity can stimulate compensatory changes in survival and recruitment (Pasko and Goldberg, 2014; Nuñez *et al.*, 2012; Weber *et al.*, 2016; Walsworth *et al.*, 2020), increasing reproductive rates and therefore potentially undermining the effectiveness of harvest programmes for delivering a long-term reduction of the AIS population. In the case of the green crab (Grosholz, this volume), the implementation of AIS control measures led to a 30-fold increase in reproductive rates. Measures will be unsuccessful if a managed site continues to be reinvaded from unmanaged sites, or where commitment and funding declines permit a new invasion to take place.

Poisoning programmes, extensively applied on terrestrial habitats, cannot usually be applied in aquatic ecosystems because the risk of poison diffusion is high; the health of entire ecosystems could be jeopardized and the fishery resources contaminated through the food chain (Terlizzi *et al*., 2001). Nevertheless, mention can be made of the case of the invasive lamprey *Petromyzon marinus* in the Laurentian Great Lakes, which was successfully controlled with lampricides (TFM: 3-trifluoromethyl-4'-nitrophenol and Bayluscide: 2', 5-dichloro-4'-nitrosalicylanilide) (Sullivan *et al*., 2021). This programme is still active under the Great Lakes Fishery Commission.[3] Although the employed lampricides are considered selective (Ionescu *et al*., 2021), there is still a risk of adverse effects on several invertebrate and vertebrate species, some of which are of conservation concern (Wilkie *et al*., 2022). Consequently, addressing and mitigating undesirable side-effects is a top priority within the sea lamprey control programme.

Key recommendations

- Shift management strategy from total eradication to maintenance management or functional eradication once an AIS is established (i.e. keeping the population at low density and limiting its negative impacts; see also measure #1 *Develop and manage a commercial fishery*). This means that the AIS control needs to be periodically repeated to counteract the spillover of other individuals from unmanaged areas.
- Identify priority areas where management measures should be concentrated in the long term.
- Define measurable goals and target exploitation rates before starting the removal of AIS. The necessary data could include AIS densities, dimensions of the waterbody, and recolonization rates (pilot studies can help in evaluating whether the desired results are attainable).
- Adopt a participatory approach (engaging fishers, volunteers and the scientific community) and build long-term commitment. Indeed, collaboration on a very large scale is often required in this kind of measure (Grosholz, this volume; Grosholz *et al.*, 2021; see also measure #5 *Foster stakeholder engagement*).
- Prevent the reintroduction of AIS, especially in high-priority areas, through prevention, sustained monitoring, early detection and rapid response.
- Consider any possible ecological risks. Great caution is needed when considering eliminating long standing invasions, due to the possible existence of positive interactions between AIS and other components of the ecological community (Simberloff, 2021).
- Effective removal of AIS can be carried out targeting vulnerable life stages (when present), so it is wise to perform studies on the biology and ecology of the AIS in order to identify the best removal strategy.
- Explore the local ecological knowledge of fishers, which can help to identify key vulnerable life stages, preferential habitats, preferential times of the year and appropriate fishing gears to implement a targeted removal of AIS.

[3] www.glfc.org/lampricide.php

#7: Implement biological control

About the adaptation measure
Living organisms – such as predators, herbivores, omnivores, parasites, pathogens, and genetically-engineered organisms – have been employed to control populations of AIS, but there are very few examples that have been successful for aquatic systems (see Bajer *et al.*, 2019) and even worse may have serious negative impacts. This practice was also the least cited in the expert survey (Appendix 1, Figure. A9) and by Giakoumi *et al.* (2019). Giakoumi *et al.* (2019) identified five different actions for biological control, which can be driven by: 1. native consumers (predators or grazers) that feed on the invasive species (e.g. by restocking predator populations); 2. native diseases and/or parasites that affect the invasive population; 3. alien parasites and/or diseases; 4. alien consumers (predators or grazers); and 5. genetic approaches that affect only the invasive species.

Keane *et al.* (this volume) reported the case of the native southern rock lobster (*Jasus edwardsii)* in Tasmania, which has been successfully restocked to prey on the invasive long-spined sea urchin (*Centrostephanus rodgersii).* One of the most interesting cases is the striking decline of the invasive comb jelly ctenophore (*Mnemiopsis leidyi)* in the Black Sea and Azov Sea, due to the accidental introduction in ballast water of another ctenophore, *Beroe ovata,* that preys on it (Shiganova, Box 1; Shiganova *et al.*, 2014). Based on this experience, a deliberate introduction of *B. ovata* was proposed as a measure to resist the invasion of *M. leidyi* in the Caspian Sea, but Caspian countries failed to reach unanimous agreement. Nevertheless, in 2019, *B. ovata* was inadvertently introduced (Roohi *et al.*, 2022) and it could be assumed that following the experience in the Black Sea (Shiganova, Box 1), this introduction would foster the recovery of the Caspian ecosystem.

Physical removal and predation by native predators are commonly employed to deal with the invasion of aquatic invertebrates and fish (Bajer *et al*., 2019), whereas the utilization of genetic technologies and microbes is still in the developmental stages. New technologies (e.g. genetic technologies) are expected to appear in the next decade, but they will have to clear regulatory and ethical concerns before they are applied. Genetic biocontrol, i.e. the release of genetically modified organisms with the specific purpose of hindering the reproductive capabilities of invasive species, which has been explored for pest species in terrestrial agricultural systems, has just started to be tested in aquatic systems (Teem *et al.*, 2020; Simberloff, 2021). For example, recent studies demonstrate that triploidy can reliably produce sterile individuals in sufficient numbers to eradicate a small target population under containment conditions, and this technique has been recently attempted in aquatic vertebrates such as invasive bullfrogs (*Lithobates catesbeianus)* in Europe (Descamps and De Vocht, 2017) and invasive lamprey (*Petromyzon marinus)* in the Great Lakes region (Bravener and Twohey, 2016). Numerous innovative genetic technologies hold the potential to offer significant advantages in the ongoing battle against invasive species. However, only a limited number of field trials have been conducted in aquatic ecosystems (Sundaray *et al*., 2022). As research progresses, a more comprehensive understanding of the potential applications, risks and limitations of these genetic technologies will be crucial for refining and implementing them as effective tools in the management of aquatic AIS.

Positive outcomes and expectations
Biological control may hold promise for controlling aquatic invaders at relatively low cost and in a self-sustaining manner, as the control agents reproduce, continuing to exert control over the targeted AIS. Some notable examples of biocontrol of aquatic pests exist, even if successful cases have been rare and have mostly relied on predation by native predators (Bajer *et al*., 2019). While technological advances in biocontrol techniques hold significant promise for managing invasive species in aquatic ecosystems, there remains a critical need to address the associated risks of developing and deploying these techniques.

BOX 1

An unplanned case of biological control in the Ponto-Caspian seas

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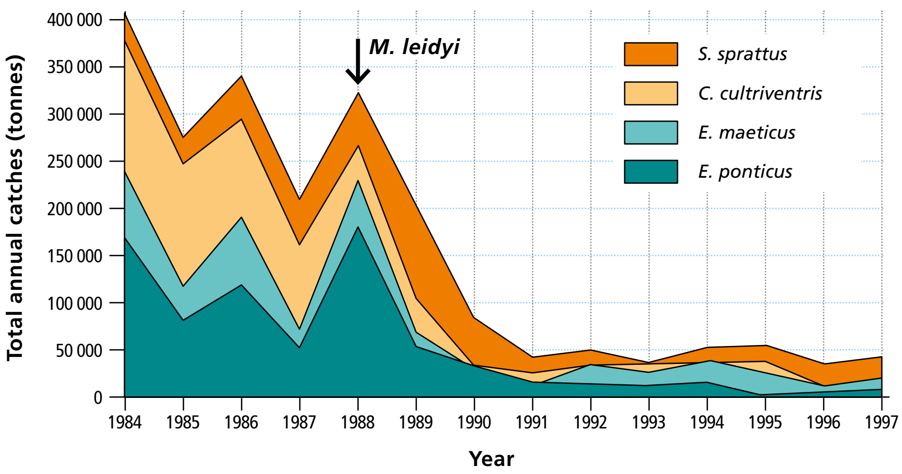
Using the Ponto-Caspian basin as a case study, we illustrate the dramatic consequences of the *Mnemiopsis leidyi* invasion on marine ecosystems and fish stocks, followed by the unplanned appearance of its predator *Beroe ovata*, which led to a unique case of biological control.

The Black, Azov and Caspian Seas (Ponto-Caspian seas) were united as a single basin several times in the past, most recently in the Pliocene. Since 1952 all three seas have been reconnected artificially by the Volga-Don Canal. The Black Sea is also connected to the Mediterranean Sea. Owing to accelerating human activities such as shipping, deliberate stocking, unintentional releases, and canal construction, many non-indigenous species of phytoplankton, zooplankton, benthos and fish have arrived and established themselves in these seas, causing ecosystem-wide effects. One of the most remarkable invasions was that of the comb jelly, *M. leidyi*, a ctenophore native to western Atlantic coastal waters (Ghabooli *et al.*, 2011), which was introduced accidentally to the Black Sea by merchant ships' ballast water. It was first observed in the early 1980s and became highly abundant in 1988. From the Black Sea *M. leidyi* then every year spread to the Sea of Azov during spring warming every year, giving rise to new reproductive populations.

In 1999 *M. leidyi* was first recorded in the Caspian Sea, causing a major decline in fish resources. Its massive predation on zooplankton produced cascading effects at higher trophic levels, from a decrease in zooplankton to the collapse of planktivorous fish (Figure 1). Dramatic declines among large pelagic fish and marine mammals (dolphins in the Black and Azov Seas, seals in the Caspian) were also documented. The decrease in zooplankton also caused an increase in phytoplankton and increases in bacterioplankton, which led to increases in their predators, zooflagellates and ciliates (Shiganova *et al.*, 2004 a, b). Economic losses from the *M. leidyi* invasion for the Black Sea and Caspian states were estimated at billions of US dollars each year. Fisheries for small pelagic fish, first of all anchovy, were closed in Russia as well as in other Black Sea countries (Dumont, Shiganova and Niermann, 2004).

FIGURE 1

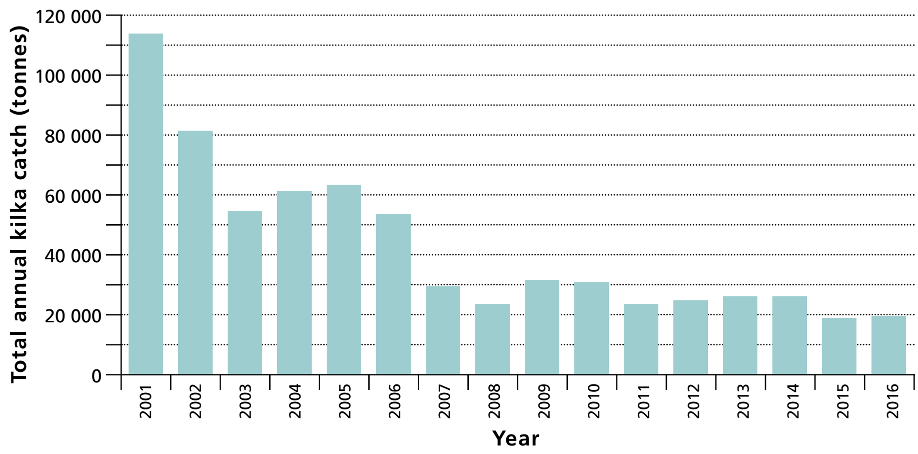
Change in total catch (tonnes) of four planktivorous fish, *Sprattus sprattus*, *Clupeonella cultriventris*, *Engraulis maeoticus* and *E. engrasicolus* in the Black Sea and Sea of Azov before and after the *Mnemiopsis leidyi* invasion. The year of the beginning of the *M. leydi* invasion (1988) is also indicated.



Source: Shiganova, T.A. & Bulgakova, Y.V., 2000. Effects of gelatinous plankton on Black Sea and Sea of Azov fish and their food resources. ICES Journal of Marine Science, 57(3), pp.641-648. https://doi.org/10.1006/jmsc.2000.0736

The *M. leidyi* invasion caused a sharp drop in catches of the anchovy kilka *Clupeonella engrauliformis* and of the big-eyed kilka *C. grimmi* in the middle and southern Caspian Sea. Notably, the spawning season of these species overlaps with the abundance peaks of *M. leidyi*, which means there is high competition for planktonic food (i.e. zooplankton). The common kilka *C. caspia* suffered less, because it can migrate to the brackish and even fresh waters of the northern Caspian and feeds on brackish and freshwater plankton (Paritsky and Razinkov, 2014).

FIGURE 2
Total annual Russian catches of kilka in the Caspian Sea, 2001–2016



Source: Shiganova, T.A., Kamakin, A.M., Pautova, L.A., Kazmin, A.S., Roohi, A. & Dumont, H.J. 2023. An impact of non-native species invasions on the Caspian Sea biota. *Advances in Marine Biology* 94: 69–157.

Small-scale fisheries are a crucial fishery subsector for Russia in the Black, Azov and Caspian Seas, representing 83 percent of the fleet, 57 percent of vessel crew, 29 percent of revenue and 15 percent of total catch (Shlyakhov *et. al.*, 2023). However, even sturgeons, the most valuable fish of all, suffered from the impacts of *M. leidyi*. Before its invasion, molluscs were the main food of Russian sturgeons, and juvenile and adult sturgeon also fed on Caspian kilkas (anchovy, common and big-eyed). Kilka was an essential food for sturgeon populations in the Middle and Southern Caspian, with the share of kilka in their diet reaching 40 percent. In the diet of both Russian sturgeon (*Acipenser gueldenstaedtii*) and stellate sturgeon (*Acipenser stellatus*), a high share of kilka was observed in winter and spring, making up 20–40 percent of sturgeons' food. Since 2000, total stocks of kilka have decreased – and so has their contribution to the sturgeons' diet. Only the common kilka has been recorded in the diet of the Russian, stellate, and beluga sturgeon (*Huso huso* (Kamakin *et al.*, 2018).

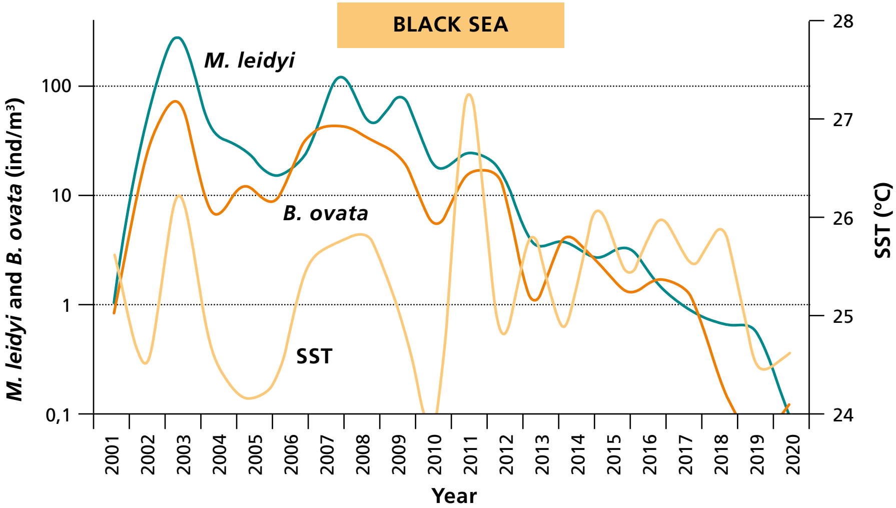
In 1997, ten years after the first observation of *M. leidyi* in the Black Sea, another warm-water ctenophore, *Beroe ovata* Bruguière, 1789, a voracious predator on *M. leidyi*, was introduced through ballast water from the same area of North America as *M. leidyi* (Shiganova and Abusova, 2021). The *B. ovata* invasion resulted in a rapid decline of the *M. leidyi* population, and the ecosystem began to recover at all trophic levels. It should also be noted that *M. leidyi* can reproduce to a maximum temperature of 27.5 °C, therefore the temperature increase in 2010 also contributed to a decrease in its population (Figure 3).

Since 2000, small pelagic species stocks and catches began to gradually recover in the Black Sea. The highest catches comprised Azov anchovy and sprat (Figure 4), followed by Mediterranean horse mackerel and red mullet. The process is ongoing in the Sea of Azov, and is likely to begin in the Caspian Sea following the recent *B. ovata* invasion.

In order to assess the ability of *B. ovata* to control the *M. leidyi* population in the Caspian Sea, an international research team performed extensive laboratory experiments in Iran using *M. leidyi* individuals from the Caspian Sea as food for *B. ovata* individuals collected in the Black Sea (Drs Shiganova T., Kideys

FIGURE 3

Relationship of *M. leidyi* and *B. ovata* abundance (ind/m³) after *B. ovata*'s appearance in the Black Sea



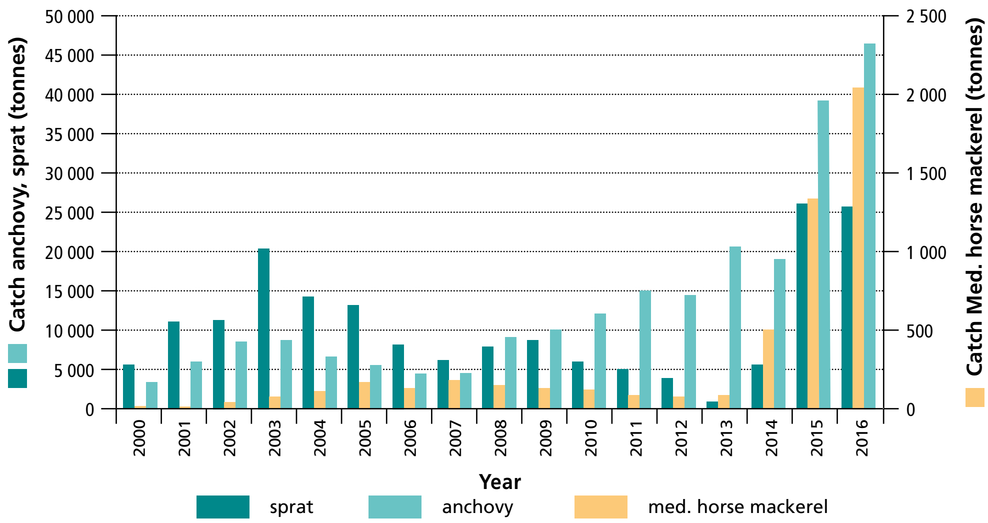
Source: Kazmin, A.S. and Shiganova, T.A., 2024. Ctenophore invasions in the Ponto-Caspian Seas: role of abiotic factors variability. *Biological Invasions*, pp.1-17. https://doi.org/10.1007/s10530-024-03252-2

A., Finenko G. and Anensky B.). In addition, Dr Shiganova and Dr Bulgakova performed experiments in Gelendzhik, Russia, with Black Sea *B. ovata*: they determined that the species is able to survive to a minimum salinity of 7‰, and reproduces at a minimum salinity of 10‰, which was confirmed during following field observations in the Caspian Sea. Other studies have indicated that *B. ovata* starts to release eggs at a minimum temperature of 19 °C, peaks at 25–26 °C, and ceases at 29 °C (Shiganova, 2004a).

On the basis of these results a team of international experts, supported by the Commission of the Caspian Sea Environmental Programme (CEP), proposed that *B. ovata* should be introduced into the Caspian Sea to biologically control the population of the invasive *M. leidyi;* the proposal

FIGURE 4

Change in small pelagic fish catches following the arrival of *B. ovata* in the Black Sea



Source: Shlyakhov, V.A., Shlyakhov, O.V., Nadolinskiy, V.P. & Perevalov, O.A. 2023. *Commercial and biological indicators of Russian fisheries for the most important distributed stocks of aquatic biological resources of the Black Sea in 2015-2016 and in the retrospective period.* Kerch Branch (YugNIRO) of FSBSI "AzNIIRKH".

was accompanied by an "Environmental impact assessment on *B. ovata* introduction" (Shiganova, 2004). However, not all Caspian countries were in favour of the suggestion, due to doubts over the effectiveness of the biological control proposed. While a decision was pending *B. ovata* eventually arrived in ballast waters from the Black Sea via the Volga-Don Canal, as happened with other pelagic invaders. In the event, *B. ovata* was first recorded in the southern Caspian in 2019, and in 2022 a decrease of the *M. leidyi* population was observed for the first time (Shiganova *et al.*, 2023).

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Challenges

A major challenge posed by biological control is that an introduced control agent might itself become a problem in an unforeseen way. Some of these species have indeed become invasive, causing catastrophic ecological impacts (Bernery *et al.*, 2022). Releasing non-native species or genetically altered organisms as controlling agents might not be publicly or politically acceptable (Thresher and Kuris, 2004; Giakoumi *et al.*, 2019). In freshwaters, non-indigenous herbivorous fishes such as grass carp (*Ctenopharyngodon idella*) and tench (*Tinca tinca*) have frequently been employed to control invasive aquatic plants, but later these species have had to be removed using rotenone[4] to prevent damage to native plant species (Rowe and Champion, 1994). In marine environments, biological control ranked among the least successful strategies for controlling AIS (Giakoumi *et al.*, 2019) and was the least cited measure among the best practices in the expert survey (Appendix 1, Figure A9). Lionfish control has been attempted by training native predators (groupers and sharks) to feed on the species, but it has had limited or no results (Harris, Kleitou and Hall-Spencer, this volume). Finally, it is crucial to consider that climate change can alter the effectiveness of existing biocontrol methods, influencing the dynamics between invasive species and the control agents.

Enabling factors

Solid scientific knowledge is essential. Experiments show that restricted water bodies provide easier conditions for bio-manipulation and reduced risks.

Key recommendations

- Before implementing any biological control programme, a thorough risk assessment should be conducted. This includes evaluating potential impacts on non-target species, ecosystems, and any unintended consequences.
- Introducing non-native species or genetically modified organisms as controlling agents in aquatic systems can bring a high degree of uncertainty and may not be publicly or politically acceptable.
- In situations of uncertainty, it is crucial to adopt a precautionary approach when considering the selection and deployment of biological control agents and to prioritize ethical considerations.
- In a few cases, biological control can be achieved by restocking native consumers (predators or grazers) that feed on the invasive species. Protecting or restocking native predators or grazers may be preferable to the risky option of introducing biological control agents.
- Communicate transparently with stakeholders, including the local community, environmental groups, and government agencies. Address concerns, provide information, and foster public awareness and engagement throughout the entire process. Implement monitoring programmes to track the effectiveness of the chosen biological control methods and detect possible unexpected outcomes.
- Any possible ecological concern needs to be carefully assessed through solid scientific studies before plans are made for the use of biocontrol methods.
- Consider possible effects of climate change on the dynamics between invasive species and their natural predators.

[4] A crystalline insecticide ($C_{23}H_{22}O_6$) obtained from the roots of several tropical plants. It is highly toxic to fish but exhibits minimal toxicity to warm-blooded animals.

#8: Restore ecosystems

About the measure

Invasive species can be a major cause of ecosystem degradation, and these impacts may necessitate interventions beyond controlling the target alien species (Holmes *et al.*, 2020). Ecological restoration is originally defined as the "process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER, 2002). This strategy includes a number of different kinds of actions. In some cases, AIS impacts can be mitigated by restoring the natural ecosystem to a former structure or, most often, by reinstating specific components or functions of the natural ecosystem. This strategy was often referred to in the expert survey, although with variable results (Appendix 1, Figure A9). Nakamura (this volume) presents an example of functional restoration, showing how native spawning grounds were re-established after damage caused by climate-induced changes, and similar examples can be cited for AIS-related impacts. The scientific literature is increasingly enriched with examples of ecological restoration, although only a limited number are directly related to the impact of aquatic invaders. Keane *et al.* (this volume) illustrates how the native southern rock lobster has been restocked in an attempt to restore predatory control of invasive sea urchins (see also measure #7 *Implement biological control*). Other evidence illustrates that maintaining a higher biomass of upper-trophic fishes could reduce lower-trophic AIS densities, but also invasive predators, through trophic competition and behavioural interactions (Chagaris *et al.*, 2017). Similarly, the enhancement of marine protected areas, and protecting keystone species, have also been suggested (Kleitou *et al.*, 2021). It remains crucial to customize restoration efforts according to the specific context, needs and characteristics of the impacted ecosystem.

Positive outcomes and expectations

Restoration efforts, focused on mitigating the impact of aquatic invasions, offer a range of potential outcomes that may extend beyond ecological benefits. These positive impacts may manifest across multiple levels, including native biodiversity, habitat structure and functionality, and water quality; and they may improve the general health and resilience of aquatic ecosystems. The benefits of restoration efforts can further extend to positively impact fisheries and contribute to social, cultural and recreational aspects.

Challenges

The effectiveness of restoration actions, which can be measured by a combination of ecological and socioeconomic outcome indicators (Smith *et al.*, 2022), requires meticulous evaluation, especially given the potential challenges generated by anthropogenic impacts, notably climate change. Specifically, the pursuit of reinstating historical ecosystems or achieving specific ecological and socioeconomic goals may face hurdles due to the altered climatic conditions (Harris *et al.*, 2006). Hence, it will be crucial to acknowledge and address these challenges comprehensively to foster a nuanced understanding of the dynamic interaction between restoration initiatives and the changing climate. Similarly, the duration of restoration efforts may be limited if the invasive species responsible for ecological damage has not been effectively eradicated or if certain traits or components of the ecosystems are irreversibly changed and cannot be restored to their original state (Albano *et al.*, 2021). Manipulated aquatic ecosystems often have nonlinear and unpredictable behaviour (Harris *et al.*, 2006), and failure to recognize and address this uncertainty can lead to unsuccessful outcomes (Hilderbrand *et al.*, 2005).

Enabling factors

The first prerequisite for successful restoration is to halt or control the drivers of the loss of the ecological components that need to be restored. In the case of invasions of aquatic species, this may entail a functional eradication of AIS. The probability of success increases under stable environmental conditions and low anthropogenic pressure. In addition, restoration/restocking can be easier in areas of limited size. Successful restoration often involves collaboration among various stakeholders, and educational initiatives to raise awareness and foster shared responsibility and support.

Key recommendations

- Before planning restoration measures, it is important to halt or control the drivers of the loss of the ecological components that need to be restored, and to know the key processes and habitat features that allow for recovery after halting the disturbance.
- Prioritize areas/habitats/species targeted by restoration/restocking measures.
- Restorations should not be one-time events, but require periodic monitoring and continuous adaptive management to increase the probability of a sustainable result.
- Aquatic ecosystems containing a mix of native and non-native species can be a possible goal when the conditions prior to the invasion cannot be re-established, especially in a climate change scenario. Nevertheless, restoring ecosystem functions by deliberately introducing non-indigenous species should be avoided, because related outcomes are highly risky and unpredictable.
- Engage key stakeholders in discussions and establish realistic restoration goals during the project planning phase.
- Measures to protect native biodiversity are always relevant.
- Carefully assess the potential challenges to the restoration efforts generated by climate change.

1.4. OTHER

#9: Do nothing

About the measure

In addition to all the above-mentioned measures, one option when dealing with an established AIS is to do nothing. In some cases, the do-nothing approach has ranked high among the management options probably because of its perceived acceptability, and the absence of intervention cost (Giakoumi *et al.*, 2019). In the expert survey, the do-nothing approach was the choice for 21 percent of reported cases (Appendix 1, Table AII). Opting for non-intervention in management does not imply that nothing will happen. For instance, an intense rabbitfish (*Siganus* spp.) fishery has emerged in the Eastern Mediterranean Sea, where invasive rabbitfishes have become a significant fishery resource. Remarkably, this fishery has thrived without receiving any support as a means to control the invasion (Giakoumi and Azzurro, personal observation). Nevertheless, it is important to clarify that the do-nothing approach is not advisable in cases where any of the other measures are feasible, as a precautionary approach entails not postponing cost-effective measures to prevent environmental degradation.

Positive outcomes and expectations

Doing nothing and waiting for the invaders to diminish, or for the local fishery to spontaneously adapt to the invasion, would be the easiest and least expensive choice for controlling an AIS in certain contexts (see Singh, this volume).

Challenges

Spontaneous population crashes have occurred in a limited number of cases after AIS have caused persistent ecological damage. Unmanaged invasions can produce irreversible impacts on ecological systems, including the extinction of native species (Natugonza, this volume). Unmanaged fisheries can be more vulnerable to AIS and are more often subject to economic losses and conflicts.

Enabling factors

In a few cases, the population of aquatic invaders has decreased spontaneously, after an initial growth phase, without human intervention. This is the case for the African jewelfish (*Hemichromis letourneuxi*), which collapsed without a clear causal mechanism, and of other invasive freshwater fishes, in Florida, United States of America (Hill, 2016). Boom-and-bust events have also been observed with the topmouth gudgeon (*Pseudorasbora parva),* an Asian cyprinid fish, which disappeared from some ponds in England and continental Europe after a period of population explosion. Another well-known case involved *Caulerpa taxifolia* algae populations, which suddenly collapsed in several Mediterranean areas after a long period of rapid expansion (Montefalcone *et al*., 2015). These boom-and-bust dynamics represent a well-known but unpredictable phenomenon in invasion biology (Simberloff and Gibbons 2004).

Key recommendations

- The “do-nothing” option should be contemplated with caution and should only be adopted after careful consideration and analysis of the risks, costs and benefits of other potential management measures.
- In any case, both the ecological and the socioeconomic impacts of unmanaged invasions should be closely investigated and monitored to understand the consequences of the invasion.

1.5. FINAL REMARKS

While this set of case studies has been compiled to illustrate various aspects of fishery management in the context of aquatic invasions, it is crucial to acknowledge that the selection is not intended to be exhaustive. Rather, the compilation aims to provide insights into different approaches, successes, and challenges encountered in various regions, and to offer a precious opportunity to learn lessons on responses to the increasing threats posed by AIS. Managing AIS is a difficult task, given the high uncertainty and complexity of biological invasions in aquatic ecosystems and the limited understanding of the effectiveness of management methods in response. Critical questions regarding the way in which fisheries could adapt to the changing conditions of fishery resources should be considered while taking into account the specificities of each ecological and socioeconomic context. Furthermore, technical considerations necessitating a shift towards more dynamic and climate-resilient benchmarks are likely of paramount importance, deserving further in-depth investigation. Despite its limitations, it is hoped that this compilation of experiences will prove to be effective in presenting viable options for improving fishery management and policy within the highly complex context of the ongoing transformation of the world’s aquatic ecosystems and climate change. As new research emerges and diverse management practices evolve, the landscape of fishery management in relation to AIS/NIS continues to expand. Further exploration and consideration of additional case studies should be pursued to gain a comprehensive understanding of the multifaceted nature of this field and to inform future endeavours in sustainable fishery management.

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Part 2

Case studies

This part includes 11 case studies illustrating how fisheries around the world have managed aquatic invasive species. These case studies represent a range of regions, sectors, species, environments and governance systems. They also encompass responses to a diverse range of invasive taxa with very different backgrounds, ranging from species deliberately introduced for commercial purposes to unwanted invasions caused by inadvertent introductions and empowered by climate warming. This wealth of experience also covers different socioeconomic contexts, different scales of fishery, and different amounts of available human and financial resources.

Chapter 2
Round goby *(Neogobius melanostomus)* fishery in Latvian coastal waters

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SUMMARY
This case study focuses on the Latvian coastal fishery for the round goby (*Neogobius melanostomus*), an invasive fish species originating from the Ponto-Caspian region. Round goby was first observed in the Baltic Sea in the Gulf of Gdansk in 1990, and it now occurs throughout the Baltic Sea, except in the most northeasterly parts where it is considered too cold for the species to thrive. The species' presence and distribution in the Baltic is most likely a result of repeated introductions to ports via ballast water in ships, following which it has spread from these sites via secondary dispersal.

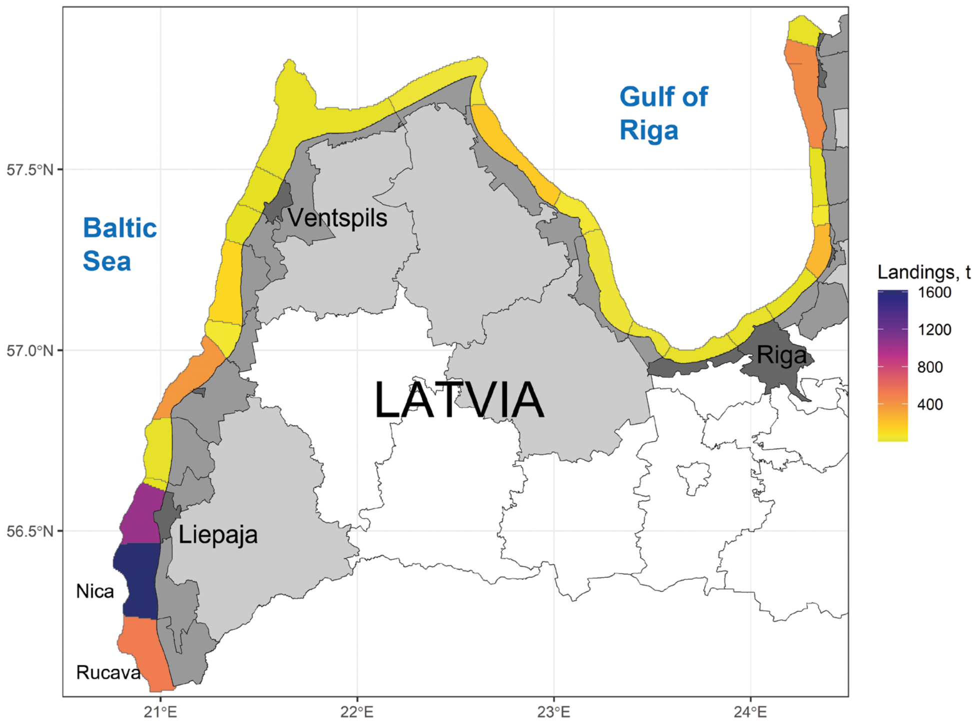
The round goby fishery in Latvia is a small-scale coastal fishery that occurs during spring and early summer, mainly with specialized round goby gillnets and round goby trap-nets. Round goby appeared in the commercial fishery logbook for the first time in 2006, and in the following years catches increased, peaking at 1 113 tonnes in 2018. Catch rates then began to fall. Stock assessments indicate that the size of the round goby population in Latvian coastal waters has mainly been affected by high fishing pressure. The most rapid rise in the number of juvenile fish was observed from 2013 to 2014. This period ensured a rich increase in fish of suitable size for the fishery for the following years. After 2018 fishing mortality increased by 600 percent, mainly driven by emerging market opportunities and increased fishing effort. As a result, the population size decreased by half – after which it was no longer able to recover to the same abundance, and catches have declined. However, catch rates are still considered to be high and round goby remains a very important target species for local fishers: in recent years, round goby has become the second most fished species by total landings after herring in the Latvian coastal fishery. A positive effect of the round goby fishery is thus the additional income possibilities it creates for local fishers, especially at a time when the Eastern Baltic cod population is on the verge of collapse, and the abundance of many other locally important species is decreasing.

There is as yet no dedicated monitoring programme for round goby, and abundance data is only available for areas where it is commercially exploited, like Latvia. This is despite the fact that there are ecological impacts linked to the abundance of the species: scientific studies have revealed that round goby has negative impacts on flatfish recruitment, and it also has the capacity to alter the benthic macrofauna community through predation (van Deurs *et al.*, 2021). There is no comprehensive monitoring for RG in the Baltic Sea, but it is clear that such a programme is needed. A monitoring strategy will not result in the conservation of the RG population size. The best period to monitor RG is in coastal areas during the spring using "Nordic nets", based on inter-calibrating historical data sets and commercial fisheries landings. This combination makes it easier to catch specimens (Kruze *et al.*, 2023).

1. FISHERY CONTEXT

In the present case study, the focus is on the Latvian fishery for the invasive round goby (*Neogobius melanostomus*), as this is the largest fishery for the species in the Baltic region. Notably though, Lithuania and Estonia also have a targeted fishery for the species (ICES, 2022). The round goby fishery in Latvia is a small-scale coastal fishery that occurs at depths of up to 20 m, with the main part of the catches being taken in the Baltic Sea on Latvia's southeastern coast in Nica, Rucava and Liepaja municipalities (Figure 1) – although since 2018 catch rates have also increased rapidly on the west coast of the Gulf of Riga (BIOR, 2022).

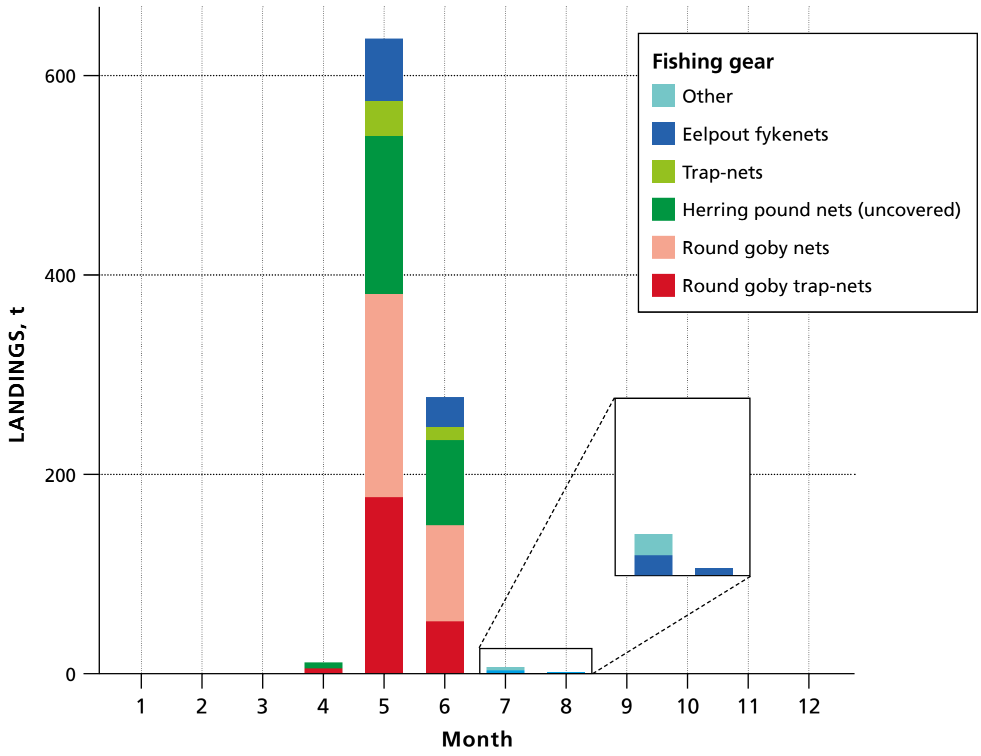
FIGURE 1
Total round goby landings in Latvian coastal municipalities in 2016–2021 (coastal areas are coloured up to 20 m depth)



Source: Authors' own elaboration based on data from BIOR.

Catch rates normally peak from April to June, and the fish are mainly caught with round goby gillnets (60–70 mm mesh size, diagonal width) and round goby trap-nets (24–36 mm mesh size, diagonal width). These specialized gears are similar to other coastal gears; the main differences are their smaller mesh size, a gillnet height limit (1.5 m), and seasonal and spatial restrictions. Some catches are also taken using herring pound nets and trap-nets, and eelpout fyke nets (Figure 2).

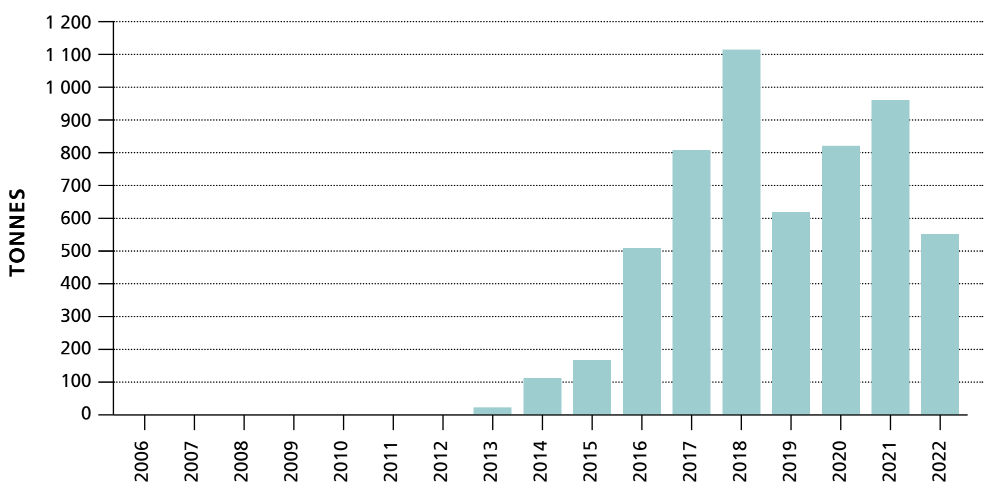
FIGURE 2
Round goby monthly landings by fishing gears in the Latvian coastal fishery in 2021



Source: Authors' own elaboration based on data from BIOR.

In 2006 round goby appeared in the commercial fishery logbook for the first time, although the total catch was only 6.3 kg. Catches then increased annually until 2018, which saw a total catch of 1 113 tonnes. The following year the first drop in catches was detected. However, total landings for the coastal fishery still remain high, at 550–933 tonnes per year (Figure 3) (BIOR, 2022).

FIGURE 3
Annual round goby landings in the Latvian coastal fishery



Source: Authors' own elaboration based on data from BIOR.

In 2022, the round goby catch made up more than 80 percent of the total catch (by volume) in 5 of Latvia's 15 coastal municipalities. The recent (since 2016) increase in catches was mainly due to market opportunities –the majority of the landings are exported as frozen, mainly to Ukraine. Only a minor amount is sold on the local market; local consumers are in general reserved about eating round goby, but if they do eat the larger specimens these are usually smoked or canned, while the smaller fish are mainly used for fishmeal. The purchase price of the round gobies may exceed EUR 0.7 per kilo, but it depends on the size of the fish. Round goby was recorded in 71 fishing companies' logbooks, and in 17 of these companies the total catch exceeded 10 tonnes. The species is considered a very important target for local fishers, and in recent years round goby has become the second most fished species by total landings after herring in the Latvian coastal fishery.

2. HISTORY AND IMPACTS OF ROUND GOBY *(NEOGOBIUS MELANOSTOMUS)* ON LOCAL FISHERIES AND ECOSYSTEMS

Round goby has a Ponto-Caspian origin, and was first observed in the Gulf of Gdansk, central Baltic Sea, in 1990 (Skóra and Stolarski, 1996). In the following years, up to 2005, the fish was observed along the Polish, Lithuanian and German coastlines, along with one observation on the Estonian coast (Kotta *et al.*, 2016). Since then, observations of round goby have been made along the coastline in the western, central, eastern and northeastern parts of the Baltic, and the fish is now found in the whole region except the most northerly (Bothnian Bay) and northwestern parts (the transition zone to the Kattegat-Skagerrak area) (ICES, 2022). Its current distribution (Figure 4) suggests that the oceanic conditions in the transition zone to the Kattegat-Skagerrak area and low temperatures in the most northern parts of the Baltic may limit its spread. This is supported by studies revealing reduced physiological performance of adult fish under high salinity and low temperatures, and negative effects of high salinity on reproductive output (Behrens *et al.*, 2017; Green *et al.*, 2021; Christensen *et al.*, 2021; Quattrocchi *et al*., 2023).

The species' presence and distribution in the Baltic is most likely a result of repeated introductions to ports via ballast water in ships (Kotta *et al.*, 2016; Holmes *et al.*, 2019). From these sites of introduction the fish has spread via secondary dispersal, which may occur at up to 30 km per year along the coastline (Azour *et al.*, 2015). Although it appears to prefer shallow, warmer and coastal areas protected from wave action, round goby does undertake a seasonal migration to deeper waters during winter months, likely to avoid the very cool shallow waters during this period (Behrens *et al.*, 2022).

There is no dedicated monitoring yet in place for round goby, and very limited abundance estimates are available, despite the fact that ecological impacts are clearly related to the abundance of the species. Abundance data is only available for areas like Latvia where the species is already commercially exploited (ICES, 2022). The results of scientific and commercial fishing indicate population declines in Latvia: these are most likely related to the reduction of food availability and increased fishing mortality, which according to BIOR estimates has increased by 600 percent since 2018 (BIOR, 2022).

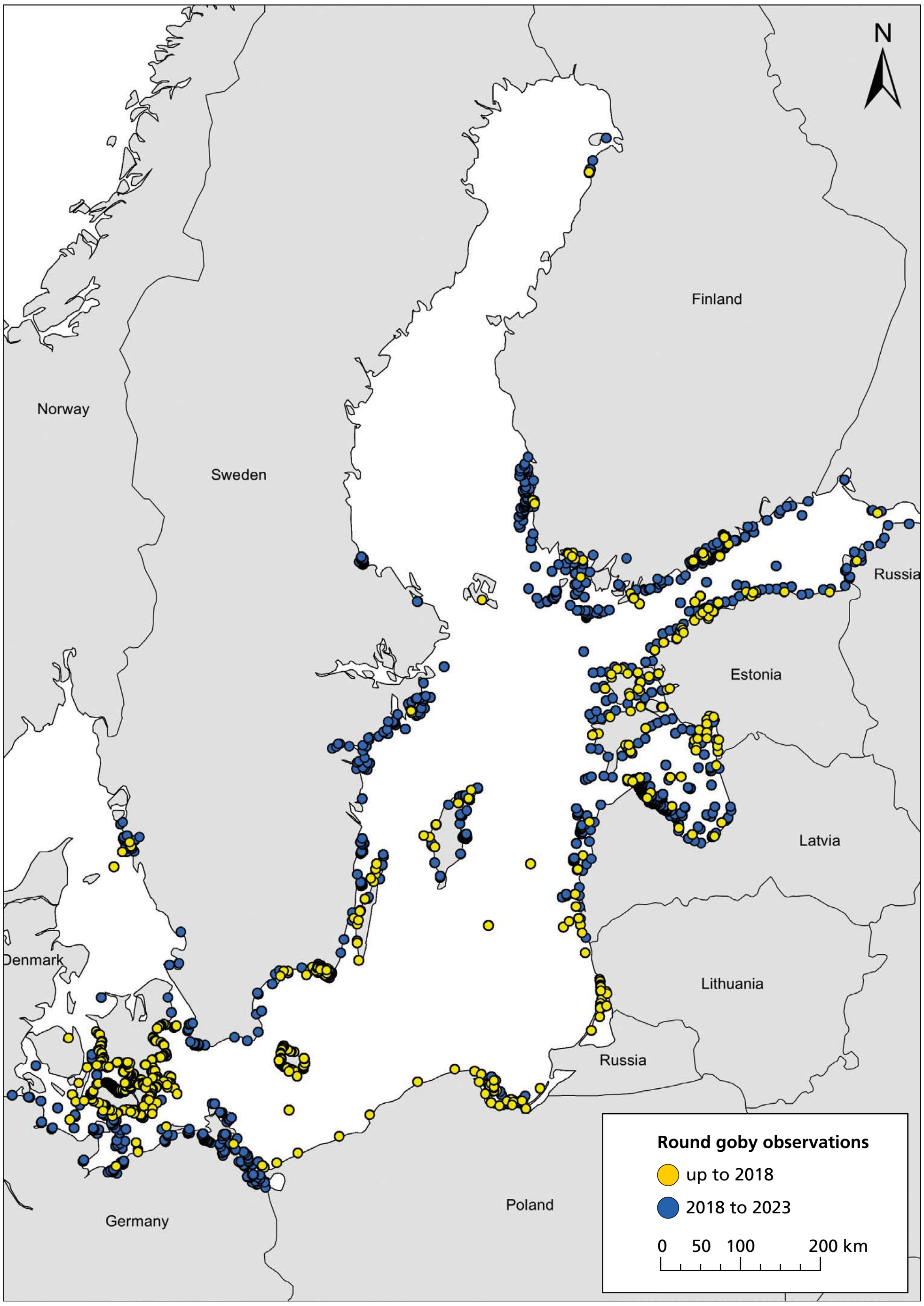
Additional income possibilities for local fishers mean that the round goby fishery has a positive effect. This is particularly important given that the Eastern Baltic cod population has decreased and fishing has recently been limited only to cod bycatch, while many other locally important species are decreasing as well: the additional fishing opportunities offered by round goby can compensate for lost income. However, this is heavily dependent on the round goby size and on market accessibility, both of which can be very different across the coastal municipalities.

Round goby became an important food item for local predators as well. There is evidence from fishers that cod and turbot have better body condition in coastal waters where they can feed on round gobies.

The species may have negative effects on native species populations due to competition. There are studies suggesting that round goby has a negative impact on flatfish recruitment (Ustups *et al.*, 2016); and since predation by round goby has the capacity to alter the benthic macrofauna community (van Deurs *et al.*, 2022), this may also alter feeding opportunities for co-occurring benthic species.

FIGURE 4

Known round goby occurrence in the Baltic Sea: yellow circles show observations up to 2018, blue circles show additional observations up to 2022



Source: ICES. 2022. Workshop on Stickleback and Round Goby in the Baltic Sea (WKSTARGATE). ICES *Scientific Reports* 4: 77. https://doi.org/10.17895/ices.pub.21345291

3. ADAPTIVE RESPONSES

Several management activities have been implemented in Latvia to effectively utilize the abundant round goby resource, including the design of specialized fishing gears and methods to minimize the bycatch of non-target species. A specialized fishery using round goby gillnets was started back in 2015. The fishing season and gear mesh size were set based on results from scientific coastal gillnet surveys. The effectiveness of round goby trap-nets was tested in cooperation with local fishers, and as a result new gear has been in use in Latvia since 2018. Both gears led to an increase in round goby fishing selectivity and total landings. The Latvian coastal fisheries management scheme involves annual data collection from the commercial and scientific fishery followed by information analysis and biological parameter estimates to assess stock status. All available information is used to develop annual scientific advice for local policymakers, and suggestions are made regarding changes in fishing policy and definitions of fishing gear limits in each coastal municipality. There is no information currently available on active round goby fishery management in other Baltic Sea countries (ICES, 2022).

Combining the population change indices from scientific monitoring (CFM, GORDEM, and BITS) data in the Latvian EEZ the results suggest a steep population increase until 2017, followed by a rapid decline. Population size in 2021 was about 7.6 times higher than that of 2006, but 30 times smaller compared to that recorded in 2017 (Kruze *et al*. 2023). Also since 2014, the institute BIOR has collected round goby biological samples from commercial and scientific fisheries in Latvian coastal waters. Based on this information, the first attempt was made to assess the round goby population biomass along the Latvian coast in 2020, using ICES-approved analytical XSA and SAM models. The biomass estimates from the stock assessment models were different, but both models showed the same population trends. The results showed a decrease in spawning stock biomass, recruitment and total stock biomass, but they also indicated an increase in fishing mortality. The stock of round goby on the coast of Latvia is expected to decline in the coming years, which will lead to a decline in total catches (BIOR, 2022). Analytical fish stock assessment models, which are annually updated using the most recent data, are the best tools to assess stock status and estimate changes in fishing mortality – and are thus the most robust way to provide understanding of the impact of fishing on the future growth of the round goby population. In future, BIOR is planning to supplement the existing data and use this for the regulation of round goby fishing in Latvia. Additionally, the LIFE REEF project (Research of marine protected habitats in EEZ and determination of the necessary conservation status in Latvia (2020–2025)) aims to develop an action plan to limit the impact of invasive marine species and to develop mitigation measures to reduce seabird and marine mammal bycatch in coastal fisheries. Project activities include round goby tagging, habitat mapping in various coastal fishing grounds, and bycatch assessment in the coastal fishery. In future, the results of these activities will be included in the national scientific advice to improve spatial and seasonal regulation of the Latvian coastal fishery.

In Denmark, a project (2016–2019) dedicated to paving the way for potential utilization of new species in inner Danish waters for human consumption described the seasonal dynamics in catch rates, size distribution, condition factor, lipid and protein content, fatty acid profile, and meat texture. Results from this project revealed that catch rates peaked in spring, and that the fish overall had enough quality for human consumption, including a good texture and a highly favourable fatty acid composition (Brauer *et al.*, 2020). However, logistical challenges in collecting large enough amounts of fish and having them cooled rapidly and transported to manufactories were recognized as major obstacles for the establishment of a cost-efficient fishery, as was the lack of suitable (for the size and shape of the fish) equipment, which would necessitate a great deal of manual processing.

4. OUTCOMES

An increase in round goby population size, emerging market opportunities, and national fisheries policy promoted the rapid growth of a specialized goby fishery in Latvia. According to initial BIOR recommendations, the fishing season was set from April to July. However, due to high market demand, fishers asked to open the fishery in the autumn too, when round gobies are in better condition. In response, in collaboration with the fishers, BIOR ran experimental autumn fishing trials using round goby gillnets. However, results revealed negligible round goby catches and a high bycatch rate of other fish species, many of them undersized. Based on these findings, the autumn fishery was not implemented.

5. CHALLENGES

There are no catch quotas or other limitations on the round goby fishery in the Baltic Sea, and management activities depend on national legislation and initiatives.

At a more general level, managing an invasive species for fisheries purposes – e.g. by setting quotas – is a double-edged sword. This is because on one hand it is an invasive species and the ultimate aim is to eradicate it, but on the other hand the species has become (or could become) a valuable resource for a targeted fishery, in which case it should be managed under a quota system to ensure its sustainability. This conflict is referred to as the "bioeconomic paradox" (Harris *et al.*, 2023). A targeted fishery may also involve unwanted bycatch, which is especially problematic in the Baltic region, where most species (e.g. cod, herring, sprat) have experienced declining (or no) populations.

There is also high pressure from local fishers – and indeed the entire fishing sector – who are interested in developing a round goby fishery, which they feel is justified by the invasive nature of the species. Scientists providing advice try to follow a precautionary approach, and in many cases there are disagreements between fishers and scientists.

The current coastal fishery only targets round goby during the spring. It would be challenging to develop a winter fishery because knowledge on round goby winter migrations and preferred habitats is poor.

Moreover, in several countries, the costs related to catching round goby exceed its sales value. An additional issue is that the term "invasive species" is often considered to have negative connotations, and in Denmark tabloid newspapers have termed round goby "the slug of the sea". Such negative branding unavoidably affects consumer attitudes towards utilization of this potential new resource, as well as the willingness of fishers to embark on this new fishery.

In Latvia, local consumers are often not familiar with this new species and avoid trying it, despite its appealing price tag. This phenomenon is known as neophobia (Barrena and Sánchez, 2012). It is thus clear that efforts must be made to brand round goby in a positive way.

6. LESSON LEARNED AND KEY RECOMMENDATIONS

- Round goby scientific monitoring in combination with commercial fishery observations and biological sampling is needed to provide data for the kind of analytical assessments that are carried out for other commercially important Baltic Sea stocks.
- In many countries, the current joint monitoring methodology needs improvements to adequately track round goby population trends. According to HELCOM guidelines (HELCOM, 2019) in many countries fisheries-independent coastal fish monitoring is implemented in the late summer, when round goby activity – and hence its catchability in passive gears – is decreasing.

- Catch quotas are not set for invasive fish species, but the fishery could be regulated by defining fishing gears, fishing season and effort. An uncontrolled increase in fishing pressure can result in an increased risk of bycatch of unwanted species or undersized individuals of desirable species.
- In the central part of the Baltic catch rates and stock assessments indicate a decline in the round goby population. However, despite the decline in numbers, round goby will not disappear from the local ichthyofauna and will continue to be an important fishing target. For the resource to be used successfully, round goby must be integrated into Baltic Sea markets and kitchens.
- The round goby fishery can significantly increase catches and profits in coastal regions. However, fishers are interested in this fishery only as long as there are profitable market opportunities – and currently, based on the Latvian example, these opportunities exist mainly outside the EU.
- Product development should be prioritized, enabling a higher price for the fish to be paid to the fishers.

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Chapter 3

Managing the explosion of the blue swimming crab *Portunus segnis* (Forskål, 1775) in Tunisia

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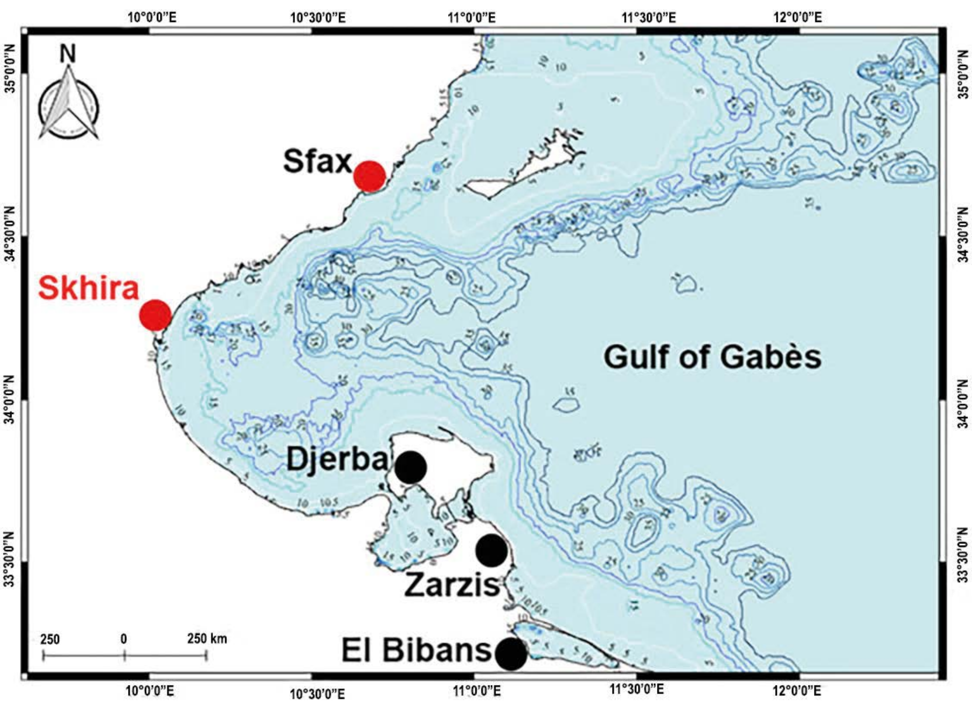
SUMMARY

The blue swimming crab *Portunus segnis,* native to the western Indian Ocean, entered the Mediterranean Sea through the Suez Canal and was first reported in Tunisia in the Gulf of Gabès in 2014. Since then it has spread throughout Tunisian waters, especially on the southern coasts. This sudden invasion has had dramatic socioeconomic consequences for small-scale fisheries: *P. segnis* has affected fisher incomes by damaging fishing gears, altering the range of species caught, and reducing catches of many commercial species. In view of these issues, the Tunisian government has established a national plan to promote the fishing and marketing of blue crab. New traps, specifically designed to catch *P. segnis*, have been produced and distributed to Tunisian fishers; while a range of awareness-raising activities have been carried out, including tasting campaigns and cooking shows to promote the consumption of blue crabs at local level. A number of studies to broaden scientific knowledge on the biology, behaviour, stock assessment and trophic habits of the species have been supported by the Tunisian government. In light of limited domestic demand, work to increase blue crab exports has turned out to be the most effective strategy for adaptive management. Today, nine years on from the first sighting of *P. segnis* in Tunisia, 49 processing and exporting factories are involved in the blue crab industry, with annual exports of about 7 000 tonnes to 23 countries across 3 continents. The commercial harvest of blue crabs can be a compelling solution to control their abundance and reduce their impacts on ecosystems. However, reducing their population can also lead to reduced catch rates, thus challenging their economic exploitation along the entire value chain and threatening the new-born blue crab industry of Tunisia.

1. FISHERY CONTEXT

Since 2015, massive numbers of blue swimming crabs have invaded southern Tunisia, especially the Gulf of Gabès. This area is known as “Petite Syrte”, and extends from Ras Kapoudia to the Tunisian–Libyan border (Figure 1), extending over a wide continental shelf area (Béjaoui *et al*., 2019) which represents approximately one-third of Tunisia’s

FIGURE 1
Map of the Gulf of Gabès



Source: Rjiba. W. 2019. Proceedings of the 42nd CIESM Congress. Cascais, Portugal.

coastal waters and nearly one-third of its 2 190 km coastline. The Gulf of Gabès covers approximately 15 000 km^2 and is relatively shallow, with an average depth of around 60 m. It shelters various islands (Kerkennah, Kneiss and Djerba) and lagoons (Boughrara and Bahiret El Bibane).

The Gulf of Gabès is high in marine biodiversity, with more than 1 900 recorded species (Hattour and Ben Mustapha, 2015) including several non-indigenous species (Ounifi Ben Amor *et al*., 2016). This area has a high importance for Tunisian fisheries, with a catch of 75 732 tonnes making up 62 percent of total national production in 2021 (DGPA, 2021). It's the base for nearly 60 percent of the Tunisian fleet, and it provides work to 59 percent of Tunisia's maritime population (DGPA, 2021).

All national fishing activities, except for coral and lobster harvesting, take place there. This includes bottom trawling (12 045 tonnes in 2021, representing 53 percent of the total national bottom trawling production) for species with high commercial value such as shrimps (*Panaeus kerathurus, P. aztecus* and *Metapenaeus monoceros*) and demersal fishes (including *Mullus barbatus*, *Sparus aurata, Solea solea, Merluccius merluccius* and *Pagellus sp*). Small craft fishing produced 45 243 tonnes in 2021, representing 82.5 percent of the national small craft total, with main catches including *Octopus vulgaris* and *Sepia officinalis*, *Mullus surmuletus, Solea senegalensis, Sparus aurata, Sarpa salpa, Pagrus pagrus, P. auriga* and *Lithognathus mormyrus*, among others (DGPA, 2021).

With regard to fisheries for small pelagic species (including *Sardina pilchardus, Sardinella aurita, Scomber scombrus* and *Engraulis encrasicolus*) and large pelagic species (including *Thunnus thynnus, Xiphias gladius*, *Coryphaena hippurus* and *Seriola dumerili*), in 2021 the Gulf of Gabès respectively produced 16 314 tonnes (39.5 percent of the national catch) and 1 886 tonnes (70 percent of the national catch) (DGPA, 2021). Sponge and clam collecting also takes place in the area, as does lagoon fishing.

The most commonly used gears are bottom trawls, gillnets, trammel nets and purse seines. In addition, traditional Mediterranean fixed traps – such as "Charfia" in the Kerkennah Islands and "bordigue" in the Bibans Lagoon – are used in the Gulf of Gabès. In 2021 the full fleet comprised 7 607 active boats with a total of 20 795 fishers (DGPA, 2021).

2. HISTORY AND IMPACTS OF *PORTUNUS SEGNIS* ON LOCAL FISHERIES AND ECOSYSTEMS

The blue swimming crab *Portunus segnis,* previously often reported as *Portunus pelagicus*, was the first species to enter the Mediterranean Sea through the Suez Canal (Zenetos *et al*., 2010).

It was detected in the Suez Canal in 1889 and reached Port Said (Egypt) in 1898 (Fox, 1924). Early studies document its commercial use in the easternmost countries of the Mediterranean since the 1920s (Fox, 1924; Gruvel, 1928), and today the species is reported in many eastern Mediterranean countries (Galil and Zenetos, 2002; Falsone *et al*., 2020).

In Tunisia, the first occurrence of the crab was reported in 2014 in the Gulf of Gabès (southern Tunisian coast) (Rifi *et al*., 2014; Rabaoui *et al*., 2015). One year later it had invaded all the central areas of the Gulf, with dramatic socioeconomic consequences for local fisheries (Crocetta *et al*., 2015), and it has since continued its geographical expansion to the northern coasts of Tunisia (Bdioui, 2016; Shaiek *et al*., 2021).

Since October 2015 the invasion has taken place on a massive scale, with reported catches of 50 kg per 20 m of trammel nets in the shallow area of Ghannouch (less than 15 m depth) in the Gulf of Gabès (INAT, unpublished data). Such huge quantities of the crab have put artisanal fisheries, which mainly operate with set nets, in crisis: entangled crabs can damage nets to the point where they are no longer a usable gear in invaded areas (Figure 2A). This has resulted in a significant reduction in catch rates along with a general increase in the time and effort needed to extract the crabs from the nets, making fishing more challenging and less productive. In addition, and depending on the level of clogging involved, the average time needed to extract crabs from the net has increased from 12 hours to more than 72 hours of intensive work since the beginning of the invasion (GIPP, 2017). The nets also damage the blue crabs and limit their commercial use, since they typically lose many of their appendages when entangled. With regard to the "Charfia" – an artisanal fishing method using gear mainly made with palm leaves where sea currents, tides, winds and other hydrodynamic factors drive the entry of the fish into traps (Boughedir *et al.,* 2015) – the rate of catch per single Charfia fishing structure was almost 40 kg of *P. segnis* per day, while the yield of the targeted fish species declined significantly (GIPP, 2017). Inside the traps, *Portunus segnis* was aggressive, very voracious, and showed cannibalistic behaviour (INAT, unpublished data).

Furthermore, *P. segnis* predates the other entangled species, thus damaging valuable fishery products (Figure 2B). The mutilated catches must be discarded, leading to a decrease in production and fishery value. Crab predation affects shrimp and fish species (e.g. *Sparus aurata, Lithognathus mormyrus, Solea solea*), which are traditional targets of small-scale fisheries and have a high commercial value (INAT, unpublished data).

The interviews carried out by Khamassi *et al.* (2019) in the Gulf of Gabès show that the crab invasion has had dramatic consequences for the local fishery because of the crabs' negative interactions with set nets. More than 60 percent of fishers capture this crab in their gill nets, and in 40 percent of cases the crab is abundant and can clog the nets, with extreme cases reaching more than 150 kg of crabs in 50 m of nets in 24 hours. As a result, fishers have had to increase the frequency with which they haul their nets by 20 percent – and some have stopped mending their nets altogether, preferring to replace them instead.

The impact of this crab invasion on the Gulf of Gabès fishery has been severe, with an 86 percent drop in cuttlefish catches (the trammel nets targeting them require longer immersion times). Fishers have reported that *Portunus segnis* damages their catches, with

FIGURE 2

A: Damage to fishing gears caused by blue crab; B: Damage caused by *Portunus segnis* to small-scale fishery catches in the Gulf of Gabès (set nets and gillnets); C: Injuries caused by crabs' claws; D: Breaking the crab with a type of sledgehammer

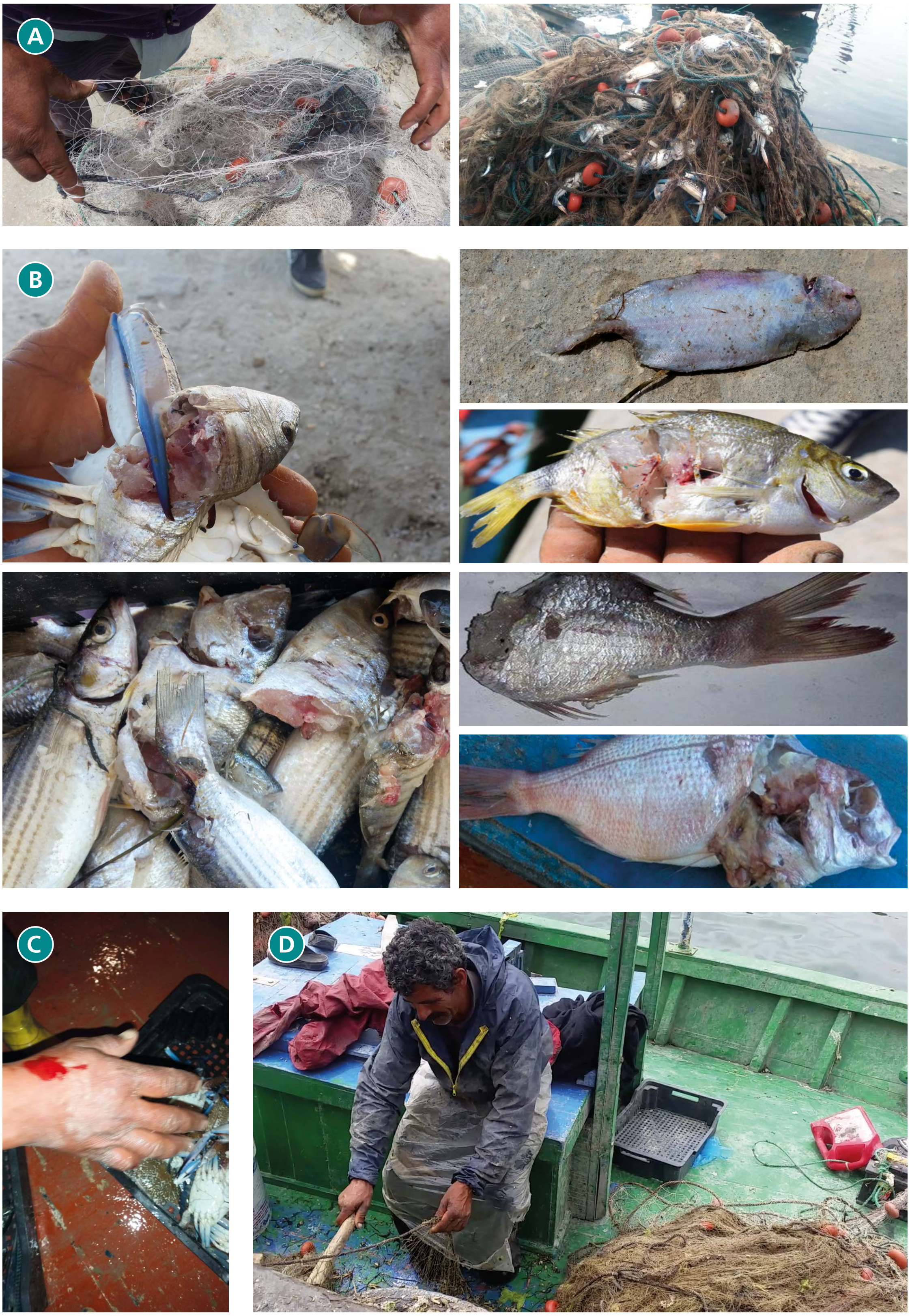


Photo credits:
Figure 2A: ©J. Ben Souissi and W. Rjiba; Figure 2B: ©S. Khamassi and J. Ben Souissi; Figure 2C: ©S. Khamassi; Figure 2D: ©A. Chafai.

losses estimated to range from 10 percent to 60 percent (Khamassi *et al*., 2019). This has led to a significant reduction in annual income per fisher, with an average of 77 000 USD declining to 21 500 USD after the invasion (Khamassi *et al*., 2019). The number of annual working days has also fallen from 205 to 153, resulting in an additional loss of labour, representing 25 percent of total losses. In addition to the economic impacts, the clogging of nets has also reduced fish catches by 37 percent and has led to a considerable increase in the frequency of net replacement, from every three years to as often as every six months, and – in some extreme cases – even monthly (Khamassi *et al*., 2019). When nets are severely damaged, replacement is more beneficial than mending.

Fishers have also reported injuries from crab claws (Figure 2C). These incidents, which typically happen when the crabs are being removed from the fishing gears, leads to medical expenses and can prevent the fishers from working for a number of days – with consequent loss of incomes. At the beginning of the invasion, fishers tried to get rid of the crabs with a kind of sledgehammer to avoid cutting their fingers (Figure 2D). After 2015, *P. segnis* populations increased in abundance and distribution not only in Tunisia but also in Libya and along the Greek–Turkish coasts (Castriota *et al*., 2022). Climate change is expected to favour the success of tropical invaders (D'Amen and Azzurro, 2020) including *P. segnis,* since temperature is thought to play a key role for the species (Castriota *et al*., 2022).

3. ADAPTIVE RESPONSES

At the beginning of the *P. segnis* invasion, and in the absence of any immediate action by the Tunisian government, fishers tried to find solutions themselves – and by referring to the internet and social media networks they realized that *P. segnis* is an edible species with high commercial value. Some of them took the initiative to get in touch with potential investors and exporters, particularly from Asia. In addition, they used the species for their own consumption and tried to market the product locally.

Since 2015, the Tunisian government has been working with stakeholders on a series of actions to deal with the impacts of blue crab on ecosystems, and to help local fisheries.

Meetings have been held at several levels, including between fishers and regional authorities, within the Ministry of Agriculture with various professional organizations including the Tunisian Union of Agriculture and Fisheries (UTAP), and at a very high level including at a ministerial council dedicated to the blue crab problem.

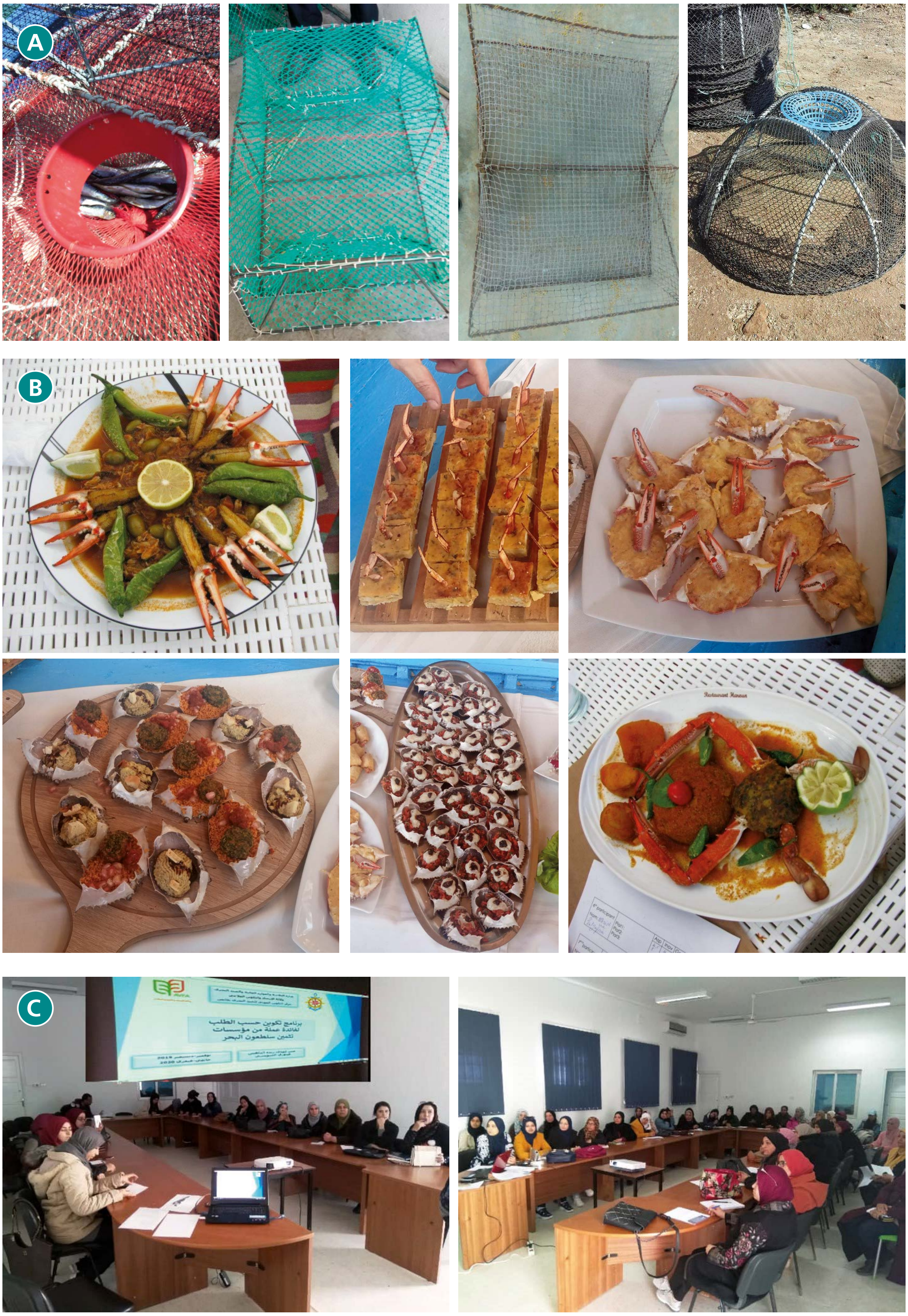
In 2017, a national plan to encourage the fishing, promotion and marketing of crabs was officially implemented (Decree No. 273 on 31 October 2017). The key elements of this strategy (Anonyme, 2017) were:

1. The establishment of collecting areas for blue crabs to stop them being put back into the sea and to guarantee incomes for fishers. Three collection points were set up in Mednine and in Gabès, then at the request of fishers another point was set up in Boughrara.
2. The government buys all catches without limit at the rate of USD 0.8/kg, with USD 0.4 coming from government funds and USD 0.4 being charged to manufacturers.
3. Stimulate demand by marketing blue crabs nationally and seeking international markets.
4. Stimulate national and international investments to set up processing factories.
5. Boost scientific research on the rational management of this new edible resource, including stock assessment and the design of appropriate fishing technology.

In this context, new trap models were designed and tested to ensure a better quality and more cost-effective *P. segnis* fishery (Anonyme, 2020) (Figure 3A). Experiments carried out in 2017 (GIPP, 2017) indicated that a hemispherical trap with an upper lattice hole is the most efficient equipment for catching blue crabs and avoiding bycatch (the crabs must be caught alive and retain a high level of quality). The average yield of a single trap was more than 5 kg from February to March 2017, especially at depths ranging from 5 to 10 m. Catches reached a maximum of 8 kg per trap in 12 hours during the same

FIGURE 3

A: Different kinds of blue crab traps designed through government projects; B: Tasting campaigns to promote blue crab consumption (Bleu-Adapt Project: Blue crab festival Kerkennah, 2022; GIPP: Jerba, 2019); C: Training sessions on crab-shelling (Gabès, 2019–2020)



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period, using *Sardinella aurita* as bait. The average weight of crabs caught in traps was 278 g, compared to a maximum of 196 g for crabs caught in nets (GIPP, 2017). As for rectangular folded traps, these also brought in profitable catches of fish and squid, in addition to their effectiveness in catching crabs (they yielded an average of 2 kg of squid per trap per cruise). Practical hands-on training sessions were organized for fishers to compare the effectiveness of these gears.

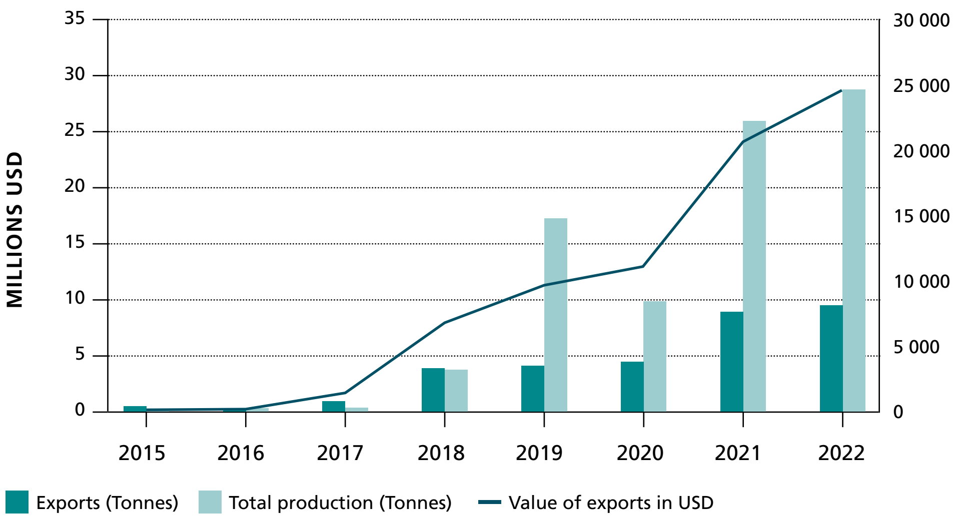
Bait trials were carried out too, involving many different kinds of fishes as well as chicken waste.

Another key action conceived by the government and other stakeholders – including the Interprofessional Group of Fishery Products (GIPP), the Tunisian Union of Agriculture and Fisheries (UTAP), WWF, the Tunisian Association of Marine Sciences (ATSMer), and projects such as Bleu-Adapt and Nemo-Kantara – was the organization of tasting campaigns and cooking shows to promote the consumption of blue crabs (Figure 3B), creating a change in the culinary culture of some Tunisians. Competitions were organized for chefs and fishers' wives, with prizes awarded for the best dishes and recipes. Even in Tunisia, where crab has never been a traditional dish or ingredient in cooking, the product is now starting to appear on the menus of local restaurants.

Finally, women were trained in shelling and on how best to remove meat from crabs, while manufacturers trained their workers in hygiene (Figure 3C).

The action plan and strategies have ensured benefits not only for the manufacturers who have invested in this sector but also for women, especially fishers' wives, who now have the opportunity to work in the processing industry. Their success has led to a significant increase in production and exports, while the efforts and initiatives taken by the authorities to promote and support the industry have had a positive impact on the economy (Figure 4). Other initiatives to manage the invasion of blue crabs (both *Portunus segnis* and *Callinectes sapidus*) have been taken in other Mediterranean countries, including a programme involving the entire Mediterranean region coordinated by the General Fisheries Commission for the Mediterranean (GFCM) (www.fao.org/gfcm/researchprogramme-bluecrabs/en/).

FIGURE 4
Total *P segnis* production in Tunisia and exports from 2015 to 2022



*(Production during 2015 and 2016 is underestimated due to catches returned to the sea)
In 2017, production of some landing sites is missed in official statistics, which explains why exports excced catches

Source: GIPP. 2022. *Rapport technique du Groupement Interprofessionnel des Produits de la Pêche: Etat de la pêcherie du crabe bleu en Tunisie, Décembre 2022.*

4. OUTCOMES

The new *P. segnis* fishery in the Gulf of Gabès has turned a pest into a valuable opportunity. It has contributed to the development of the local economy, particularly for crab processors and fishers' wives who have benefited from new jobs related to processing and increasing product value. The processing and export of blue crab has become a significant industry in the region, with a substantial number of factories dedicated to the activity. Today there are 49 seafood-processing factories (spread out over the whole country) that are involved in the processing and export of blue crabs, and 17 of these factories specifically focus on processing blue crabs.

The blue crab sector has also attracted foreign investment. As an example, the largest investment for the establishment of a blue crab processing factory in Ghannouch comes from the Middle East (Al Bahrein), and amounts to USD 70 million dollars. This investment has enabled the employment of 1 600 people, including 1 400 women. The factory has a production capacity of 110 tonnes per day, intended for export, and it has a large cold room storage capacity of up to 6 000 tonnes (Factory Manager 2023, personal communication).

As a scientific outcome, numerous studies related to growth, feeding, habitats and reproductive biology have been carried out for *P. segnis* (Ben Abdallah-Ben Hadj Hamida *et al*., 2019a, b, 2022), enhancing the capacity to provide scientific advice for its effective exploitation.

With regard to the crab stock, the intense harvesting of *P. segnis* was followed by signs of declining landings after 2019 (Figure 4), but the small-scale fishery appears not to have been affected by this change (Ben Souissi, personal observation). The estimation of the apparent biomass relative to the different surveys that have been carried out showed that *P. segnis* is mostly landed in spring and summer, with catches varying between 8 000 and 46 000 tonnes between May and September, with a decreasing trend observed since 2018. Similarly, the analysis of pseudo-cohorts has shown that in the Gulf of Gabès the blue crab stock is overexploited (Ben Abdallah-Ben Hadj Hamida, unpublished data).

5. CHALLENGES

- Another species of blue crab (*Callinectes sapidus* of Atlantic origin) is also present: this generates confusion and gaps in fishing statistics, as it can be difficult to accurately distinguish between the two species in fishing surveys or catch data. This could make it challenging for the Ministry of Agriculture to accurately assess the state of the *P. segnis* fishery and to develop appropriate management strategies.
- Managing the by-products and waste generated by the exploitation and processing of blue crab poses significant environmental challenges, particularly in areas with large-scale production and processing facilities. In the Gulf of Gabès, where blue crab fishing and processing activities are concentrated, there has been a reported storage of 6 tonnes of waste per day in the town of Ghannouch. Since the edible part of the crab constitutes only a small fraction of the entire animal (around 26 percent), the remainder ends up as waste. The accumulation of this waste can pose several environmental problems, including the risk of contamination and pollution of local waterways, soil and air. It can also lead to the production of unpleasant odours and attract pests and other nuisance animals.
- Turning blue crab into a commercial resource provides a solution to mitigate the negative ecological and socioeconomic impacts of a widespread and massive invasion. However, overfishing the invasive population leads to reduced catch rates, and can make the commercial exploitation of *P. segnis* uneconomical. This bioeconomic paradox could threaten the blue crab industry and the investments made so far.

6. LESSON LEARNED AND KEY RECOMMENDATIONS

Tunisia's blue crab invasion is an instructive example of the management of a biological invasion in the context of fisheries and climate change. Based on the experiences of managing this invasion, a series of important recommendations can be made:

- Effective management requires a careful and regularly updated blue crab stock assessment. This information is crucial for making informed decisions about fishing quotas, seasons, and other management measures that can help maintain the long-term sustainability of the fishery. In addition, a stock assessment is necessary for the development of an appropriate crab value chain. For example, by providing information about the size and distribution of the resource, a stock assessment can help identify areas with the highest concentrations of blue crab and inform decisions about where to locate processing facilities or other value-added activities.
- Current fishery goals are oriented toward sustainable blue crab exploitation. If the only aim is a sustainable exploitation of the *P. segnis* population, it is advisable to adopt regulations that ensure sustainable harvesting practices such as size limits to prevent the over-harvesting of smaller individuals (individuals retained should have a carapace length of at least 11 cm, corresponding to a weight of about 100 g). In the same way, the landing of egg-bearing females should be prohibited. Fishing campaigns should be limited to 4 months per year (January–April) to ensure the sustainability of the resource and help maintain the reproductive capacity of the population.
- While the commercial opportunities for blue crab are being well exploited, the ecological impacts of the invasion should be better evaluated in order to improve management strategies.
- To avoid confusion between the two blue crab species present on Tunisian coasts, it may be necessary to provide training and resources to fishers and other stakeholders to help them accurately distinguish between the species and improve catch data. A collaborative and data-driven approach that engages stakeholders from across the fishing, research and management sectors will be important for ensuring the sustainable and responsible management of the blue crab fishery in Tunisia, and for addressing the challenges posed by the presence of multiple species.

To address the issue of the environmental impacts of crab by-products, and based on a circular economy approach, crab waste could be used in a number of ways including as a feed supplement for animals, as crab meal for fish-farming, or as fertilizer. Crab shells could also be an important feedstock for the production of chitin and chitosan. The development of these by-products will require collaboration and engagement from a range of stakeholders, including government agencies, fishing and processing industries, and local communities.

Considering the ongoing pressures on natural resources and the growing impacts of climate change, fisheries will increasingly be forced to adapt to these changes and to sustainably exploit natural resources.

ACKNOWLEDGMENTS

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Chapter 4

A case study of the Lake Tanganyika sardine *Limnothrissa miodon* in Lake Kariba (Zimbabwe/Zambia)

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SUMMARY

The deliberate introduction of the Lake Tanganyika sardine *Limnothrissa miodon* created a new fishery in the manmade Lake Kariba by filling the large open-water niche, and it soon overtook the inshore gill net fishery. The total catch rose to about 20 000 tonnes between 1990 and 1994 but decreased after that, falling to 11 000 tonnes in 2002, then recovering to about 20 000 tonnes, but the catch per unit effort (CPUE) declined from about 0.20 tonnes per boat-night in 1995 to 0.09 tonnes in 2011. It has been suggested that climate change may be responsible for this decline, but the main cause is most likely to be excessive fishing effort. A stock assessment recommended that a maximum of 500 boats should be permitted on the lake, but there may now be as many as 2 000 of them.

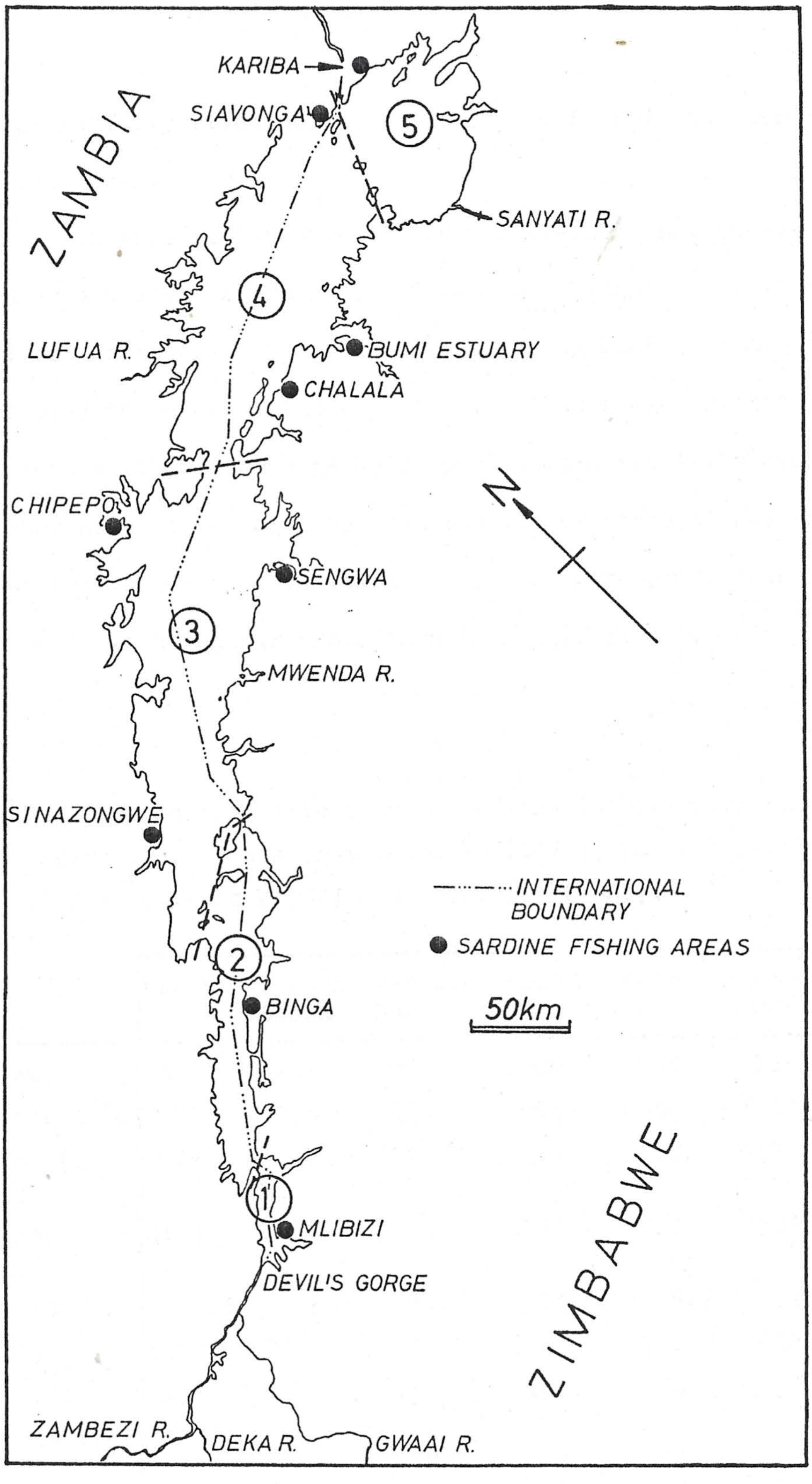
Limnothrissa is a short-lived species in Lake Kariba and responds to seasonal and annual changes in nutrient availability. Its extraordinary abundance shortly after its introduction could be explained by the release of nutrients following the collapse of the *Salvinia* mats that once covered some 22 percent of the lake. There was a strong correlation between CPUE and the flow of the Zambezi River, the main source of nutrients, until 1995 when fishing effort likely became the main influence on the stock. Although the lake has warmed, there has been no correlation between CPUE and temperature; arguments that warming promoted the growth of toxic blue-green algae, thus reducing the zooplankton eaten by *Limnothrissa,* are unfounded since the blue-greens became dominant before any warming was detected, while the fish changed the zooplankton soon after their introduction.

Although both Zambia and Zimbabwe have promulgated regulations for managing the *Limnothrissa* fishery in Lake Kariba, their effectiveness can be questioned. This has resulted in some conflict and political problems, and resolving these is the most urgent management priority. Intergovernmental bodies have been established to coordinate research and management but they appear to be ineffective. These bodies need to be revived and given the authority to establish a standardized and binding plan for managing the fishery, and provided with the means to enforce them.

1. FISHERY CONTEXT

Lake Kariba, one of the world's largest manmade lakes (approximately 5 400 km^2; mean depth 29 m), is located on the Zambezi River and was created in 1958, reaching full supply level in 1963 (Figure 1). It supports two separate fisheries: a gill-net fishery based on native Zambezi River fish species, largely restricted to water <20 m deep (Coke, 1968), and a pelagic fishery for the non-native Lake Tanganyika sardine *Limnothrissa miodon* ("kapenta"), which after its introduction gave rise to the most important fishery on the lake.

FIGURE 1
Lake Kariba, showing the main tributaries and kapenta fishing bases (Zimbabwean side only)



Source: Marshall, unpublished.

Efforts to capture this species by replicating the artisanal fishing methods used on Lake Tanganyika failed. The paraffin or gas lamps used on that lake were not bright enough to attract the fish in Lake Kariba, probably because its water transparency was much lower (Begg, 1974). Consequently, a capital-intensive semi-industrial fishery was developed, requiring an investment of USD 15 000 (Zambia) to 18 000 (Zimbabwe) to cover the cost of boats, engines, generators and powerful lamps, and drying racks (Kinadjian *et al*. 2014). Today, the kapenta fishery in Lake Kariba employs relatively large boats, commonly twin steel pontoons, with an onboard generator powering mercury-vapour lights mounted both above the water and submerged over the mouth of conical lift nets, about 3–5 m in diameter (Figure 2).

The fishery began in mid-1973 (Zimbabwe) and 1981 (Zambia). The catch rose rapidly to a peak of just under 30 000 tonnes from 1990 to 1994 (Figure 3) but then decreased to around 11 000 tonnes in 2002. This may have partly been a result of the 1991-92 drought, one of the worst experienced in southern Africa (Masih *et al*., 2014), and the relatively dry seasons that followed until about 2001, after which the catch rose to about 20 000 tonnes. However, the data have become unreliable in recent years, partly because of losses through theft and illicit trading of fish on the lake before they reach shore facilities (Overå, 2003; Kinadjian *et al*., 2014; Mhlanga and Mhlanga, 2014). This problem became acute on the Zimbabwean side from about 2000 onwards when hyperinflation left the local currency worthless and boat crews used fish to barter for essential goods. Zimbabwean operators estimate that such losses could exceed 50 percent of the catch (Mhlanga and Mhlanga, 2014) and these would not be accounted for in the official catch estimates.

Kapenta catches can equal or exceed their biomass in the lake, but small fish such as kapenta usually have production/biomass ratios >5.0 (Kolding *et al*., 2019) so this is not a cause for concern. However, biomass estimates should be treated with caution because they may not have come from the whole lake or taken seasonal variation into account; for example, two estimates from 1992 came to 25.3 and 42.0 kg/ha, probably reflecting seasonal changes. The exceptionally high biomass in 1981 was at the end of the "boom" years that followed the kapenta's introduction, but later estimates tend to be around 20 000 tonnes.

FIGURE 2
A typical kapenta fishing rig, Lake Kariba
Like many of these vessels this one is moored offshore during the day, providing a roost for gulls and terns which increased in numbers after the introduction of kapenta. Note the large diesel generator under the canopy and the two powerful mercury-vapour lights on the boom above the net mouth; most of the net is stowed on board.

2. HISTORY AND IMPACTS OF *LIMNOTHRISSA MIODON* ON LOCAL FISHERY AND ECOSYSTEMS

Kapenta were introduced in 1967–68, when about 360 000 fry were airlifted from Lake Tanganyika to fill a vacant ecological niche in Lake Kariba (Bell-Cross and Bell-Cross, 1971). Adult fish appeared in the stomachs of tigerfish (*Hydrocynus vittatus)* in 1969, some of them >150 km from their point of introduction at Sinazongwe (Figure 1). By 1970 they were distributed throughout the lake (Junor and Begg, 1971; Woodward, 1974), and they became so abundant that they occasionally blocked the intake screens for the hydroelectric turbines (F.J.R. Junor, personal communication). They also colonized the Zambezi River, having passed through the turbines at the Kariba dam (Kenmuir, 1975), and established themselves downstream in the Cahora Bassa reservoir, Mozambique, where there is now an established fishery for the species. They also colonized the Zambezi River further downstream (personal observations).

The immediate impact of kapenta was an increase in predators, notably bird species such as gulls, terns and kingfishers (Junor, 1972; Begg, 1973; Hustler, 1986), and tigerfish which became a significant bycatch in the kapenta fishery (Cochrane, 1976; Junor and Marshall, 1979; Marshall, 1991). The zooplankton changed dramatically after 1970, with copepods and larger cladocerans being virtually eliminated within five years of kapenta's introduction (Table 1). This was accompanied by a significant reduction in biomass, with crustaceans falling from 513.1/m^3 in August 1972 to 74.7/m^3 in August 1983 and rotifers from 222.8/m^3 to 157.1/m^3 (Green, 1985). This may have resulted in changes to the phytoplankton, but there are no data to confirm this.

In Lake Kariba kapenta is a short-lived species, with few surviving beyond six months (Marshall, 1987). Thus the population responds to short-term environmental changes, and fluctuations in abundance have been linked to river flow (Marshall, 1982; Chifamba, 2000). The retention time (volume/outflow) of Lake Kariba is around three years, but it's shorter in drought years when outflow exceeds inflow, so nutrients are lost through the outflow and replenished during the rains when river flow is greatest. Catches were also highly seasonal, at least in the early years, reaching a peak in August after lake turnover released nutrients and stimulated the growth of phyto- and zooplankton (Cochrane, 1984; Marshall, 1988b).

Shortly after it began to fill, Lake Kariba was infested by the floating non-indigenous weed *Salvinia molesta,* which at its peak covered about 22 percent of the lake (approximately 1 000 km^2) and stored significant quantities of nutrients (Mitchell, 1973). These mats began to collapse from about 1972, possibly as a result of biological control by

TABLE 1
Changes in the zooplankton (% composition) of Lake Kariba after the introduction of *Limnothrissa miodon* in 1967–68.

	1967–68*	1970	1972	1975–76	1983
Diaptomids	18.7	0.2	0	+	0
Cyclopoids	17.6	12.5	10.1	13.8	1.1
Nauplii	9.3	16.4	17.1	3.1	14.8
Bosmina	4.8	15.9	17.1	10.5	2.1
Ceriodaphnia	43.0	14.3	0	0.3	0
Diaphanosoma	10.5	0.2	0	+	0
Daphniids	0.3	0.2	0	0	0
Rotifers	4.0	40.3	55.7	72.3	81.3

The symbol * indicates values based on weight (mg/m^3), all others are based on numbers (no/L). From Bowmaker (1973), Mitchell (1975), Begg (1986), Cochrane (1978) and Green (1985).

the South American grasshopper *Paulinia acuminata* (Mitchell and Rose, 1989), releasing nutrients into the lake (Figure 3a). This almost certainly facilitated the kapenta population explosion, but the catch per unit effort (CPUE) decreased rapidly, with a two to three-year lag, as nutrients were lost. This was not an impact of fishing since fishing effort was still low and mostly restricted to the eastern basin, and CPUE became relatively stable from about 1983 onwards after *Salvinia* covered <1.0 percent of the lake.

The Zambezi River, which supplies about 85 percent of the lake's water, fluctuates considerably but there was a general downward trend between 1955 and 1995, exacerbated by serious droughts in 1967–68, 1972–73, 1980–82, 1984–85 and 1991–92 (Masih *et al*., 2014). There was a close correlation ($r = 0.564$, $p < 0.01$) between Zambezi River flow and kapenta CPUE up to 1995 (Figure 3b). Thereafter the CPUE declined even though the Zambezi flow tended to increase, and there was no correlation between CPUE and river flow. This suggests that some other factor now controls the fishery, and it has been suggested that climate change has caused the stocks of kapenta to decline because climate-induced warming of the lake led to a decrease of their zooplankton food resources (Magadza, 2011; Magadza *et al*., 2020). These authors discounted fishing effort – however, this is unrealistic since fishing may lead to changes in life history traits that alter the production potential of harvested species (Chapman and Sharpe, 2016).

There can be no doubt that the lake has warmed. There was no change in temperature between 1968 and 1986, but it increased by about 2 °C at the surface and 4 °C at 40 m between 1986 and 2011 (Marshall, 2021). The temperature at a depth of 20 m, approximately the average for the water column (Marshall, 2017), did not change significantly in July when the lake was isothermal ($r = -0.144$, $p > 0.05$) or in March when it was fully stratified ($r = 0.566$, $p > 0.05$). There might, however, have been a significant increase in March were it not for the cooling trend that occurred from about 1985 to 1992 (Figure 3c).

Although thermal gradients in the water column have declined, it has been suggested that this caused the thermocline to ascend, reducing the depth of the epilimnion and cutting off the supply of nutrients from deeper waters, thus reducing pelagic productivity. These arguments were summarized by Ndebele-Murisa *et al*. (2014) but a re-analysis of their data found that the opposite was occurring: the epilimnion was becoming deeper and more homogenous (Marshall, 2021). More significantly, however, warming is more rapid in deeper waters than at the surface. Thus, between 1986 and 2009 the summer temperature increased by about 1.5 °C at the surface and about 4 °C at a depth of 40 m, but winter temperatures showed little change (Marshall, 2017, 2021). Changes to the seasonal thermal regime of the lake could therefore impact the fishery by altering the supply of nutrients and plankton growth.

Warming was thought to have caused the phytoplankton to become dominated by cyanobacteria, notably the toxic species *Cylindrospermum raciborskii*, which was said to have suppressed the zooplankton and deprived the kapenta of food (Magadza, 2011; Magadza *et al*., 2020). However, *Cylindrospermum* was the dominant cyanobacterium in 1982–84 (Ramberg, 1987), but the overall kapenta catch was still increasing and there had been no warming of the lake. Moreover, changes in the zooplankton occurred well before there was any evidence of rising temperatures in the lake (Table 1). Of course, the influence of warming may increase in future, and climate-induced changes to the hydrology of the Zambezi River could have a more significant long-term impact on the fisheries in the lake.

At present, however, the most likely explanation for the post-1995 decline in CPUE is overfishing (Chali *et al*., 2014; Marshall, 2012, 2021), mainly caused by the great increase in Zambian fishing effort (Figure 4). This may have been driven by the collapse of sardine fisheries in the intensively-fished Zambian sector of Lake Tanganyika (Government of Zambia, 2015), where the average density of fishers was 36.6/km^2 compared to 2.9/km^2 over the lake as a whole (calculated from frame survey data in van der Knaap, 2014).

FIGURE 3

(a) The relationship between *Salvinia molesta* coverage and kapenta CPUE; note that CPUE values were computed differently from those in panels (b) and (c).
(b) The relation between the annual discharge of the Zambezi River at Victoria Falls and the CPUE of kapenta, Lake Kariba.
(c) CPUE of kapenta in relation to temperature at 20 m depth, Lake Kariba (basin 5) in March (fully stratified) and July (isothermal).

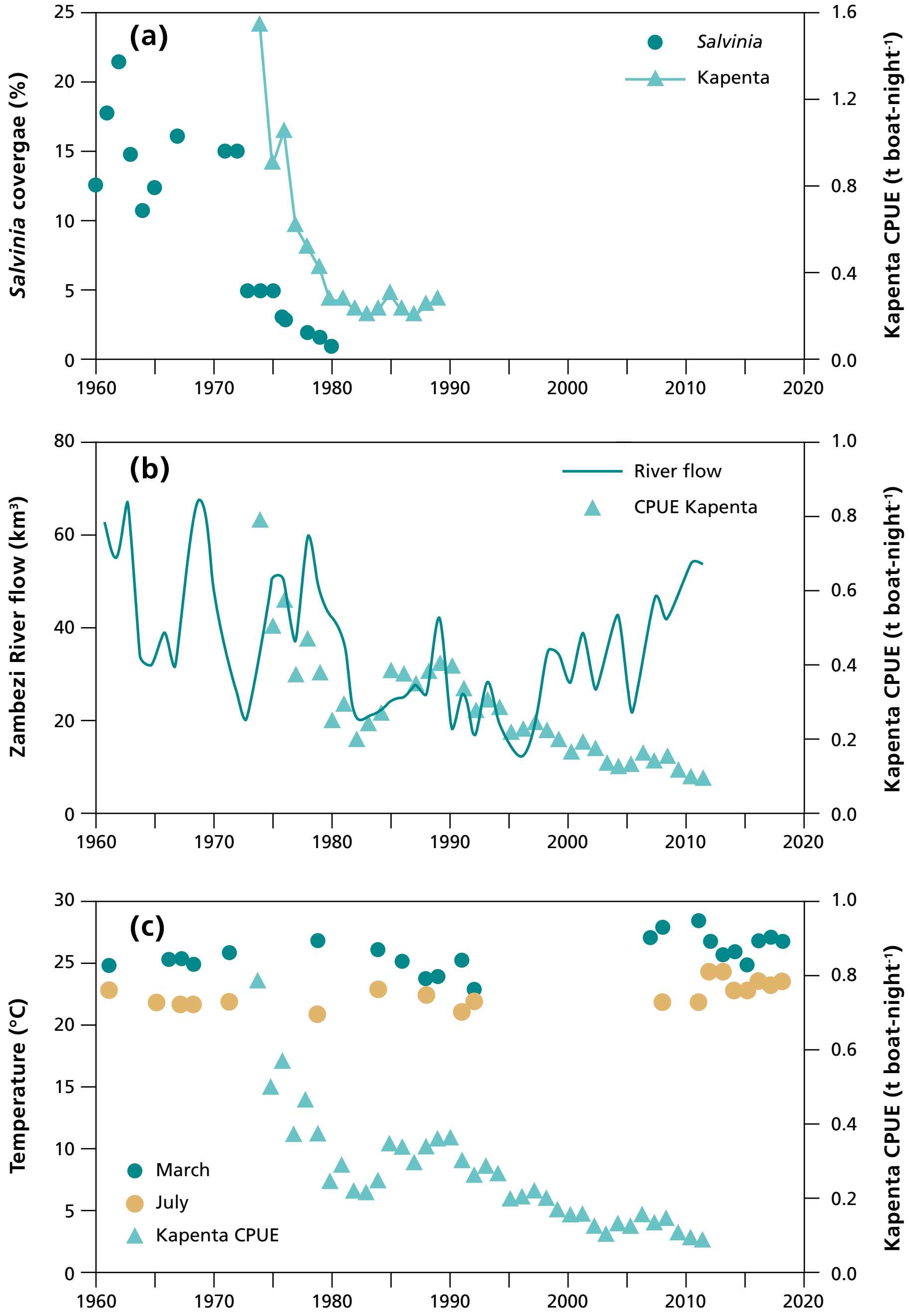


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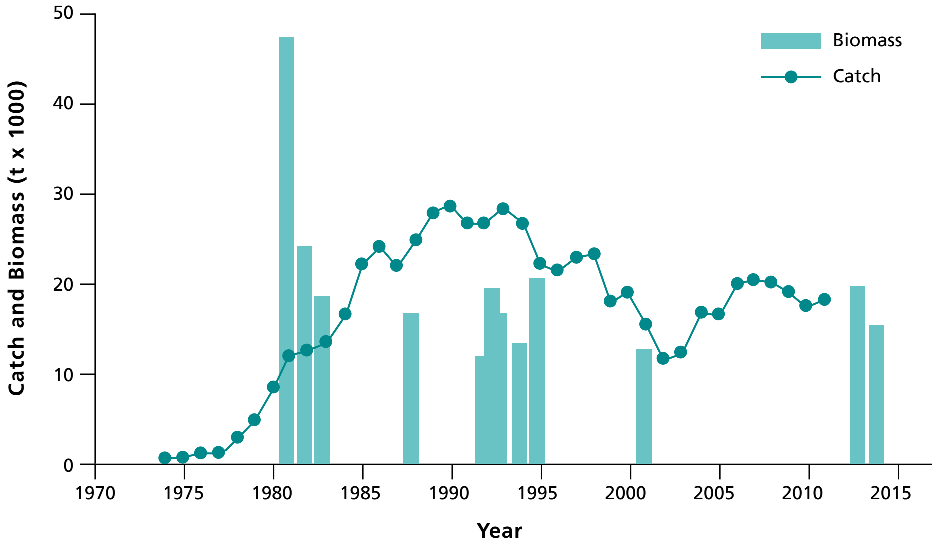
FIGURE 4
The nominal catch in the kapenta fishery of Lake Kariba, 1974–2011, along with some estimates of kapenta biomass



Source: Catch data from Kinadjian, L., Mwula, C., Nyikahadzoi, K. & Songore, N. 2014. *Report on the bioeconomic modelling of kapenta fisheries on Lake Kariba*. Report: SF-FAO/2014/22 March 2014. Indian Ocean Commission, Ebène, Mauritius. Biomass from Marshall, B.E. 1988a. A preliminary assessment of the biomass of the pelagic sardine, *Limnothrissa miodon*, in Lake Kariba. *Journal of Fish Biology* 32: 515–524. Lindem, T. 1988. *Results from the hydro-acoustic survey in Lake Kariba, September 1987*. Zambia-Zimbabwe SADCC Fisheries Project, Kariba, Zimbabwe. Mhlanga, W., Ngalande, P. & Songore, N. 1995. Hydroacoustic assessment of kapenta (*Limnothriss a miodon*) abundance in Lake Kariba. Paper presented to the First Pan-African Fisheries Congress, Nairobi, Kenya, 31 July-4 August 1995. Mafuca, J.M. 2014. *Preliminary results of the hydroacoustic survey conducted on Lake Kariba*. Indian Ocean Commission Report SF-FAO/2014/33. Ebène, Mauritius. Chifamba, P.C. & Olff, H. 2019. Developing a sustainable pelagic fishery in an African reservoir: trends in the catches of the introduced freshwater sardine *Limnothrissa miodon* and associated species in Lake Kariba. In: Chifamba, P.C. The biology and impacts of *Oreochromis niloticus* and *Limnothrissa miodon* introduced in Lake Kariba. PhD thesis, University of Groningen, Netherlands.

3. ADAPTIVE RESPONSES

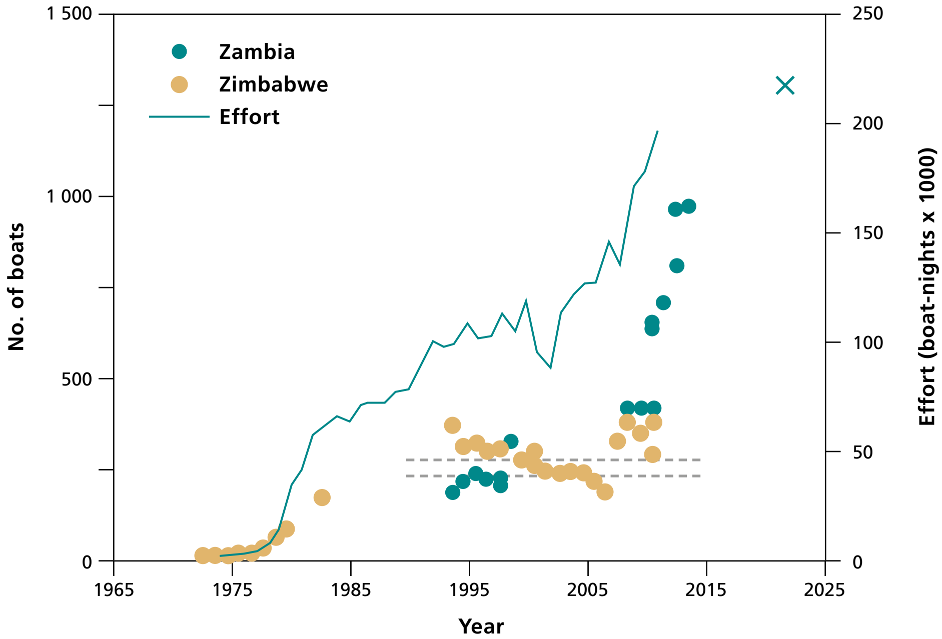
Both Zambia and Zimbabwe promulgated regulations for the management of the kapenta fishery. In both countries, every vessel must be licensed and licence-holders are required to submit monthly catch returns to their respective national authorities. An 8-mm minimum mesh size was imposed, and a 2011 survey indicated that about 80 percent of operators complied with this requirement (Kinadjian *et al.*, 2014). In Zimbabwe fishing is prohibited in water <20 m deep and in river mouths, to protect both juvenile kapenta in shallow water (Begg, 1974; Marshall, 1987) and the inshore fishery that takes species other than kapenta. Such restrictions are not imposed in Zambia, which relies on "traditional" approaches to protect stocks (Kinadjian *et al.* 2014).

Non-compliance with fishing regulations is an issue in both countries, but it appears to be especially serious in Zambia. For instance, the 2014 annual report of the Fisheries Ministry stated that there were 460 licensed fishing vessels on the lake (Government of Zambia, 2015) when there were in fact 962 vessels, so more than 500 of them were illegal, unreported and unregulated (IUU). It was further noted that only 18–19 percent of operators complied with the requirement to submit monthly catch returns.

When the fishery began, the Zimbabwean authorities adopted a conservative approach in awarding fishing licences (Marshall *et al*., 1982), but this was overtaken by political changes and the development of the Zambian fishery. A major donor-funded project – the Zambia-Zimbabwe Southern African Development Community (SADC) Fisheries Project – carried out a kapenta stock assessment and estimated that a maximum sustainable yield (MSY) of 30 000 tonnes should be possible. It suggested a maximum limit of 500 fishing rigs, with 230 (45 percent) being allocated to Zambia and 270 (55 percent) to Zimbabwe, in accordance with the area of the lake within each country (FAO, 2012; Chali *et al*., 2014). A later bioeconomic model estimated MSY to be around 21 000 tonnes and concluded that in 2011 fishing effort exceeded the optimum level by 45 percent (Kinadjian *et al*. 2014). Fishing effort, on the Zambian side at least, has more or less doubled since then (Figure 5).

FIGURE 5
The total fishing effort (line) and the estimated number of kapenta fishing boats (points) in each country on Lake Kariba

The horizontal broken lines indicate the recommended number of boats for Zimbabwe (upper) and Zambia (lower).



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4. OUTCOMES

Since there was no fishery for small pelagics before kapenta were introduced, the kapenta fishery was expected to have little impact on the local inshore fishery. In Zimbabwe it quickly overtook that fishery in terms of both volume and value, and was responsible for infrastructure development and employment in some of the country's least developed areas (Bourdillon *et al.*, 1983); the same must also apply to Zambia. The overall economic impact of the fishery has not been fully assessed, but some estimates valued the catch at USD 12.5 million in 1996 (Mhlanga and Mhlanga, 2014). The catch was at its peak around this time so this may be a consistent estimate, but it does not include added value through ancillary activities such as boat maintenance, transportation, retail profit, or taxation. Kinadjian *et al.* (2014) calculated that the fishery supported about 3 800 jobs, both as fishers and in shore-based employment – a significant contribution in an area where there is little formal employment.

5. CHALLENGES

The principal challenge is to maintain the sustainability of the kapenta population, and this involves controlling fishing effort. Zimbabwe and Zambia signed a protocol in 1999 for the management of shared fishery resources on Lake Kariba, which included the establishment of joint management and technical committees (Mhlanga and Mhlanga, 2014), but these seem to be ineffective. It has been reported that Zimbabwe and Zambia may be taking steps to improve this situation (Anon., 2022).

The recommended limit of 500 fishing boats was never implemented, and press reports suggest that Zimbabweans blame Zambia for breaking this protocol (Anon., 2016, 2017a, 2019, 2021) – although Zimbabwe has also done so, but to a lesser extent. The issue of illegal fishing vessels was perceived as a major problem over a decade ago (Anon, 2010) but it has still not been solved, at least in Zambia (Government of Zambia, 2015). Other reports claim that Zimbabwean fishers have been attacked by armed Zambians (Anon, 2014), and that Zimbabwean police have arrested and harassed Zambian fishers (Anon, 2017b). In any case, fishing effort is likely to fall as declining catches become unprofitable and operating costs increase; this process has already begun on the Zimbabwean side (Anon 2021).

This situation has led to other conflicts; for example, inshore fishers complain that kapenta crews steal their gillnets during the night and fish in the shallow areas where kapenta breed, while catching other species attracted to the lights (Mhlanga and Nyikahadzoi, 2017). Conversely, kapenta fishers in Zimbabwe argue that when the lake level is low, the 20 m restriction diminishes the area in which they can fish, thus reducing their catches and forcing them to operate in shallower water. These conflicts are especially problematic in the narrower and shallower western basins of the lake (basins 1 and 2, see Figure 1).

6. LESSONS LEARNED AND KEY RECOMMENDATIONS

- The Lake Tanganyika sardine *Limnothrissa miodon* created a major fishery on Lake Kariba, without obvious adverse impacts, but this was an unusual situation because the newly-created lake provided a vacant open-water niche.
- Fishery models suggest a sustainable yield of around 30 000 tonnes per annum could be achieved, but CPUE is declining in real terms, even allowing for deficiencies in data collection.
- *Limnothrissa* is sensitive to environmental variability, but since 1995 fishing effort appears to be controlling catches. As yet there is no evidence that climate change is affecting the fishery, although long-term climate-induced changes to the Zambezi River flow may become more influential.

- Uncontrolled fishing effort could reduce CPUE to uneconomical levels, with adverse impacts on the industry and those involved with it. Both Zambia and Zimbabwe should investigate possible solutions which could include the reduction of fishing effort, such as eliminating IUU vessels and not reissuing licences after operations have collapsed.
- Effective management can only be achieved through international cooperation. The Protocol for Management of the Shared Fisheries Resources on Lake Kariba, facilitated through the Zambia/Zimbabwe Joint Permanent Commission (Mhlanga and Mhlanga, 2014), should be fully implemented.
- The two organizations established under the terms of the protocol – the Joint Fisheries Management Committee (decision-making) and the Joint Fisheries Technical Committee (scientific/technical) – should be revived and given powers, and provided with the resources to manage the fishery more effectively.

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Chapter 5

Adaptive management of the invasive species *Arapaima gigas* (Osteoglossiformes) in the Bolivian Amazon

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SUMMARY

Commercial fisheries in the Bolivian Amazon are artisanal, multispecies, and form part of diversified livelihoods. In the lower basin of the Madre de Dios and Beni rivers, fisheries have changed drastically in recent decades due to a range of factors including improved access, changing market demands, and the invasion of the paiche fish *Arapaima gigas*, an osteoglossiform species introduced from Peru. Paiche is now also invading the upper stretches of these rivers, as well as the Iténez and Mamoré river drainage basins. The various stakeholders concerned have responded in different but complementary ways to the arrival of this new resource. A new value chain has emerged and evolved, bringing paiche meat by air and land to exclusive markets in the larger cities (La Paz, Cochabamba, Santa Cruz). Paiche is not consumed much locally, whereas the income from its sale helps to sustain mixed livelihood activities and improve resilience to climate variability. The skin is used in the tanning industry, pre-tanned leather being exported mainly to Central America. There is an ongoing discussion as to whether paiche should be adopted as "native", or if efforts to control and prevent its spread should be increased. While eradication is likely impossible at this point, given paiche's extent and pervasiveness, some control may be possible by promoting human consumption and prohibiting paiche farming to avoid secondary introductions or accelerated expansion – these are the main strategies adopted by the government. Environmental authorities play a dominant role in this approach, but regulations are contradictory and enforcement is weak. A recent study predicts an increase in paiche production in the recently invaded Mamoré and Iténez river drainage basins, which may lead to the emergence of new regional value chains – and associated with this, may exacerbate existing social conflicts related to resource access. A national policy, effective enforcement and environmental assessments are urgently needed to reduce the negative impacts of this invader on native species and the subsistence fisheries which rely on them.

1. FISHERY CONTEXT

Bolivian Amazon commercial fisheries are low in volume overall, with total annual production estimated at 3 400 tonnes, mostly destined for national consumption (Van Damme *et al.,* 2011). Fisheries resources are exploited in the main river channels, tributaries and oxbow lakes of the Beni and Mamoré whitewater river basins, and to a lesser degree in the Iténez River, which is an international river shared with Brazil. The types of fishing gear used are mostly passive – gillnets, hooks (attached to longlines and to floating devices) and, to a lesser extent, drift nets – as well as occasionally active in the form of cast nets. The main fish resources belong to two groups: Siluriformes (catfish or "bagres") and Characiformes (*Colossoma macropomum* and *Piaractus brachypomus* being the main species). Fisheries are multispecies and are focused mainly on the larger-bodied migratory species, although recently some medium-sized species such as the scavenging *Calophysus macropterus* and the detritivore *Prochilodus nigricans* are becoming popular as a consequence of increasing market demand (Van Damme *et al*., 2023). Many of these fisheries in the area of the upper Madeira River drainage basin exploit migrating fish seasonally during their annual spawning and/or food migration. This seasonality is one of the reasons why both urban-based and rural indigenous fisheries in the region are characterized by a low degree of specialization and form part of diversified livelihood strategies. Urban-based fisheries are mostly boats travelling up and down the main rivers and entering into tributaries and lakes. Indigenous commercial fisheries operate from rural community bases (fishing in "community-managed" shallow lakes within indigenous territories) from where fish is transported to the nearby town (mostly Riberalta) by motorcycle or trucks, or is sold to commercial fishers on boats.

Although the fisheries sector has not been fully mapped and studied, it is estimated that 10 000 people are involved in the fish value chain (including those who are involved directly or indirectly, permanently or seasonally/occasionally, and in pre- and post-harvest activities) (Van Damme *et al.,* 2011). While very little data is available on subsistence fisheries, it is thought that they involve many more fishers overall, and several studies have found that they are a key contributor to household food security and nutrition, especially in Native Indigenous Peasant Territories (Territorios Indigenas Originarios Campesinos, TIOCs) in the region (Baker-French, 2013; Macnaughton *et al*., 2017; Montellano *et al*., 2017). These subsistence fisheries mainly exploit diverse and all-size fish resources in floodplain (oxbow/meandric) lakes, where interactions and conflicts with commercial fishers are commonplace.

Aquaculture has long played a marginal role in fish production, but over the last two decades it has emerged as a viable livelihood option in the central region of the Bolivian Amazon (upper Mamore River drainage basin). Small-scale farmers are growing almost exclusively hybrids of tambaqui (*Piaractus brachypomus*) and pacu (*Colossoma macropomum)* in earthen ponds, and selling them in local or urban markets. However, some farmers occasionally try out other species, such as sábalo (*Prochilodus nigricans)*, surubí (*Pseudoplatystoma* spp.) or paiche (*Arapaima gigas)*, but these are only used for local consumption (Zubieta *et al.,* 2023). Although still incipient, local interest in intensifying the farming of catfish species and paiche is growing.

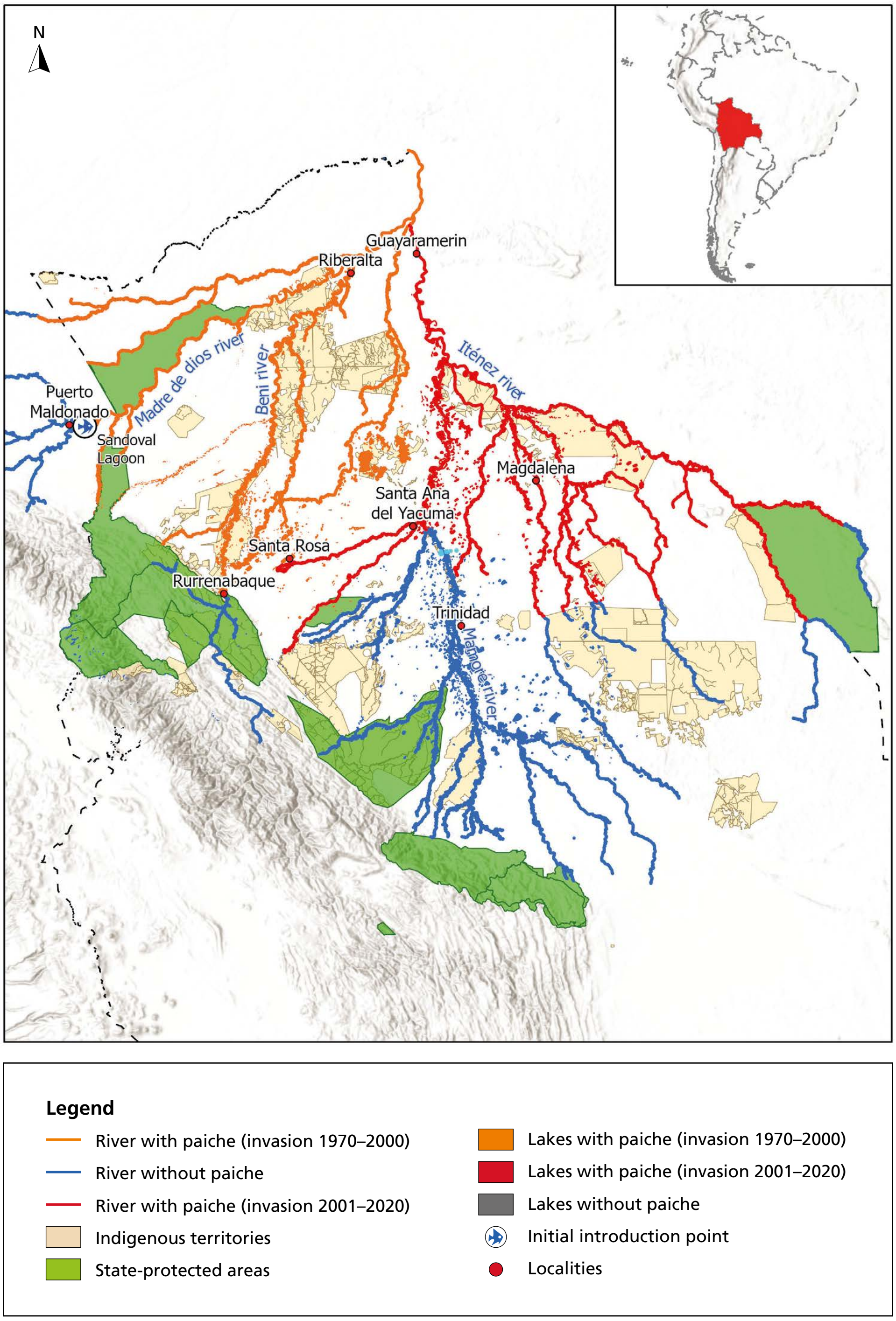
2. HISTORY AND IMPACTS OF PAICHE ON LOCAL FISHERIES AND ECOSYSTEMS

Paiche is one of the world's largest scaled freshwater fish. It has an omnivorous to carnivorous diet (Villafán *et al.,* 2017; Rejas *et al*., 2023), and reaches a length of 4 m and a weight of 200 kg (Castello, 2004; Castello *et al.,* 2011). Native to the Amazon Basin outside Bolivia, it dwells in slow-flowing rivers and floodplain lakes. It is considered a "perfect invader" in Bolivia due to a combination of biological characteristics such as nesting, parental care, fast growth (Carvajal-Vallejos *et al.,* 2017) and high colonization ability (Castello, 2008).

Paiche individuals were introduced into the southern Peruvian Amazon (upper Madre de Dios drainage basin), where they are non-native, in the framework of a governmental aquaculture programme in the late 1960s (Miranda-Chumacero *et al*., 2012). After an accidental escape, a small number of individuals swam downstream and invaded the lower Madre de Dios River in Bolivia in the early 1980s (Carvajal-Vallejos *et al.,* 2011; Macnaughton *et al.,* 2015; Van Damme *et al*., 2015; Carvajal-Vallejos *et al*., 2017). The species soon colonized all available habitats in the lower Beni and Madre de Dios River drainage basins, where it came to dominate landings in a relatively short period of time after it was first recorded in a commercial catch in 2001 (Farell and Azurduy, 2006; Carvajal-Vallejos *et al.*, 2011). More recently, the paiche invasion has expanded towards the llanos de Moxos (Moxos lowlands), a vast floodplain of between 100 000 and 140 000 km^2 intersected by river tributaries, streams and oxbow lakes, located in the middle and lower Mamoré River drainage basin (Carvajal-Vallejos *et al.* 2017). The species has now expanded all the way to the headwaters of the Mamoré River, reflecting the fact that fishers lack adequate methods to catch it efficiently (Van Damme *et al.*, 2015). Paiche has also recently been reported in the Iténez River drainage basin (Lizarro *et al*., 2017; Carvajal-Vallejos *et al.,* 2017) (see Figure 1).

Based on historical data obtained for the Madre de Dios and Beni River basins, the speed of the invasion was initially calculated at 30–32 km of river per year (Van Damme *et al*., 2015; Carvajal-Vallejos *et al*., 2017). However, the invasion speed seems to be much higher in the Iténez basin, probably due to the predominance of clearwater slow-flowing rivers. According to recent reports, the species has colonized even the most remote headwaters in this basin in a very short period of time (Van Damme, unpublished information). Van Damme *et al.* (2015) put forward the hypothesis that the expansion of paiche towards the Mamoré headwaters may have been slowed down by the high turbidity of the river channel. Altitude and the absence of a natural floodplain may act as natural barriers in the headwaters. In this same area, cold shocks caused by southern winds can cause multi-decade fish mortality, both in aquaculture and in natural aquatic environments (Petheric, 2010). These shocks may also affect paiche, which is cold-sensitive and does not tolerate water temperatures below 16 °C (Lawson *et al*. 2015), but the impact of this type of rare climatic event on paiche colonization is not yet fully understood and requires further study (Van Damme *et al.*, 2015). On the other hand, a rise in mean water temperature as a consequence of climate change is to be expected in the coming decades, favouring paiche and possibly allowing it to expand its distribution range further south (Oberdorff *et al*., 2015). Invasion speed is probably also affected by other undocumented factors such as secondary introductions, with individuals originating from fish culture and translocations in the Brazilian part of the Iténez River basin (Sousa *et al*., 2022; Santos Catâneo *et al.,* 2022). Fish may also occasionally escape from fish ponds in the Mamoré River drainage basin in Bolivia, where paiche fingerlings are occasionally stocked (Zubieta *et al*., 2023). Given this scenario, it is difficult to fully separate the role of the different factors driving paiche expansion.

FIGURE 1
Map of the paiche invasion in the Bolivian Amazon



Source: Authors' own elaboration based on published data and personal observations.

FIGURE 2
Experimental paiche fishing in the Manuripi Wildlife Reserve

3. ADAPTIVE RESPONSES

Management responses – government

National authorities have been slow in proposing management strategies for the invasive paiche. Some 35 years after the initial introduction of the species, the environmental authorities (Ministerio de Medio Ambiente y Agua – Ministry of Environment and Water) enacted two specific regulations for paiche control. The first one – Administrative Resolution No 13/2015, enacted by the Viceministerio de Medio Ambiente, Biodiversidad y Cambio Climático (Vice Ministry of Environment, Biodiversity and Climate Change) – introduced paiche control as a means of protecting native fish fauna. It forbids juvenile fish (whether originating from aquaculture or capture) to be stocked in rivers, and promotes the involvement of Indigenous communities in species control by capture. It also allows for the possibility of reaching foreign markets with meat products. A second regulation – enacted by the División de Áreas Protegidas (Division of Protected Areas) of the same Ministry (Administrative Resolution No. 060/2017) – specifies procedures for the control of paiche within protected areas. Following this resolution, a first management plan aimed at controlling paiche in the Reserva Nacional de Vida Silvestre Amazónica Manuripi (Manuripi Wildlife Reserve) (see Figure 2) was drafted and approved through Administrative Resolution No. RA06/2020. All these regulations rely heavily on commercial fishing as the principal tool for the control of the species. Supreme Decree No. 3048 (2017), approving the procedures for exporting paiche meat and leather, further helped to develop the value chain. A recent Supreme Decree (No. 3856) enacted by the national Environmental Authority forbids the farming of paiche.

Meanwhile, also in 2017, the Ministerio de Desarrollo Rural y Tierras (Ministry of Rural Development and Lands), which is officially in charge of the fisheries and aquaculture sectors, promoted the approval of the first ever Ley de Pesca y Acuicultura

Sustentables (Sustainable Fisheries and Aquaculture Law) No. 938. This law does not include specific regulations on the control of invasive species. The Ministry has not declared a formal position on paiche control or management, and its farming is de facto promoted. However, paiche farming is so far only being tried out in some isolated ponds.

Fishery response/adaptations and changes in value-chains

Two decades after its initial introduction, paiche became the main target species in the urban-based commercial fisheries in the Beni and Madre de Dios river drainage basins. Fishers shifted from fishing for native species in river channels and oxbow lakes to the capture of paiche inhabiting the same lakes, often illegally entering lakes in TIOCs, or paying access fees to the indigenous peoples who hold the property rights. The landings of these commercial fisheries in Riberalta in 2011 consisted of 70 percent paiche and 30 percent native species. Some Indigenous communities located close to Riberalta also shifted their fishing to paiche, and used improved road access to transport paiche meat to town. Indigenous communities further from the markets only occasionally capture paiche, and their focus remains primarily on native species for local consumption. In 2011 20 percent of the landings of Indigenous commercial fisheries consisted of paiche, while 80 percent were native fish sold in local markets (mainly Riberalta) (Rico Lopez *et al*., 2023). Thus, commercial and indigenous fisheries take advantage of the abundance of this invasive species in different but complementary ways, in some cases avoiding conflicts by partitioning the fish catch and supplying different urban or local markets (Rico Lopez *et al*., 2023). In other cases, the conflict is somewhat mitigated by a user-pays system, where commercial fishers pay for temporary access rights to the lakes. Notably, many indigenous fishers say they would like to fish paiche, but they lack adequate gear and resources to do so (Macnaughton *et al*., 2017) – this means access to paiche fishing is unequally distributed, as are the benefits.

The arrival of paiche coincided with changing access rules which gradually granted more rights to indigenous people, increasing fish market demands, and improved roads. Within this enabling context, paiche fishing has become part of a diversified livelihood strategy for many Indigenous communities (Macnaughton *et al.,* 2017; Montellano *et al*., 2017). Conflicts between Indigenous communities and commercial fishers or merchants have in some cases been resolved, securing exclusive access for indigenous communities and community organizations (Macnaughton *et al.,* 2015). Conversely, conflicts have emerged as a result of uncoordinated agreements to fix the price of a kilogram of meat, and this became a negative factor that destabilized relationships between stakeholders.

In the Mamoré River, paiche recently appeared in commercial fish landings in Santa Ana de Yacuma, in the heart of the Llanos de Moxos lowlands (Coca Méndez *et al.,* 2022). The oxbow lakes in the Mamoré River basin occupy a surface area of 4 409 km^2, nine times the lake surface of the well-studied area in the Beni and Madre de Dios drainage basins, and thus have a potentially high paiche production capacity (Rico Lopez *et al.,* 2023) which may give rise to a fisheries boom in the next decade. Also, the main markets for paiche meat in big cities (i.e. Santa Cruz, La Paz, Cochabamba) are closer to landing ports in the Mamoré River drainage basin than Riberalta in the north of Bolivia, and this reduces transportation costs and increases the market value. Finally, in the Iténez River basin, paiche is captured as far as the middle stretches of the Paraguá, Blanco and San Martin rivers. Fishing pressure here is low and value chains are underdeveloped, which provides the ideal conditions for further and faster expansion of the species.

The fishing industry has reacted swiftly and effectively to the appearance of paiche (Rico Lopez *et al.,* 2023). In the course of a single decade (2000–2010) an entire new value chain was created, with bank support enabling merchants to upscale their enterprises and transport paiche meat by air and terrestrial public transport to the larger urban markets in the cities of La Paz, Cochabamba and Santa Cruz. Paiche meat is now sold as a luxury product in restaurants, supermarkets and local markets, at a price of around USD 6–7/kg (Navia *et* *al*., 2017). Various studies have identified a growing demand for fish meat in urban centres, and promotional campaigns to increase consumption have been organized (e.g. "Hoy día se come paiche!" or "Today one eats paiche!"; FAUNAGUA-MIGA-ACEAA-CA, 2021).

Paiche is now commercialized and consumed in large cities (La Paz, Cochabamba and Santa Cruz), and this trend is actively promoted as a control mechanism by non-governmental environmental organizations. On the other hand, the species is not typically consumed locally due to taste preferences and its high market value (Macnaughton *et al*., 2015). It has created a new value chain, which has resulted in new economic benefits for certain social groups, but it may in the longer term negatively impact subsistence fisheries and leave some groups excluded or with more limited access to its benefits (Macnaughton *et al*., 2017). Problematic issues are likely to include differences in distance and road access between communities and markets, the gear and expertise needed to start paiche fishing (including a means of transport to market such as motorcycle, truck or boat), equitable agreements with commercial fishers, fair market prices, and more.

The use of the skin of paiche and its transformation to leather, initiated as part of a development project in the mid-2010s (www.pecesvida.org), brought additional value-added opportunities to the region (Navia *et al*., 2017). The introduction of best practices for skin preparation (Faunagua-ACEAA-CA, 2020) brought an increase in product quality and a higher sale price, generating more economic benefit for tanning businesses as well as the fishers involved. Skins from approximately 40 percent of individuals caught are now bought by domestic tanneries, and the pre-tanned fish leather ("wet blue") is exported, mostly to Mexico, for the manufacture of high-quality leather products prized in exclusive markets. A very low percentage of the fish skins are tanned and transformed into leather goods for local markets. Paiche leather has replaced caiman (*Caiman yacare*) leather: this had provided a substantial income for some TIOCs in the region over the past 20 years, within the framework of the CITES-endorsed Program for Sustainable Use of Yacare Caiman, but the caiman leather markets collapsed due to decreasing international demand.

FIGURE 3
Paiche landed

4. OUTCOMES

The lack of a national policy for the management and control of invasive species in Bolivia is a key challenge. Resolutions enacted by environmental authorities to date have not been effective in managing the paiche invasion, and contrasting policies from different ministries have impeded species control. In contrast with other aquatic species introduced in Bolivia (e.g. trout, tilapia), paiche is an Amazonian species, and there is no clearcut vision on how to deal with it – either by "nationalizing" it (i.e. adopting it as a native species and then managing it in a similar manner to other fisheries) or by increasing efforts to control it (as an invasive species that negatively impacts native species). Some non-governmental organizations have highlighted the problems caused by the invasive species and have made limited attempts to support species control locally, especially in protected areas. However, these local efforts have not been effective: they have not been framed within a national strategy, and they have lacked adequate financial resources for implementation. Prohibitions on cultivating paiche and introducing juveniles into natural water bodies were enacted belatedly, after several fish culture units had already begun stocking paiche and escapes to natural water bodies had already occurred, especially in inundation-prone areas of the upper Mamoré River basin. At the time of writing, the prohibitions on transporting paiche fingerlings and on cultivating the species in fishponds are not being enforced. A study conducted in 2015 showed that paiche was present in fish culture units in the upper Mamoré river drainage basin (Zubieta *et al.,* 2023).

Meanwhile, paiche has become a key target for commercial fisheries all over the Bolivian Amazon. Estimated total paiche production was 700 ton in 2011, roughly 20 percent of total fish landings in the region at that time (Navia *et al.,* 2017; Rico Lopez *et al.,* 2023), but present-day market volumes may be twice as high. Paiche landings in the Beni and Madre de Dios basins seem to have stabilized at around 1 000 ton/year (see Figure 3), and so far there are no signs of severe overfishing. The species is also increasingly featuring in landings data in the fisheries of the Iténez basin. This basin seems to have a huge number of adult paiche which are not intensively fished, but quantitative estimates are lacking. In the Mamoré basin the species has reached the Yacuma River, where its contribution to fish catches is increasing yearly. Rico Lopez *et al*. (2012), based on a calculation of floodplain surface area, estimated potential paiche production in the Mamoré basin to be 12 times higher than in the Beni and Madre de Dios river drainage basins (approximately 12 000 tonnes).

Paiche has become an important product for consumption, but the species is suspected to be significantly impacting local ecosystems and native fish fauna (Carvajal-Vallejos *et al*., 2011; Miranda-Chumacero *et al*., 2012; Macnaughton *et al.,* 2015). Many local testimonies along the Madre de Dios and Beni river drainage basins suggest that subsistence fisheries are being negatively impacted by paiche (Montellano *et al.,* 2017), but these collateral effects have not been well studied. Ecosystem impacts may be highly significant in the clearwater Iténez River basin, due to its extreme vulnerability to human disturbance (Van Damme *et al*., 2012).

The accidental introduction of paiche, its expansion and its increasing role in commercial fisheries may have contributed to the alleviation of poverty and the improvement of food security for some rural communities. However it is difficult to separate this contribution and its associated challenges from the many other shocks, stressors and rapid changes in the region, including improving telecommunications, internet access, road transport networks, rural/urban connectivity, rapidly growing urban populations, increasing intensity and frequency of seasonal flooding and drought (associated with climate change), the COVID-19 pandemic and associated restrictions and impacts on health, and more. In the northern Bolivian Amazon, many commercial fishers (with the exception of a few who act as both boat owners and fish distributors) are hampered by a debt peonage system which makes them highly dependent on credits provided by fish distributors and other middlemen (Rico Lopez *et al*., 2023). Moreover, paiche meat has not been incorporated in the local diet due to taste preferences and the fact that the species has a high value on external markets (Montellano *et al*., 2017). Despite high levels of participation in subsistence (year-round) and seasonal commercial fishing, the income generated through fishing, and specifically through paiche, is secondary to other sources of income (e.g. the Brazil nut harvest, agriculture) for many indigenous communities in the region (Macnaughton *et al*., 2017). Paiche's contribution is highly seasonal, occurring generally after the Brazil nut season, when the rainy season has ended and floodwaters are receding. The additional income generated by paiche is used to invest in dwelling improvements, to purchase goods including inputs for smallholder farming, and for education and health (Macnaughton *et al.,* 2017). Women play an important role in the paiche value chain (see Figure 4). However, the highest proportion of profit from paiche fishing goes to the end points in the value chain, which is also where the lowest levels of risk are assumed.

5. CHALLENGES

The country faces numerous challenges in addressing the impacts caused by paiche on ecosystems and value chains. Bolivia possesses an extraordinary aquatic biodiversity, with at least 800 fish species known to science (Carvajal-Vallejos *et al*., 2014) and many more still to be described. This diversity supports local livelihoods, and the state should act to secure subsistence fisheries which are entirely focused on native fish species. Invasive species such as paiche, through their negative impacts on ecosystems, may harm native fish species and affect subsistence fisheries. The state has the obligation to take measures to protect subsistence fisheries and fisheries-based livelihoods, but it faces many practical difficulties in doing so. Invasive species were not considered a problem by governmental authorities until 2007, when the Vice Ministry of Environment, Biodiversity and Climate Change organized the Biological Invasions, I3N-IABIN Invasive Information Network workshop, which underlined the need to update

FIGURE 4
Women play an important role in the paiche value chain

information on biological invasions in Bolivia and to develop plans and strategies for their management and control (Tejada *et al*., 2021). However, these recommendations were never taken up at decision-making levels, and strategies for controlling invaders are still pending. So far governmental control of invasive species has been ineffective due to various legal and political impediments. The considerable time lag between the formulation of an environmental policy and its real-world application has meant that regulations have already been outdated by the time they have been legally approved or implemented. Moreover, conflicting approaches from different ministries have made control inefficient or completely non-existent, reflecting the lack of coordination and the absence of a national policy on invasive species. The first paiche management plan approved by the national authorities (in the Manuripi Wildlife Reserve) was not put into practice, owing to a lack of financial resources and access restrictions during the COVID-19 pandemic.

Although paiche is very vulnerable to overfishing and extinction in its original distribution range (Castillo *et al.,* 2017), it is widely recognized that its extermination in the Bolivian Amazon is an unrealistic goal, both logistically and socially. The species has now invaded remote areas where fishing is not intensively practised and where source populations thrive, and from where recolonization can easily occur during the high-water season (Castello, 2011). Commercial participants in established value chains would also strongly reject efforts to completely exterminate paiche.

There is a tremendous lack of knowledge on the impacts of paiche on native species in the Bolivian Amazon. Studies on ecosystem impacts are lacking due to methodological issues and the lack of baseline studies (see Miranda-Chumacero *et al*., 2012). It should therefore be an academic priority to find conclusive evidence of ecosystem impacts, which could then be used to inform management policies. Academic capacity is in place, but there is a total lack of financial resources for scientific follow-up of the invasion process. Additionally, available resources generally come from external sources and are often dedicated to funding isolated studies, usually conducted by non-Bolivians, as opposed to providing stable funding to promote Bolivian excellence and future professionals in this field.

The most appropriate approach in the Bolivian context – and the one that is currently being promoted by the Ministry of Water and Environment – is population control in areas which harbour the highest diversity of native fish species, especially protected areas. Commercial capture for the meat market and human consumption is considered by many as the only realistic strategy to effectively control paiche and reduce its impacts on native biota (Miranda-Chumacero *et al*., 2012); this is also the strategy adopted in the management plan for the Manuripi Wildlife Reserve. However, the efficiency of a fishery-based control for native species conservation has not been tested and is not guaranteed, and there are several difficulties involved in promoting selective paiche fishing. Nevertheless, controlling this invader by promoting human consumption remains the main feasible strategy to reduce its environmental impacts, notwithstanding the many challenges involved (Nuñez *et al.,* 2012).

The use of paiche in both fisheries and aquaculture makes its management extremely complex. Indeed, it has been shown that escapes of individual paiche from fish farms leads to secondary introductions, which may accelerate the invasion process in remote areas. The regulation of the use of paiche in aquaculture is a major challenge, made difficult by the dispersed nature of the activity and the lack of monitoring systems or enforcement.

The introduced paiche presents both new opportunities and new challenges to local fishing communities, and may influence their well-being and resilience. Fisheries in remote river drainage basins are slow to respond to the invader due to a lack of adequate fishing techniques, a lack of financial resources to buy fishing gears, and the great distance to the main markets. Current capture strategies and management mechanisms may not be conducive to sustainability or equitable distribution of returns. Indeed, the unequal distribution of benefits from the paiche fishery is one of the key challenges to resolve. Paiche is a revenue generator for only a few, even though it is considered a communal resource. Trinidacito (Madre de Dios drainage basin) is the only community within the TCO TIM II with established local norms regulating fishing activity, including specific rules for the exploitation of paiche. In this locality, gillnets are officially prohibited, but are still used (Macnaughton *et al*., 2017).

Management of introduced species to maximize equitable social benefit and minimize environmental damage is a topical concern. Introduced species are considered to be one of the prime factors that contribute to the decline of native species and cause significant negative impacts on fishery-related livelihoods. However, introduced species can also present new, economically valuable resources.

FIGURE 5
Introduction of best practices along the value chain

6. LESSON LEARNED AND KEY RECOMMENDATIONS

The eradication of paiche from the Bolivian Amazon would be an unrealistic goal logistically. Key recommendations for its control and adaptive management are:

1. Take into account socioeconomic factors.
2. Develop and implement national and regional policies that address the paiche as a priority environmental problem, in line with the Convention on Biological Diversity (CBD) which states that each party should "…control or eradicate those alien species which threaten ecosystems, habitats and species."
3. Establish national databases with updated information on the paiche invasion and integrate them with regional (Doria *et al*., 2022) and global databases, such as the GBIF and GEO BON, and reporting mechanisms such as iMapInvasives, iNaturalist and ICTIO (Tejada *et al.,* 2021), which are used in global targets such as the CBD.
4. Prioritize investment in providing stable support to Bolivian expertise by establishing centres of excellence for fisheries research. In this context, conduct research on the ecological and socioeconomic impacts of paiche, with a particular and urgent focus on native fish species and subsistence fisheries. Priority should be given to the most sensitive ecosystem, i.e. the Iténez River basin (Van Damme *et al*., 2017). A systematic screening of local perceptions might provide additional input to inform policy-building.
5. Plan and implement control and management activities for paiche in protected areas, where pristine assemblages of native species should be protected from the negative impacts of the invasion.
6. Introduce monitoring, registration and environmental licensing of aquaculture enterprises by means of a publicly accessible official register; design specific regulations for its use including enforcement mechanisms and sanctions for non-compliance.
7. Begin fisheries monitoring to understand the front of invasion and reveal the relationship dynamics among stakeholders that influence the supply and demand of paiche meat.
8. Explore alternative models for using the paiche as a secondary source of income in Indigenous communities; calculate the potential costs and benefits under different scenarios in which it is a potential source of physical and financial assets. Given the limitations that exist – access, connection to markets, resource abundance, and minimum sustainable price – communities that already meet conditions for paiche fishing should be prioritized. Organization should be strengthened, and changes that are necessary and possible within the fishing regulations should be made. A programme that helps reduce the loss of fish meat as a result of supply chain inefficiencies is recommended.
9. It is advisable to work with all the participants in the value chain (see Figure 5), optimizing the commercialization of the product and aiming for a more equitable redistribution of the profits.
10. Promote paiche fishing and human consumption of paiche meat both locally and regionally, since for now this is the only control strategy currently available.
11. The introduction of best practices for skin preparation (Faunagua-ACEAA-CA, 2020) provided an important support to the development of the tanning sector (see Figure 6). The use of paiche skin in the Amazon region should be promoted through the creation of tanning microenterprises, which as well as generating employment opportunities and income, and increasing the added value of the fishing resource, will provide more motivation for increased capture of the invasive species.
12. Promote a dialogue between traders and fishers in order to optimize paiche profits and value chains from different main fish landing sites – these are currently competing with each other.

FIGURE 6
Paiche skin is an important by-product which adds value to the resource

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Chapter 6

Non-indigenous African catfish *Clarias gariepinus* (Burchell 1822) and common carp *Cyprinus carpio* (L.) in India: invasion risks and management strategies

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SUMMARY

The introduction of non-indigenous species (NIS) can have significant ecological and economic impacts. Two are discussed in this chapter: the African catfish, *Clarias gariepinus*, and common carp, *Cyprinus carpio*, which were introduced to India in 1994 and 1939 respectively for aquaculture purposes. The farming of *C. gariepinus* is discouraged by government institutions due to environmental and ecological concerns; *C. carpio* is preferred and has economic importance. High growth rates, efficient utilization of a variety of cheap feeds including slaughterhouse and chicken wastes, and low management input attracted farmers all over the country to raise African catfish. Similarly, common carp introduced for aquaculture is now well acclimatized to inland waters and is present throughout the country. After their initial introductions, these NIS have escaped into rivers, streams, lakes, reservoirs, and even into backwaters and coastal areas, where they have established invasive populations which threaten native fish biodiversity and ecosystems. Gut content examination of escaped African catfish reveals the presence of fish, molluscs, insects, detritus and crustaceans. The risk of African catfish becoming established in the wild has been assessed and has been found to pose a high level of threat to fish biodiversity; while *C. carpio* has been shown to pose moderate risks to ecosystems. However, increasing trends of invasion and dispersal have raised several concerns about their management, as the invaders potentially threaten native species which have significant economic and social value for local communities who fish for them. Management strategies, such as monitoring risks and careful assessment of potential impacts, are in place to protect native aquatic ecosystems and the socioeconomic conditions of the fisherfolk. Nevertheless, a range of difficulties and challenges – such as changing temperatures, rainfall, and weather conditions under climate change – are crucial, since they do nothing to limit the expansion of introduced African catfish and common carp. Existing regulatory frameworks and guidelines do not appear to do enough to make fisherfolk and other stakeholders respond adequately to the situation. Therefore, effective monitoring, stringent enforcement of regulations, and awareness-raising campaigns are needed to mitigate the adverse ecological impacts of *C. gariepinus* and *C. carpio* and protect native species fisheries and socioeconomic conditions. There is a need for continued collaboration and communication between researchers, managers and institutions to develop a national management strategy to support inland fisheries.

1. FISHERY CONTEXT OF NIS *CLARIAS GARIEPINUS* AND *CYPRINUS CARPIO*

The African catfish (*Clarias gariepinus* Burchell 1822) is the largest non-indigenous clariid catfish, reaching up to 130 cm in length and 70 kg in weight (Tonguthai *et al.*, 1993; De Graaf and Janssen, 1996). It has severely threatened the existence of native *C. magur* and is particularly challenging to distinguish it from the native magur (Rainboth, 1996) especially during fingerling stage. Introduced *C. gariepinus* a native of the Niger, Nile, Limpopo, Orange Vaal, Okavango and Cuene river basins, is now widely farmed in several countries including India, Bangladesh, Nepal, Malaysia and China (Weyl *et al.*, 2016). It naturally inhabits calm waters such as lakes, rivers and floodplains (De Graaf and Janssen, 1996). African catfish is generally a nocturnal benthic feeder which occasionally feeds at the surface. It preys on live fish, reptiles, amphibians, macroinvertebrates, plant matter and plankton (Singh and Lakra, 2011; Singh *et al.*, 2015). Solitary feeding, social hunting, foraging behaviours and feeding migrations have also been reported (Willoughby and Tweddle, 1978). As the fish grows, its gill rakers increase both in length and number, thereby increasing its filter feeding efficiency (Rainboth, 1996). African catfish production is mainly practised in ponds, tanks and cement cisterns, utilizing slaughterhouse waste and chicken waste or other cheap feed. Intensive aquaculture of this non-indigenous catfish has been booming due to its fast growth and simple management requirements, providing employment opportunities for landless labourers and food security for the wider population. It is important to mention that aquaculture systems in India largely depend on natural waters and natural food chains, and hence become part of the aquatic environment and biodiversity. Raising African catfish for large-scale food production is primarily intended to generate economic profit: this has led stakeholders to seek diverse strategies to optimize fish production, even if they cause issues for biodiversity and the environment. African catfish have accessed reservoirs and lakes beside rivers such as the Ganga, the Yamuna, the Godavari, and many others including the backwaters of Kerala and coastal areas (Singh and Lakra, 2011; Krishnakumar *et al.*, 2011; Singh, 2014; Ranjan, 2018).

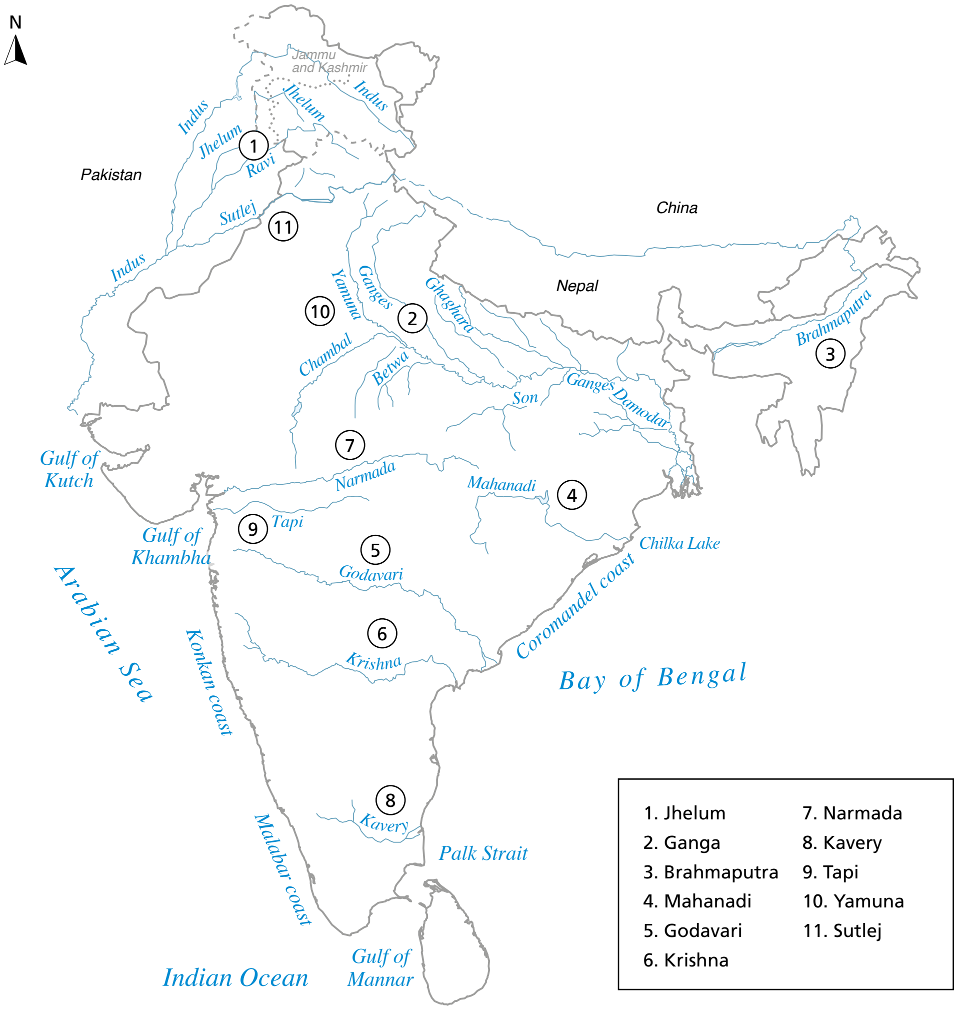
Common carp is one of the world's top ten aquaculture species (Subasinghe, 2017). The total annual production was 4.2 million tonnes in 2018 (FAO, 2020). Scale carp is commonly produced in ponds, lakes and reservoirs throughout India, while in the Himalayan region all three phenotypes of common carp – i.e. the mirror carp, leather and scale carp – are present (Sehgal, 1999). Induced breeding of the three varieties of *C. carpio* in controlled conditions is successfully practised, hence seed production for stocking is plentiful. Carp is largely produced as a food fish, yet its ornamental variant, koi, is also popular in aquariums, with more than 40 varieties available – these are very attractive, with distinct colouration and scale patterns (Jeney and Jian, 2009; Sahoo *et al.*, 2020).

Many years after the introduction of common carp, its performance in aquaculture began to deteriorate, leading to stunting, reduced growth, early maturity and precocious breeding (Basavaraju *et al.*, 2003). Stakeholders alerted scientists and policymakers, who decided to introduce improved species strains. The introduced Amur strain was found to grow 29.68 percent and 40.33 percent faster than local strains in mono and polyculture systems respectively. There was little difference in survival rates for the Amur and existing strains under monoculture (74.47 percent and 70.85 percent) and polyculture systems (74.16 percent and 75.30 percent). The Amur strain showed greater potential than existing strains in low-input aquaculture systems due to its better growth (Basavaraju *et al.*, 2003). There was 30 to 35 percent higher weight gain in the introduced "Ropsha scaly" and "Felsomogy mirror carp" during nursery rearing, and 40 to 50 percent higher weight gain during the grow-out phase, with a survival rate 80 to 82 percent higher than the existing common carp (Singh and Pandey, 2016).

The non-indigenous common carp (*Cyprinus carpio*) is now well adapted to a variety of aquatic environments, both in aquaculture and in the wild. It has a high economic value in both rural and urban markets (Das *et al.*, 2015) and a wide range of environmental tolerance (Das *et al.*, 2016). The production of common carp has been increasing steadily in India over the years, and it has become an important source of income for small and marginal farmers (Mohanty *et al.*, 2017). The status and prospects of carp aquaculture in India show its potential to contribute to food and nutritional security, poverty alleviation, and employment generation in rural areas. (Bhatta *et al.*, 2021). Overall, common carp has become an important species in Indian freshwater aquaculture, and it can contribute significantly to the aquaculture production. Today, it has found access to most of the aquatic areas where prized Indian major carp, a common name for resident carp species which are commercially important freshwater fish (*Catla catla*, *Labeo rohita* and *Cirrhinus mrigala*), as well as a cyprinid mahseer (*Tor putitora*) and snow trout (*Schizothorax richardsonii*) (Figure 1). Common carp is now widely present in rivers, lakes and reservoirs, with significant dominance over native Indian major carp species and catfish followed by small indigenous cyprinids (Sehgal, 1999; Singh and Lakra, 2011; Das *et al.*, 2023).

FIGURE 1

Map of India (8°4 0 to 37°6 0 North latitude and 68°7 0 to 97°25 0 East longitude) showing genetic resources of native Indian major carp, mahseer and snow trout where non-indigenous *Cyprinus carpio*, and to a lesser extent *Clarias gariepinus*, have found access



Notes: Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties (apply this to every other map, if there are any, that include Jammu and Kashmir.

Source: Modified after Reddy, P.V.G.K. 1999. Genetic resources of Indian major carps. FAO Fisheries Technical Paper No. 387. Rome, FAO.

2. HISTORY AND IMPACTS OF NIS AFRICAN CATFISH AND COMMON CARP ON LOCAL FISHERY AND ECOSYSTEMS

The African catfish (*Clarias gariepinus* Burchell 1822) was brought into India clandestinely in 1994 without prior official approval, and rapidly spread throughout the country (Singh and Lakra, 2011). Meanwhile, the introduction of common carp to India dates back to 1939 (Singh and Lakra, 2011), and today it is well acclimatized to inland waters. The latter fish has three main varieties in India: mirror carp (*Cyprinus carpio* var. *specularis*), scale carp (*C. carpio* var. *communis*) and leather carp (*C. carpio* var. *nudus*) (Hussain and Mazid, 2005). Mirror carp was introduced from Ceylon to the Nilgiris in 1939 then brought to Bangalore in 1947, while scale carp was introduced from Bangkok to Cuttack in 1957 (Alikunhi, 1966; Shetty *et al.*, 1989). Leather carp (*C. carpio* var. *nudus*) was first introduced in 1957 at the hatchery of the Central Inland Fisheries Research Institute (CIFRI) in Cuttack, Odisha state. The fish was then distributed to various fish farms and water bodies (De *et al.*, 2010; Singh and Lakra, 2011). More recently, Amur carp and improved Hungarian carp – the “Ropsha scaly” and “Felsomogy mirror carp” – were introduced for aquaculture, as is shown in Table 1.

TABLE 1
Introduction of common carp varieties and improved strains to India for aquaculture

Strain/variety of *Cyprinus carpio*	Source of introduction	Year of Introduction	References
Scale carp (*C. carpio* var. *communis*)	Sri Lanka	1939	Singh and Lakra, 2011
	Thailand	1957	
Mirror carp (*C. carpio* var. *specularis*)	Sri Lanka	1939	Singh and Lakra, 2011
	Thailand	1957	
Leather carp (*C. carpio* var. *nudus*)	Sri Lanka	1939	Singh and Lakra, 2011
	Thailand	1957	
Amur carp	Hungary	2003	Basavaraju *et al.*, 2003
Ropsha scaly	Hungary	2007	Singh and Pandey, 2016
Felsomogy mirror carp	Hungary	2007	Singh and Pandey, 2016

Source: see References for Table 1: Introduction of common carp varieties and improved strains to India for aquaculture, p. 108

In India, farmed African catfish and common carp have escaped into rivers, reservoirs and lakes, finding access to natural aquatic ecosystems and forming established populations (Lakra *et al.*, 2008; Singh *et al.*, 2010a,b; Singh, 2014; Singh *et al.*, 2021; Khan *et al.*, 2021; Sreekanth *et al.*, 2022). The common carp has invaded areas including the Himalaya (Sehgal, 1999; Petr and Swar, 1999; Singh and Lakra, 2011). Populations of mirror carp and leather carp have not been limited to upland waters, but have extended approximately 200 km downstream on the River Ganga (Singh and Lakra, 2011). Over the years, increased populations of African catfish and common carp have been negatively impacting catches of native fish species such as *Tor putitora*, snow trout (*Schizothorax richardsonii)* and native catfish (Sehgal, 1999; Petr and Swar,1999; Singh and Lakra, 2011; Singh *et al.*, 2013; Singh, 2021), and even prized Indian major carp (Singh and Lakra, 2006; Singh and Das, 2006; Lakra *et al.,* 2008; Singh *et al.*, 2010a,b; Singh *et al.*, 2013; Singh *et al.*, 2021; Das *et al.*, 2023). The invading common carp have been found to critically reduce numbers of the endemic fish species *Osteobrama belangiri* in Loktak Lake in Manipur (Singh and Lakra 2006; Singh and Lakra, 2011); while African catfish have also adversely impacted many endemic fish species (Ranjan, 2018). The non-indigenous common carp has significantly invaded the largest Ganga River system after 60 years of pond aquaculture, and contributes substantially to commercial catches (Singh *et al.*, 2010a,b; Singh *et al.*, 2013; Singh, 2014; Singh, 2021). Catches of common carp in the mid-stretch of the River Ganga have been increasing from 2010 onwards (Figure 1). A similar phenomenon has been found in the Yamuna River, where common carp dominates most commercial catches (Singh *et al.*, 2010b; Singh and Lakra, 2011; Singh *et al.*, 2014).

The adverse impacts of introduced African catfish and common carp on freshwater ecosystems have been reported worldwide, including India (Vitule *et al*., 2006; Weber and Brown, 2009; Singh and Lakra, 2011; Weber and Brown, 2011; Pascal *et al.*, 2011; Weyl *et al.,* 2016; Crichigno *et al.*, 2016; Tessema *et al.*, 2020; Singh *et al.*, 2021). Common carp is a hardy fish and can tolerate a wide variety of conditions (Weber and Brown, 2009). It usually favours large water bodies with slow-flowing or standing water with soft bottom sediments. Both the adults and juveniles feed on benthic organisms and plant material. Adults often undertake considerable spawning migrations to suitable backwaters and flooded meadows. The larvae survive in shallow areas with submerged vegetation. As a result, its invasive population has expanded under the impact of climate change, owing disturbed temperature and rainfall patterns in India (Singh and Srivastava, 2021).

Two decades after its introduction, the presence of African catfish of different sizes has been confirmed in 23 rivers and streams surveyed by the author in the state of Uttar Pradesh (Table 2). The largest (18.5 kg) was captured from the Hindon River near Meerut, and also from the Yamuna River in Agra district (Singh *et al.,* 2013b; Singh *et al.,* 2015). Fishers use different types of nets – namely gillnets, cast nets and dragnets – to catch African catfish in rivers, streams, reservoirs and lakes.

TABLE 2
Size distribution of *Clarias gariepinus* in different river streams of Uttar Pradesh

Sl No	Name of river stream	Size (kg) of African catfish captured
1	Ganga	0.1–3.5
2	Yamuna	0.05–2.8
3	Ghaghra	0.2–0.7
4	Hindon	0.1–18.5
5	Ram Ganga	0.2–0.6
6	Tamsa	0.1–0.8
7	Senger	0.1–2.5
8	Matiyari	0.2–1.5
9	Gerua	0.2–3
10	Gomti	0.1–1.8
11	Rapti	0.2–2.3
12	Ool	0.3–1
13	Sarayu	0.2–0.9
14	Kali	0.05–2.7
15	Dhasan	0.1–1.8
16	Varuna	0.15–2.5
17	Karmnasha	0.2–1.3
18	Rohini	0.2–1
19	Gandak	0.1–2.9
20	Khannot	0.2–1
21	Devha	0.2–1.8
22	Baigul	0.2–1.5
23	Nakatia	0.1–2

Collected observations of the gut contents of the wild-caught African catfish revealed the presence of six food items, of which a large proportion was fish, molluscs and crustaceans (Table 3). The high percentage of fish in the gut demonstrates the African catfish's piscivore and carnivory habits. It has been observed to withstand climatic and environmental extremes, and is showing continued expansion.

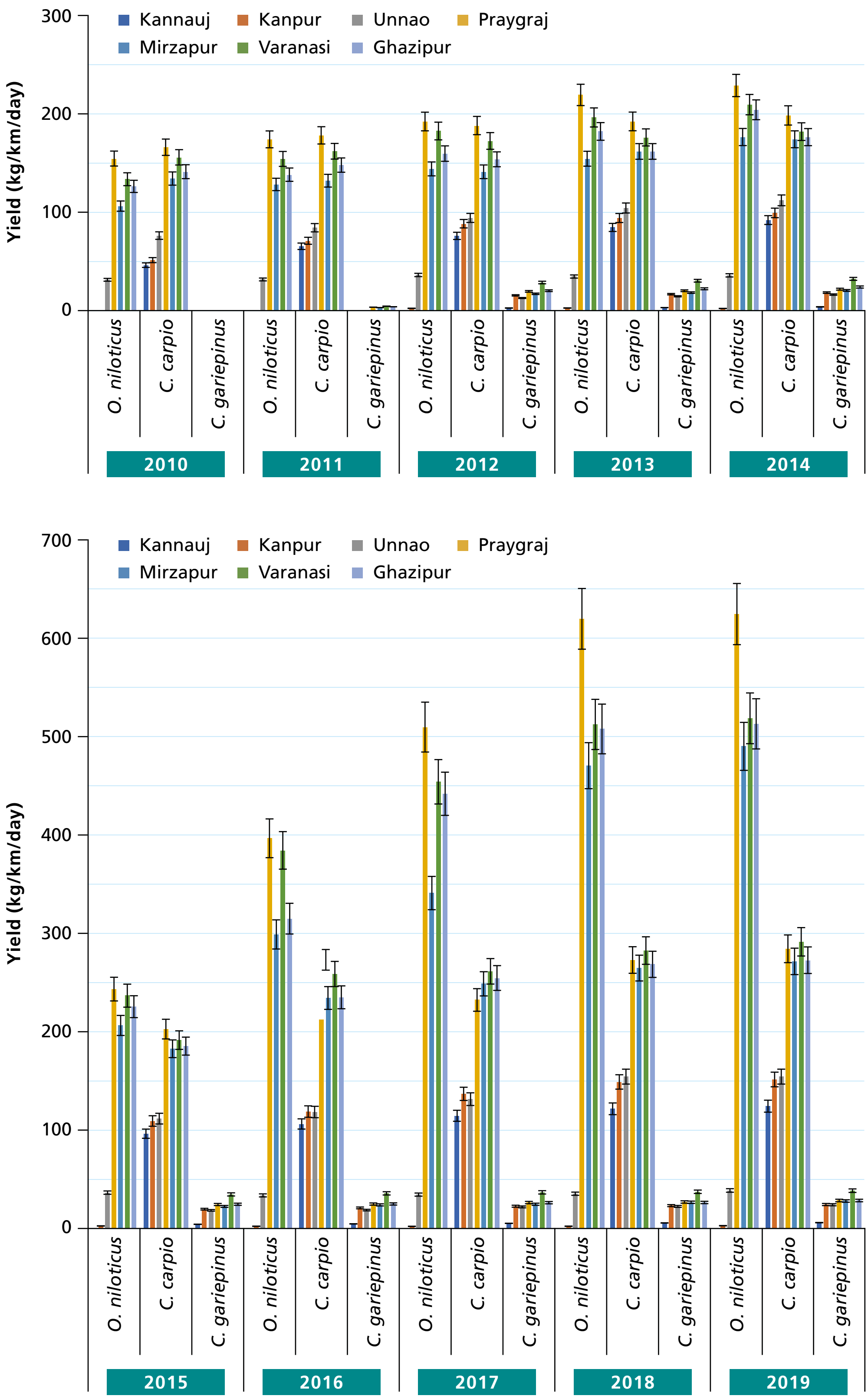
TABLE 3
Occurrences of major food items in the gut of wild-caught *C. gariepinus* from different river streams in Uttar Pradesh, India

Name of river stream	Food items observed in the gut (average percentage)					
	Detritus	Aquatic weeds	Insects	Fishes	Crustaceans	Molluscs
Ganga	16	15	10	24	20	15
Yamuna	19	20	15	27	11	8
Ghaghra	17	17	15	24	16	11
Hindon	19	18	16	26	13	8
Ram Ganga	19	14	12	25	21	9
Tamsa	17	16	14	18	18	12
Senger	18	13	16	28	15	10
Matiyari	19	14	15	29	15	8
Gerua	17	18	16	28	13	8
Gomti	19	21	18	28	9	5
Rapti	16	18	13	26	18	9
Ool	19	14	20	27	12	8
Sarayu	19	16	17	29	12	7
Kali	20	16	16	29	13	6
Dhasan	16	15	14	27	20	8
Varuna	17	16	17	28	13	9
Karmnasha	18	25	14	28	11	4
Rohini	17	19	21	28	9	6
Gandak	16	23	17	29	8	7
Khannot	17	26	16	27	9	5
Devha	16	22	20	26	11	5
Baigul	15	22	17	29	12	5
Nakatia	16	25	15	28	11	5

While *C. carpio* makes up a substantial amount of the catch in commercial fisheries, *C. gariepinus* makes up much less – yet its devastating impacts are much more significant than those of common carp. Recent catches observed in the mid-stream of the Ganga River have revealed a consistent increase year after year (Figure 2). Catches of non-native carp (*C. carpio*) contributed 47.46 percent to 58.38 percent during the study period, and *C. gariepinus* 1.52 percent to 8.4 percent (Singh and Srivastava, 2021). The yield of invasive common carp and African catfish was found to correlate with rainfall and temperature data, using analysis of variance (ANOVA): variance was $F=1.36$; $p=0.263$ for *C. carpio;*

FIGURE 2

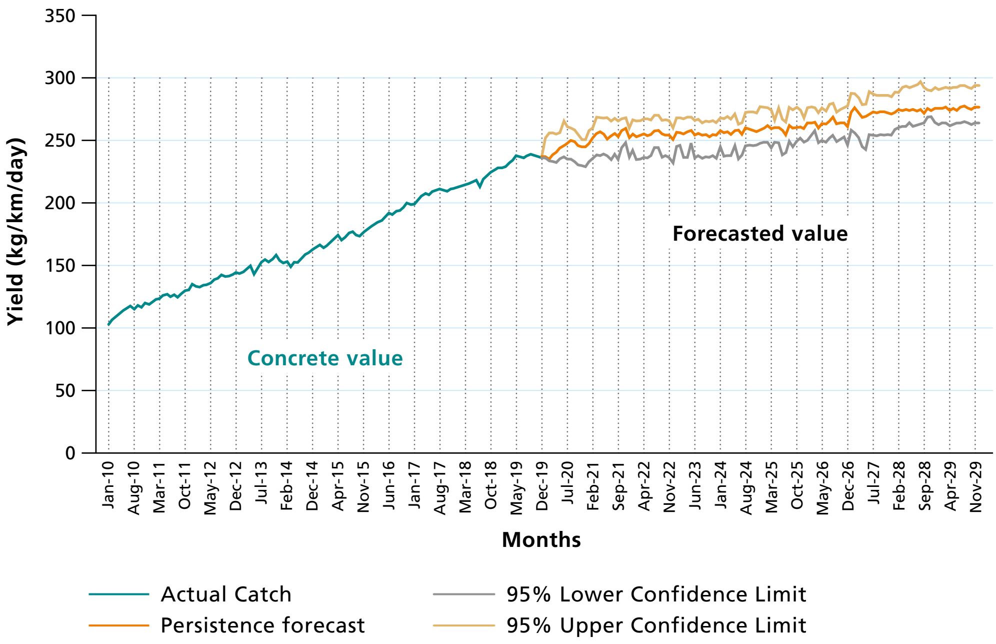
Fish yield of invasive common carp (*Cyprinus carpio*), African catfish (*Clarias gariepinus*) and tilapia (*Oreochromis niloticus*) in the mid-stretch of the Ganga River



Source: Singh, A.K., Ansari, A. & Srivastava, S.C. 2021. Morpho-meristics, maturity stages, GSI and gonadal hormone plasticity of African catfish *Clarias gariepinus* (Burchell 1822) that invaded into the Ganga River, India. *The Journal of Basic and Applied Zoology* 82: 30. https://doi.org/10.1186/s41936-021-00231-0 and F=1.63; p=0.101 for *C. gariepinus.* The calculated variance value was very close for common carp and African catfish, indicating that climatic changes will further impact dispersal and expansion of both NIS (Singh and Srivastava, 2021). The fish yield calculation based on mean abundance by weight (MAW) for *C. carpio* was found to consistently increase significantly (p<0.05) over the years from 2010 to 2019: the calculated yearly values were 113.65, 127.54, 139.08, 150.99, 158.67, 174.54, 192.22, 209.06, 219.92 and 235.83 kg per km per day (Figures 2 and 3). The biomass of invasive *C. gariepinus* was initially 2.41 ± 033 kg per km per day in 2011, increasing to 39.82 ± 2.4 kg per km per day in 2019. The predicted yield for 2029 was found to be 139.2 percent, which has increased since 2011 (Figure 4). The concrete and forecast values were significant (p<0.05), and the annual regression was p<0.499 for African catfish. The MAW-based forecast catch of non-indigenous African catfish and common carp for the period from 2020 to 2029 (at 95 percent confidence limit) indicates stable production in the Ganga River (Figures 3 and 4), even in 2029 showing a positive pattern of invasion meltdown i.e., increased invasibility via facilitative interactions between the two NIS (Singh and Srivastava, 2021).

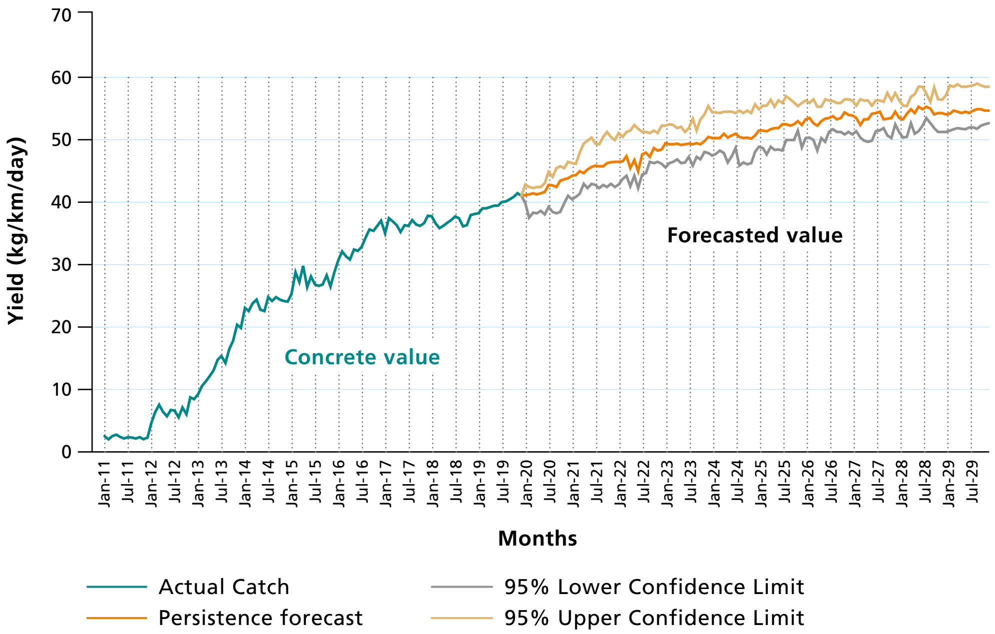
The spread of African catfish in natural aquatic ecosystems is associated with a high risk to fish biodiversity in general (Vitule *et al*., 2006; Singh and Lakra, 2011; Weyl *et al.,* 2016; Singh *et al.*, 2021) and to native *C. magur* in particular – this species has declined notably in recent years in India (Sahoo *et al*., 2003; Singh *et al.,* 2015; Ranjan *et al.,* 2018; Singh *et al*., 2021). The highly carnivorous *C. gariepinus* has been found to occur in all areas where local *C. magur* naturally exist. Further, *C. gariepinus* has the potential to hybridize with local *C. magur,* as has been proved in experimental trials in Bangladesh and also in India (Rahman *et al*., 1995; Sahoo *et al*., 2003) – this suggests the possibility of genetic pollution as escaped African catfish may interbreed with native magur in the wild. In the Western Ghats, a biodiversity hotspot, farmers raise *C. gariepinus* in preference to the endemic yellow catfish *Horabagrus brachysoma*, which has now critically declined due to the increased expansion of African catfish (Singh and Lakra,

FIGURE 3
Predicted invasion of common carp in the Ganga River to 2029, using a spatio-temporal population dynamics model



Source: Singh, A.K., Ansari, A. & Srivastava, S.C. 2021. Morpho-meristics, maturity stages, GSI and gonadal hormone plasticity of African catfish *Clarias gariepinus* (Burchell 1822) that invaded into the Ganga River, India. *The Journal of Basic and Applied Zoology* 82: 30. https://doi.org/10.1186/s41936-021-00231-0

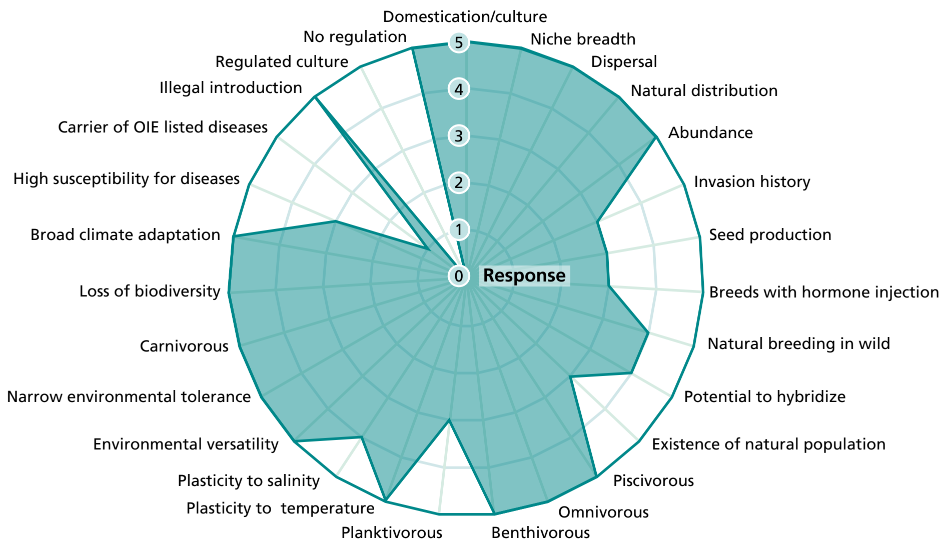
FIGURE 4
Predicted invasion of African catfish in the Ganga River to 2029, using a spatio-temporal population dynamics model



Source: Singh, A.K., Ansari, A. & Srivastava, S.C. 2021. Morpho-meristics, maturity stages, GSI and gonadal hormone plasticity of African catfish *Clarias gariepinus* (Burchell 1822) that invaded into the Ganga River, India. *The Journal of Basic and Applied Zoology* 82: 30. https://doi.org/10.1186/s41936-021-00231-0

2011; Ranjan *et al.*, 2018). The threat posed by *C. gariepinus* has also been reported following its dispersal into a river in the south of Brazil (Weyl *et al.*, 2016). The level of risk of African catfish has been assessed using the developed risk assessment module (Singh *et al.*, 2013) and has been found to be very high, as is shown in green (Figure 5).

FIGURE 5
Quantification of the risks of African catfish in India, assessed using the developed risk assessment module



Source: Singh, A.K., Kumar, D., Srivastava, S.C., Ansari, A., Jena, J.K. & Sarkar, U.K. 2013. Invasion and Impacts of Alien Fish Species in the Ganga River, India. *Aquatic Ecosystem Health & Management* 16 (4): 408–414. DOI 10.1080/14634988.2013.857974

Various biological and ecological characteristics that enable common carp to reproduce, spread and persist have also been examined. Feeding guild, overall life history (fecundity, spawning, gamete viability, reproduction) and phenotypic plasticity were examined. In addition, using a score system based on 27 biological and ecological attributes of common carp, the invasion risk was quantified on a scale of 1 to 5 (Figure 6) – this information serves to provide support for the management of the fish (Singh *et al*., 2013). The assessment suggests that invasive *C. carpio* pose a moderate risk, as is shown in green. Their continued persistence in natural aquatic systems, even in degraded waters, has been a cause for concern for managers and conservationists.

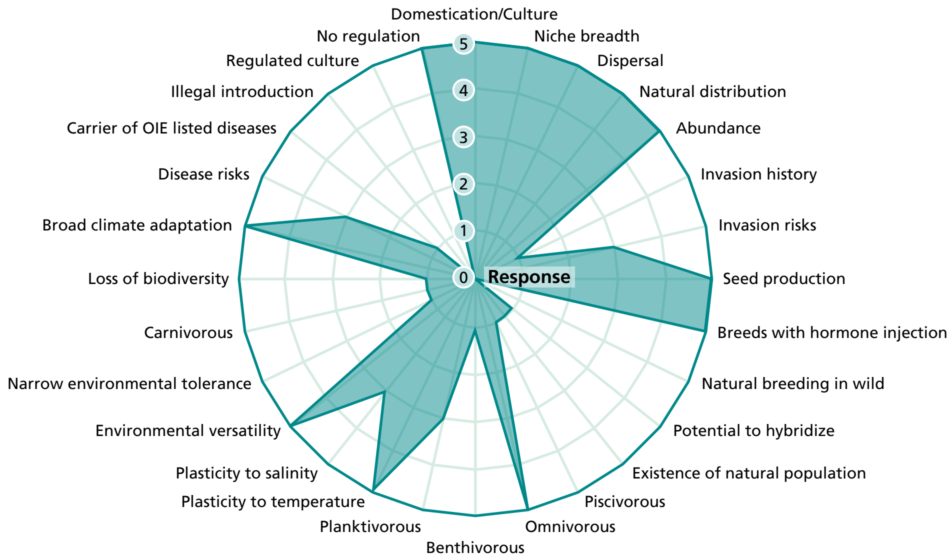
C. carpio is reported to have many harmful effects in aquatic ecosystems, especially since it has the potential to increase turbidity and consume aquatic macrophytes (Weber and Brown, 2011). Globally there are reports that invasions of *C. carpio* in freshwater ecosystems have impacted native fish communities (Koehn, 2004; Maiztegui *et al.*, 2016; Gibson-Reinemer *et al.*, 2017; Dauphinais *et al.*, 2018; Eunice and Edwine, 2021). In India, common carp has invaded many aquatic bodies (Singh *et al.*, 2010; Singh *et al.*, 2013; Singh *et al.*, 2014a; Singh, 2014; Singh and Srivastava, 2021; Ray *et al.*, 2021), aided by its high adaptability and survival rates even in a changing climate and changing environments (Singh and Srivastava, 2021).

4. ADAPTIVE RESPONSES

Overall, the adaptive management response to the common carp and African catfish in India has involved a combination of eradication, control, restoration, education and awareness efforts aiming at minimizing the impacts of these invasive species. In spite of all concerted efforts, national responses to the problem have so far been insufficient to counter the increasing impact of these invasive species on natural resources and society. Some of the adaptive responses practised in the country are presented here:

- The Department of Fisheries, Animal Husbandry and Dairying (DFAH&D), Ministry of Agriculture and Farmers Welfare, Government of India banned the farming of African catfish via office letter number 31016/1/96-FY dated 19/12/97, but the fish is still widely farmed.

FIGURE 6
Quantification of the risks of invasive common carp in India, assessed using the developed risk assessment module



Source: Singh, A.K., Kumar, D., Srivastava, S.C., Ansari, A., Jena, J.K. & Sarkar, U.K. 2013. Invasion and Impacts of Alien Fish Species in the Ganga River, India. *Aquatic Ecosystem Health & Management* 16 (4): 408–414. DOI 10.1080/14634988.2013.857974

- There are Fishery Acts and fishery policies in different state fisheries departments, yet most of the Fishery Acts are very old and do not have provisions for containing NIS like African catfish and common carp.
- Only a few states have so far made amendments to their Fishery Acts and fishery policies. Gujarat is one example: under the Gujarat Fisheries Act–2003 (G/PF/11/2003/FDX/1268/5152/Part-VI/T) no person may introduce any non-indigenous fish species like tilapia, grass carp, silver carp, common carp, gold fish, guppy, gourami, African catfish, bighead and any other harmful fish in any water without the permission of the fishery officer.
- According to the Environment Protection Act of 1986, the farming or sale of African catfish is punishable.
- Article 8(h) of the Convention on Biological Diversity (CBD), to which India is a party, calls on member governments to "as far as possible and appropriate, prevent the introduction of, control or eradicate those non-indigenous species which threaten ecosystems, habitats or species". Further, due to the adverse impacts of introduced African catfish on the environment and biodiversity, the National Green Tribunal (NGT) and many high courts have directed state fisheries departments to destroy them.
- Fishers use a variety of fishing gears to catch common carp and African catfish, including gillnets, cast nets, sein nets, traps and angling methods. The choice of gear depends on the target fish species, the fishing location, and fishing practices of the local community.
- The author himself has given advice to fisherfolk during field visits, suggesting they remove common carp and African catfish fry and fingerlings from rivers and lakes, and use them for stocking grow-out ponds. This will enable them to earn income from the sale of fry and fingerlings while also reducing the wild populations.

5. OUTCOMES

- The implementation of regulations on NIS in India has the potential to protect the country's native aquatic life. However, implementation faces several issues such as regulatory non-compliance, inadequate monitoring, uncontrolled stockings in aquatic bodies, and difficulties in removing NIS once they are established in the wild.
- Intentional or unintentional stocking of NIS in rivers, lakes and reservoirs is commonplace, highlighting the trade-off between food production and the conservation needs of native species, especially under the influence of climate change. There is no stocking policy available so far for dealing with NIS, particularly in inland waters.

6. CHALLENGES

Management of African catfish and common carp is crucial for the sustainable development of inland fisheries, but this involves several challenges. These include:

- Improved strains of common carp and hybrid African catfish are being used for food production yet their scientific management, particularly regarding breeding and proliferation, has not been sufficiently developed. Since these improved strains require an understanding of the structure and function of their genomes and how they interact with non-genetic components of production systems, such as nutrition and environment, scientists should focus on generating such information so that management practices can be optimized (Jeney and Jian, 2009; Nielsen *et al.*, 2010; Ponzoni *et al.*, 2012; Singh *et al.*, 2015; Singh *et al.*, 2021).
- The implementation of regulations and enforced actions to combat unauthorized African catfish farms is difficult due to the absence of relevant legislation.

- Capture fisheries can play an important role in removing and controlling the expansion of introduced common carp and African catfish in India. However, introduced African catfish and common carp have strong potential to expand to new environments and locations where they re-establish natural populations.
- African catfish and common carp captured in degraded waters have been found to accumulate heavy metals such as arsenic, lead and nickel, which are harmful to consumer health.
- The implementation of regulations on introduced NIS requires coordination between various agencies such as the Ministry of Environment and the Ministry of Agriculture and Farmers Welfare, as well as fisheries institutes. Coordination has been a challenge due to differing mandates, limited resources, and conflicting priorities.
- The impacts of climate change – such as changing temperatures, rainfall patterns, and extreme weather events – can affect the growth and survival of native species, yet introduced African catfish and common carp have been thriving even in degraded waters, causing a significant losses to farmers for not getting high value native species such as *C. magur* and Indian major carp which are of high commercial demand and consumers' preference.

7. LESSONS LEARNED AND KEY RECOMMENDATIONS

Key lessons learned for managing introduced African catfish and common carp in India are as follows:

- The introduction of African catfish in India has allowed increased recycling of slaughter house waste and chicken waste for aquaculture purposes, yet the fish pose serious threats to the environment, biodiversity and ecosystems.
- African catfish is a highly predatory species that can outcompete native species for resources and habitat, leading to a decline in biodiversity. Therefore, it is crucial to monitor the ecological impact of invasive African catfish and prevent its further spread to other water bodies by way of practising early detection and rapid response (EDRR).
- There is a need for greater awareness and education among the public, fish farmers, stakeholders and policymakers over the risks associated with these NIS however, this will require funding and long term monitoring.
- There is a need to establish frequent dialogues/communication with regulatory authorities for understanding how the potential environmental and ecological impacts of invasive African catfish and common carp can be managed.
- Indiscriminate stocking of common carp and inadvertent releases of African catfish can lead to increased competition with native species such as Indian major carp, minor carp, and magur for food and space. Therefore, it is important to develop appropriate stocking policies which promote the optimal growth of native fish species and reduce the adverse impacts of NIS on the environment and ecosystems.
- The development of policy and regulatory frameworks, including guidelines for aquaculture of NIS in India, has not gone far enough to mitigate the adverse impacts of introduced common carp and African catfish on the environment and native fish diversity. Therefore, stricter legislation and regulations with effective implementation and monitoring need be developed.
- Long experience of common carp and African catfish in inland waters suggests that they have become invasive in spite of existing regulations; they should be contained by more strict implementation of regulatory mechanisms and by generating knowledge on their adaptive life history traits.

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Chapter 7

Managing the impacts of the non-indigenous European green crab on commercial shellfish fisheries in North America

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SUMMARY

The European green crab (*Carcinus maenas)* is a widely distributed and notorious invasive marine predator listed as among the World's Top 100 Worst Invaders (IUCN Global Invasive Species Database, 2023). It has established non-indigenous populations on five continents including North and South America, Asia, Africa and Australia. Work in several regions has documented the ecological and economic damage caused by the green crab, including on both the Atlantic and Pacific coasts of North America. On the Atlantic coast, green crabs have been established for more than 200 years, and their geographic range now includes Atlantic Canada as far north as Labrador and Newfoundland. On the Pacific coast, green crabs arrived in the late 1980s and have now colonized sites along the entire US coast and British Columbia, and most recently southeastern Alaska. Green crabs can tolerate a wide temperature and salinity range and have a broad diet that includes bivalve molluscs, crustaceans, polychaetes and other prey. Predation by non-indigenous green crabs has resulted in substantial impacts on several commercial bivalve fisheries in both the northeastern and western United States, resulting in more than USD 20 million in losses annually. These include soft-shell clams (*Mya arenaria*), bay mussels (*Mytilus edulis*), Manila clams (*Ruditapes philippinarum*), bay scallops (*Argopecten irradians*), hard-shell clams (*Mercenaria mercenaria*), Pacific little necks (*Leukoma staminea*) and Pacific oysters (*Magallana gigas*). These are largely capture fisheries involving wild populations, although some species are grown in aquaculture facilities using seeded beds or culture bags maintained in the field. Efforts to mitigate the impacts of green crab predation have included local trapping to reduce green crab densities in and around commercial beds, as well as the use of fences and mesh netting to exclude or reduce access by green crabs. Experimental attempts to fully eradicate green crabs on small local scales have resulted in failure due to overcompensatory reproduction in response to the harvest actions that reduce adult densities. As a result of this body of work, several recommendations emerge. These include a focus on preventing future introduction and spread, continuing local-scale mitigation efforts at high-priority locations such as commercial shellfish beds, avoiding efforts aimed at complete eradication, and a new focus on functional eradication/suppression, where possible, to reduce significantly the impacts of green crabs on commercially harvested wild populations as well as native species and other ecosystem assets.

FISHERY CONTEXT

The fisheries of concern with respect to the impacts of the non-indigenous European green crab target several species of commercial bivalve molluscs. On the north Atlantic coast of North America, these primarily include soft-shell clams (*Mya arenaria*), bay mussels (*Mytilus edulis*), Manila clams (*Ruditapes philippinarum*), bay scallops (*Argopecten irradians*) and hard-shell clams (*Mercenaria mercenaria*). On the Pacific coast of North America, the commercial fisheries of concern also include soft-shell clams, bay mussels and Manila clams, along with Pacific little neck clams (*Leukoma staminea*) and Pacific oysters (*Magallana gigas*). For most of these bivalve species in most locations, the fisheries include harvest of wild stocks using a range of methods depending on the location and species. These methods include bottom trawls, mechanical grabs, hand-held rakes, and similar methods that can be used to harvest clams from sandy or muddy substrata. Some species – such as hard-shell clams, blue mussels, Manila clams and Pacific oysters – are grown in cultured beds or in mesh bags that are seeded and then subsequently harvested. Commercial aquaculture of several species is particularly significant in Massachusetts and Maine, although landings for these species are variably available by species and state. Some examples include Maine, where 2021 landings include 661 tonnes for blue mussels (value USD 4.38 million), 654 tonnes for hard-shell clams (value USD 3.28 million), and 695 tonnes of soft-shell clams (value USD 25.2 million) (Maine Department of Marine Resources, 2022). The landings and value of commercial shellfish in the western US states of California, Oregon and Washington are considerably less (Grosholz *et al.*, 2011).

Climate change can influence the success of these commercial bivalve fisheries in several ways, although quantitative impacts of specific drivers are lacking in most situations. Changes in precipitation intensity and frequency that can produce increases in river runoff are projected to result in high turbidity and low oxygen that can influence both growth and survival. However, the most important climate driver likely to impact commercial bivalve fisheries is increased sea surface temperatures, particularly in areas such as the southern Gulf of Maine region adjacent to the US states of Massachusetts, New Hampshire and Maine and the Canadian maritime provinces of Nova Scotia and New Brunswick. Increased temperatures over the past decade in this region have been linked to substantial increases in the densities of green crabs and have exacerbated their impacts on commercial bivalves. In the area of eastern Maine, climate-driven increases in sea surface temperatures are believed to have resulted in greater winter survival of green crabs and increased populations that have contributed to the 75 percent decline in commercial landings of soft-shell clams (Tan and Beal, 2015; Beal *et al.*, 2016; Beal *et al.*, 2020).

HISTORY AND IMPACTS OF *CARCINUS MAENAS* ON LOCAL FISHERIES AND ECOSYSTEMS

The European green crab is among the most successful invasive predators in coastal marine systems worldwide, having established populations on five continents including South America (Argentina), Africa (South Africa), Asia (Japan) and Australia as well as the northeastern and western coasts of North America. By all estimates, green crabs are one of the most widespread and damaging invasions in marine ecosystems (IUCN Global Invasive Species Database, 2023). The European green crab is a highly successful invader, and adult crabs in particular have been shown to tolerate a broad range of temperature, salinity and dissolved oxygen (Yamada, 2001). Green crabs are very opportunistic predators and have an extremely broad diet that includes bivalve molluscs, crustaceans, polychaetes and other prey (Grosholz and Ruiz, 1996).

On the Atlantic coast of North America, green crabs have been an established invader since their introduction in the early 1800s, likely as the result of transport in the holds of wooden ships (Carlton and Cohen, 2003). During the early twentieth century, they spread along the coast of Maine and into maritime Canada including Nova Scotia and New Brunswick. The distribution of green crabs has expanded considerably over the past few decades: they colonized the Gulf of St. Lawrence and Prince Edward Island during the 1990s (Audet *et al.*, 2003; Cameron and Metaxas, 2005) and most recently reached Newfoundland and Labrador around 2007 (Blakeslee *et al.*, 2010). Although most of this expansion has been due to larval dispersal, genetic evidence suggests that ballast water aided the initial introduction into Newfoundland (Blakeslee *et al.*, 2010; Darling, 2014).

On the Pacific coast of North America, green crabs arrived in California in the late 1980s, rapidly expanded their range over the next 20 years, and are continuing to expand their range today (Yamada, 2001; Yamada *et al.*, 2021). By 2000, green crabs were well established in every significant bay and estuary from central California to Washington, almost certainly via larval dispersal (Grosholz *et al.*, 2000; Yamada, 2001). This is consistent with population genetic data that suggested a spread from the initial California introduction to the rest of the west coast (Tepolt *et al.*, 2009). In the past five years, green crabs have become established at several sites in the Puget Sound and Salish Sea areas of Washington and British Columbia, largely the result of larval dispersal (excepting their initial introduction) (Grason *et al.*, 2018; Brasseale *et al.*, 2019; Tepolt *et al.*, 2021). More recently green crabs expanded their range in British Columbia including northeastern Vancouver Island and Haida Gwaii in 2020, and most recently into southeastern Alaska in 2022 (NOAA Fisheries, 2022).

As this invasion has expanded, so have the economic impacts on commercial shellfish fisheries. Estimates of commercial shellfish losses to predation by green crabs from 2000–2005 in the northeastern United States were 23.1–27.2 million kg annually, and annual economic losses of USD 14.7–18.7 million (Grosholz *et al.*, 2011). It is important to recognize that these estimated losses are 20 years old, so current losses are likely much greater. Unfortunately, more recent economic analyses have not been conducted. In the western United States several focal bivalve fisheries have also experienced losses to varying degrees, including Pacific little necks, blue mussels, soft-shell clams, Manila clams and Pacific oysters. Estimates from the same period (2000–2005) project future losses for these fisheries due to green crab predation to be approximately USD 100 000. Importantly, these estimates were based on data from very early in the invasion and do not include impacts to shellfish fisheries following the dramatic population increases documented in the Northwest. These values also include estimated future impacts to the extensive and valuable commercial shellfish fisheries in Alaska, which are considerably greater than the mainland west coast. This means that future estimates of green crab impacts will likely be many times greater than current published estimates. Estimates of economic impacts have also been documented for shellfish fisheries in Atlantic Canada (Klassen and Locke, 2007).

ADAPTIVE RESPONSES

Efforts to reduce or mitigate the impacts of green crab predation on bivalve fisheries to date have been relatively limited in spatial extent. In the northeastern United States, where commercial shellfish beds have suffered substantial impacts from green crab predation, growers have excluded green crabs from these seeded beds by erecting fences and using mesh enclosures on the substrate surface to reduce green crab access and predation levels (Tan and Beal, 2015; Beal *et al.*, 2016; Beal *et al.*, 2020). Mitigation efforts have also included trapping programmes by shellfish wardens in areas adjacent to locally managed shellfish beds to reduce green crab abundance and thereby losses to predation (Walton, 2001).

Attempts to reduce green crab abundances in more spatially extensive areas with the expectation of mitigating green crab impacts on wild shellfish populations have been very limited until recently. Although green crabs have been established on the outer coast of Washington (Gray's Harbor, Willapa Bay) for over 20 years, new invasions in the coastal regions of the Puget Sound and Salish Sea (shared with British Columbia, Canada) only recently became established in 2016 (Grason *et al.*, 2018). This region is now the focus of intensive trapping efforts aimed at reducing populations of green crabs. These trapping efforts do not involve any secondary use of green crabs for food. The state of Washington invested more than USD 7 million and involved hundreds of volunteers in creating an extensive trapping network to achieve population suppression goals (Washington Emergency Proclamation, 2022).

Initiatives to examine the efficacy of local eradication of green crabs have also been conducted using intensive experimental studies undertaken by managers and scientists in several locations in the western United States. These efforts have largely targeted locations where management success can be easily evaluated – to date, these have been sites where the impacts of green crabs have been on non-commercial bivalve species and other ecosystem assets. One of the largest and most well-funded attempts to locally eradicate green crabs was an intensive five-year campaign conducted in central California in a confined water body adjacent to a typical estuary where commercial shellfish were abundant. This work was funded by the Pacific States Marine Fisheries Commission, since the outcome of the campaign would inform future efforts to eradicate green crabs at new and isolated invasion sites. Using an extensive trapping network, the green crab population was reduced by more than 90 percent from 2009–2013. Unfortunately, the removal programme produced a 30-fold population explosion in 2014 due to dramatic, overcompensatory recruitment. This recruitment was due to the necessity of the trapping methods, which removed only adults from the population. The dramatic "rebound" in response to the eradication programme was well documented with extensive ecological and genetic data (Grosholz *et al.*, 2021; Tepolt *et al.*, 2021). As a result of the failure of the efforts to completely eradicate green crabs, the programme shifted to functional eradication to maintain the green crab population at a level sufficiently low to minimize the predatory impacts (Green and Grosholz, 2021). The general goal of functional eradication is to reduce invasive populations to a level where they have little or no ecological impact, thus eradicating their invasive function. This functional eradication programme has been operating successfully over a six-year period, with local volunteers and community scientists maintaining the trapping activity.

OUTCOMES

Efforts to reduce green crab predation on commercial hard clam beds in the northeastern United States have been reasonably successful (see above). Fencing and caging continues to be the standard management tool for mitigating green crab impacts, as well as local trapping to reduce populations and access by green crabs in and around commercial shellfish beds. These methods have been shown to be cost-effective, although they need to be implemented annually.

Experimental studies of the efficacy of eradication in small, restricted locations failed from the perspective of demonstrating complete eradication. That said, these investigations were very instructive by revealing the risk of overcompensatory reproduction in response to harvest for management goals. However, many other control and management goals of the project were met by these studies, and the trapping effort did result in an overall reduction of the green crab population to levels approximately 30–50 percent of the original. This overall level has been maintained for another six years, demonstrating that this reduced population size could be maintained with no overcompensatory responses.

This demonstration of the failure of complete eradication is now widely understood by managers dealing with green crab impacts at all levels in North America. There is now broad agreement among managers to abandon efforts that have complete eradication as the goal (Drinkwin *et al.*, 2019). The current management goal for nearly all programmes is to conduct functional eradication/suppression to reduce green crab populations to levels that will minimize their impacts on commercial shellfish fisheries, native species and other ecosystem values.

CHALLENGES

European green crab populations, which had previously been at low abundance with little impact on surrounding habitats, can rapidly increase as the result of a larger recruitment pulse. There have been well-documented sudden increases in the densities of green crabs throughout North America as well as a rapid expansion of their distribution along the western North America coast. Local efforts to mitigate their impacts, particularly using fences and netting and local trapping to reduce predation around commercial shellfish aquaculture beds, have been successful. However, these mitigation measures are only locally effective and have little or no effect on the surrounding population of the larger area. Therefore, these mitigation actions need to be undertaken each year.

Efforts to reduce green crab populations in high-priority areas outside of commercial shellfish beds, such as areas with productive wild populations for capture fisheries, are even more challenging. These areas are often much larger in spatial scale and may require long-term functional eradication/suppression to maintain green crab populations below levels that would have significant negative impacts on wild bivalve populations. Maintaining this effort is very resource- and labour-intensive, and will likely only be possible in high-priority areas where local volunteers and community scientists are available to provide the capacity for these actions.

Experimental work has also demonstrated the likelihood of overcompensatory reproduction under some conditions in response to harvesting adult green crabs to achieve management goals. Practical methods for removing juvenile green crabs are currently unavailable. The typical methods for reducing green crab populations involving nets or traps have lower limits for mesh size, which prevent them from being effective for capturing small size classes. Other methods like chemical treatment are not practical in most situations. Therefore, complete eradication even in small, isolated populations will be unlikely with current removal methods that target adults. Given that complete eradication is an unlikely outcome, longer-term management involving functional eradication/suppression is the best approach at high-priority locations where sufficient management capacity is available.

LESSONS LEARNED AND KEY RECOMMENDATIONS

The recommendations from several decades of work managing the impacts of the European green crab on shellfish fisheries in North America include the following:

1. The top priority for managing this species, and likely all marine and estuarine invaders, is to prevent its introduction in the first place. Exclusion should be the primary focus for all non-indigenous AIS. Once established, green crabs have a high capacity for spreading to new locations via larval dispersal and efforts to reduce their impacts will likely need to be restricted to high-profile locations, such as commercial shellfish beds, or highly productive sites with wild populations.
2. Methods to mitigate green crab predation in areas like commercial fishing beds have been reasonably successful. The use of fences and screening around commercial beds, as well as targeted trapping to reduce local green crab populations, has been successful and economically sustainable. The use of these methods in high-priority areas around commercial shellfish beds is highly recommended.
3. Efforts to reduce green crab populations should avoid a focus on complete eradication, even locally, since experimental studies have demonstrated overcompensatory reproduction can occur under some conditions in response to management-related harvest. Consequently, the recommendation is to undertake functional eradication/suppression using targets for reduction based on the relationship between losses to green crab predation and the density of the green crab population (see above).
4. In larger areas involving wild shellfish populations and other ecosystem assets, conducting long-term functional eradication/suppression to minimize green crab impacts will likely require local volunteers and community scientists to provide the

capacity needed to maintain the management programme. These efforts will likely be successful only for high-priority locations where the level of concern matches the available level of resources.

5. The overall likelihood of significant, widespread management of European green crab populations is low, particularly for broadly distributed wild populations of commercial bivalves. The recommendation is to avoid activities such as the discharge of ships' ballast water or the movement of commercial shellfish or marine construction equipment into uninfested waters, which could contribute to the further spread or introduction of green crabs.
6. Projected changes in climate-driven variables including increasing sea surface temperatures and increasing frequency and magnitude of extreme precipitation and runoff events are expected to negatively impact commercial shellfish species. These climate-driven changes are also expected to facilitate future increases in green crab populations and subsequent losses to green crab predation. Shellfish producers should anticipate greater future losses to green crabs and work on new ways to reduce their populations locally to mitigate these predicted losses.

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Chapter 8

Fishery management responses to invasive lionfish in the context of climate change

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SUMMARY

Invasive lionfish (*Pterois volitans* and *P. miles*) have colonized a wide variety of marine habitats in the Western Atlantic and the Mediterranean Sea. Both invasions represent a major threat to biodiversity and ecosystem services, including marine fisheries and tourism. Given the generalist diet and broad physiological tolerances of lionfish, ocean warming is expected to drive continued range expansions in the Western Atlantic and the Mediterranean, and further warming could enable lionfish invasions along the Atlantic coasts of Europe and Africa; thus, strategic lionfish management requires international coordination and cooperation between governments and stakeholders. Overfishing has released invasive lionfish from predation and competition, so efforts to rebuild predator stocks may help control lionfish populations. Successful management approaches for lionfish have included encouraging spearfishing removals and engaging local stakeholder communities. Although concerns persist about allowing lionfish spearfishing with scuba gear, these can be mitigated with participatory management and gear restrictions, e.g. by conducting removals with short pole spears. Lionfish fisheries offer a market-based solution to control their densities while diversifying fisher livelihoods. Public education campaigns have promoted lionfish as a safe and environmentally friendly seafood choice, which has helped to raise the price of lionfish and encouraged commercial harvest. However, the labour-intensive nature of spearfishing is a challenge to profitable fishing, and the "bioeconomic paradox" of lionfish removals suggest that it will remain unclear whether commercial fisheries reduce lionfish populations to levels that would achieve ecosystem benefits. Innovative harvest technologies such as lionfish-specific traps and weaponized remotely operated vehicles have been proposed, but further research and development is needed to determine their effectiveness and environmental impacts.

CONTEXT FOR LIONFISH INVASIONS

Red Pacific lionfish (*Pterois volitans* and *P. miles*, hereafter "lionfish"), native to tropical areas of the Pacific and Indian Ocean basins, have invaded multiple marine ecosystems in two different world regions. In the Western Atlantic, lionfish (both *P. volitans* and *P. miles*) were likely introduced by multiple aquarium releases around Florida (Hunter *et al.*, 2021). Lionfish were first detected off southern Florida in 1985, and their range expansion began in the mid-2000s. Their populations are now fully established in the Gulf of Mexico, the Caribbean Sea, and along the Atlantic coasts of Brazil and the United States of America (Luiz *et al.*, 2021; Ulman *et al.*, 2022). In the Eastern Mediterranean Sea, lionfish (*P. miles* only) invaded by migrating through the Suez Canal (Bariche *et al.*, 2013; Dimitriou *et al.*, 2019). During the 2010s, lionfish spread to Tunisia, Sicily, and the Adriatic Sea, representing one of the most rapid range expansions of an invasive species ever reported (Bariche *et al.*, 2013; Kleitou *et al.*, 2016; Poursandis *et al.*, 2020; Kleitou *et al.*, 2022). Lionfish have now colonized a myriad of marine habitats in both invaded ranges: including coral reefs (Morris and Whitfield, 2009), subtropical natural reefs (Whitfield *et al.*, 2014), artificial reefs (Dahl and Patterson III, 2014), seagrass beds (Claydon *et al.*, 2012), mangroves (Barbour *et al.*, 2010), nearshore estuaries (Jud *et al.*, 2015), and mesophotic reefs (Andradi-Brown, 2019).

HISTORY AND IMPACTS OF THE LIONFISH ON LOCAL FISHERIES AND ECOSYSTEMS

Multiple traits have contributed to the success of these invasions. Lionfish are protected by venomous spines and appear to be relatively released from predator control (Ulman *et al.*, 2021), have a generalist diet (Peake *et al.*, 2018), and use foraging techniques to which prey may be naive (Rojas-Vélez *et al.*, 2019). Their rapid spread has also likely been facilitated by opportunistic life-history characteristics (Winemiller and Rose, 1992) with relatively rapid growth and early maturation (Morris and Whitfield, 2009), high fecundity (Fogg *et al.*, 2017), and range expansion due to a relatively long duration of the pelagic larval stage (Ahrenholz and Morris, 2010).

Invasive lionfish in the Mediterranean Sea share similar traits as those identified in the Western Atlantic (Zannaki *et al.*, 2019; Agostino *et al.*, 2020; Savva *et al.*, 2020; Mouchlianitis *et al.*, 2021; Ulman *et al.*, 2021). In the Western Atlantic, lionfish initially demonstrated high resistance to native parasites (Sikkel *et al.*, 2014; Fogg *et al.*, 2016; Tuttle *et al.*, 2017) until cutaneous skin ulcers were widely observed in 2017 (Harris *et al.*, 2020a). Although the skin disease's etiology and population impacts remain undetermined (Cody *et al.*, 2023), the epidemic coincided with widespread declines in lionfish densities in the Gulf of Mexico (Harris *et al.*, 2020a). Mediterranean lionfish are more genetically diverse than Western Atlantic lionfish, likely due to a high genetic flux through the Suez Canal (Bernardi *et al.*, under review), and they may thus be less susceptible to diseases.

Lionfish densities are substantially higher in their invaded ranges than in their native ones (Kulbicki *et al.*, 2012; Dahl *et al.*, 2014). These high densities and high predation success have impacted native species populations (Green *et al.*, 2012; Albins, 2015; Dahl *et al.*, 2016), and invasive lionfish are now considered a major threat to biodiversity (Green *et al.*, 2012; Hixon *et al.*, 2016) and ecosystem processes (Lesser and Slattery, 2011). Adverse impacts on marine ecosystem services include impacts on marine fisheries and potential impacts on tourism via reduced biodiversity (Ulman *et al.*, 2022).

CHALLENGES FROM CLIMATE CHANGE

The combined impacts of lionfish with climate change are of concern. Climate change is causing the poleward expansion of tropical fish along previously temperate coastlines worldwide (Côté and Green, 2012; Agostini *et al.*, 2021), and may be driving some endemic Mediterranean fish species to extinction (Ben Rais Lasram *et al.*, 2010). Experimental studies indicate that lionfish are likely resilient to increasing water temperatures (Dabruzzi *et al.*, 2017; Barker *et al.*, 2018; Hasenei *et al.,* 2020). Subtropical lionfish have higher spawning rates during warm-water months of the year (Fogg *et al.*, 2017; Eddy *et al.*, 2019; Mouchlianitis *et al.*, 2021), and higher water temperatures also increase lionfish larval and juvenile growth rates (Côté and Green, 2012; Savva *et al.*, 2020), as well as their feeding rates (Steel *et al.*, 2019).

Warming waters are expected to drive lionfish range expansion (Kimball *et al.*, 2004; Hansenei *et al.*, 2020; Kleitou *et al.*, 2022). In the Western Atlantic, lionfish have been observed as far north as Massachusetts in the United States of America (Kimball, 2004) and are expanding to the south along the coast of Brazil (Luiz *et al.*, 2021). Sea surface warming may enable Mediterranean lionfish to expand further into Italian waters and along the coast of Algeria (Savva *et al.*, 2020; Kleitou *et al.*, 2021, 2022). Further warming in the next few decades is expected to enable their range expansion along the coasts of France and North Africa (Azzurro and D'Amen, 2022). This projection may be conservative as lionfish have already been found in Tunisia, which was not anticipated (Parravicini *et al.*, 2015). Recent modelling by Loya-Cancino *et al.* (2023) highlights the risk of a lionfish invasion of the Eastern Atlantic through the Straits of Gibraltar, followed by possible northward and southward invasions along the Western European and Western African coasts.

MANAGEMENT RESPONSES

Like all major biological invasions, lionfish are unconstrained by political borders. Their control will require rapid and strategic management, international coordination, and broad cooperation among and between governments and stakeholders (Johnston and Purkis, 2015). Strategies for managing lionfish have been established throughout the Western Atlantic region via multi-scale approaches (Graham and Fanning, 2017). In the United States of America, for example, specialized responses were instituted within national parks and national marine sanctuaries (Johnston *et al.*, 2015) in conjunction with a broader national plan (Invasive Lionfish Control Ad-hoc Committee of the Aquatic Nuisance Species Task Force, 2014).

Efforts to manage lionfish populations have commenced in certain areas of the Eastern Mediterranean. As of the writing of Ulman *et al.* (2022), Türkiye, Israel, and Egypt have permitted regulated, single-day scuba removal events, while prohibitions on scuba spearfishing for lionfish remain in much of the region, including Greece, Lebanon, Tunisia, Algeria and Israel. Cyprus initiated a pilot programme permitting scuba divers to spear lionfish that removed more than 35 000 lionfish from 2018–2021 (Kleitou *et al.*, 2019; Kleitou *et al.*, 2021a). Additional Cypriot management measures include the organization of lionfish derbies and proposed bylaws to expand the number of individuals and dive operators authorized to harvest lionfish.

The need for regional collaboration is evident, especially in synthesizing research and action plans among marine managers addressing the lionfish invasion. For example, lionfish research and management "summits" organized by the Florida Fish and Wildlife Conservation Commission in 2013 and 2018 helped facilitate the sharing of experiences, prioritize research and management objectives, and advance regional management plans (Ulman *et al.*, 2022). Lionfish knowledge exchange workshops have been conducted in Türkiye and Cyprus, and a joint pufferfish-lionfish international conference was held in Türkiye in 2022. Such events have served to strengthen regional collaboration and coordinate regional management directives.

MANAGEMENT CHALLENGES

Ecosystem modelling suggests that declines in native fishes have partially released lionfish from predation and competition (Chagaris *et al.*, 2017, 2020). Unfortunately, overfishing is ubiquitous across much of the invaded regions, and populations of large piscivorous fish are now largely depleted (Jacquet and Pauly, 2022). Fishery management measures and efforts to rebuild predator stocks may thus support the natural control of invasive lionfish populations (Kleitou *et al.*, 2021), along with myriad other benefits (Worm *et al.*, 2009).

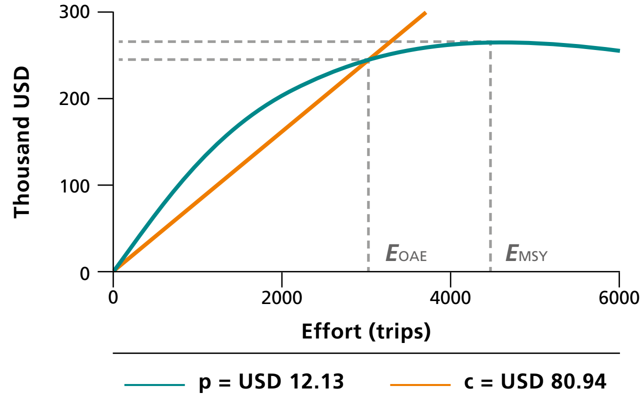
Manager concerns persist about allowing lionfish spearfishing with scuba gear (Kleitou *et al.*, 2021, 2022; Ulman *et al.*, 2022). In many Mediterranean countries, spearfishing with scuba gear is restricted, so lionfish are primarily captured as bycatch in set nets, fish traps, or trawls. Not allowing the spearfishing of lionfish with scuba gear limits their supply to consumers and poses a challenge to the development of reliable markets for lionfish.

Management efforts have encouraged the development of lionfish fisheries as a potential market-based solution to control the density of the species while diversifying fisher livelihoods (Chapman *et al.*, 2016; Kleitou *et al.*, 2021), particularly in areas where there is limited capacity to support directed removals (Graham and Fanning, 2017). Market development in some locations initially faced challenges due to food safety concerns from ciguatera poisoning (Wilcox and Hixon, 2014) or confusion that, because lionfish have venomous spines, their flesh could be poisonous (Morris *et al.*, 2012). High harvest levels have developed in some areas and have correlated with declines in lionfish density: for example, commercial lionfish spearfishing (with scuba gear) in the Mexican Caribbean correlated with declines in lionfish population density and, subsequently, landings (Malpica-Cruz *et al.*, 2021). At the same time, there are concerns that the commercialization of an invasive species could develop an economic dependency on its population and thus engender pressure to conserve it (Nuñez *et al.*, 2012; Quintana *et al.*, 2023). In this case, effective communication between scientists, managers, and fishers is needed to set common objectives for lionfish removals as a means to benefit other fisheries (ibid). Nevertheless, the relatively small size of lionfish and the labour-intensive nature of their harvest can make profitable fishing a challenge (Kleitou *et al.*, 2022). Bioeconomic models by Harris *et al.* (2023a) of the northeastern Gulf of Mexico commercial lionfish fishery indicate that profits in the fishery are relatively low, which suggests commercial lionfish fisheries will remain small (adapted model shown in Figure 1). Fishing rates below their theoretical maximum sustainable yield might make lionfish populations more biologically productive, while fishing above it would reduce potential profits (Bogdanoff *et al.*, 2020; Harris *et al.*, 2023a).

FIGURE 1

Bioeconomic modelling for a lionfish commercial spearfishing fishery in the northeastern Gulf of Mexico

Total revenues (black lines) and total costs (red lines) functions are shown where the ex-vessel price of lionfish (p) is USD 12.13 per kg, and the estimated harvest cost (c) is USD 81.32 per trip. The open access equilibrium solution calculated for effort (EOAE) is lower than the calculated effort solution for maximum sustainable yield (EMSY), demonstrated by the intersection of the total costs and total revenues functions being left of the apex of the total revenues function.



Source: adapted from Harris, H.E., Patterson III, W.F., Ahrens, R.N.M., Allen, M.S., Chagaris, D.D. & Larkin, S.L. 2023a. The bioeconomic paradox of market-based invasive species harvest: a case study of the commercial lionfish fishery. *Biological Invasions* 25(5): 1595–1612. doi.org/10.1007/s10530-023-02998-5

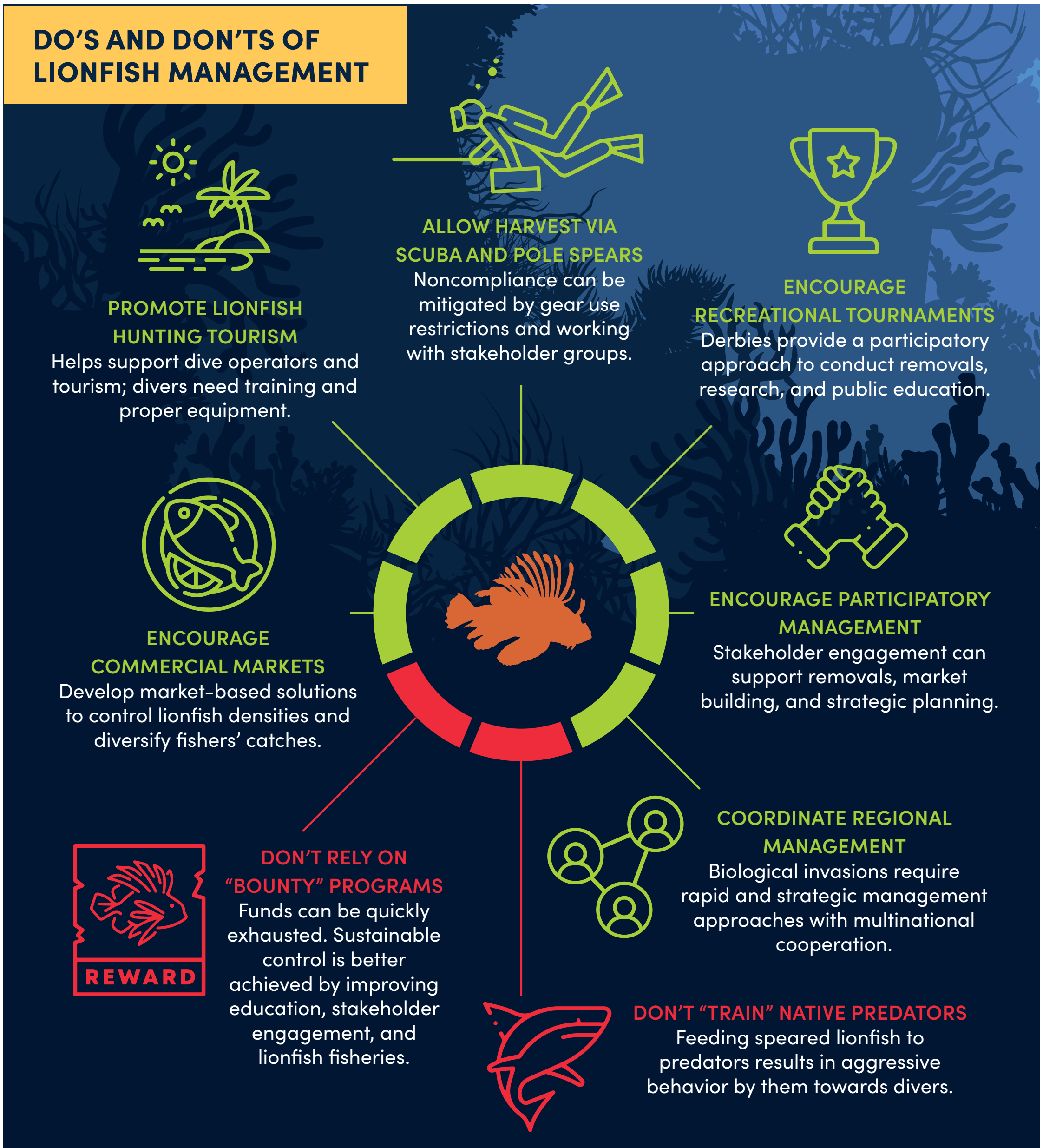
The current method of spearfishing using scuba gear is generally limited to depths of less than 30 m; however, lionfish have been observed as deep as 300 m (Gress *et al.*, 2017) and at high densities in mesophotic depths (Andradi-Brown, 2019). Innovative harvest technologies may also decrease fishing costs and expand harvest capacity (Kleitou *et al.*, 2022). Initial testing of lionfish-specific "Gittings traps" has shown that lionfish can be removed with low bycatch and environmental impact (Harris *et al.*, 2020b, 2023b). Weaponized remotely operated vehicles (Sutherland *et al.*, 2017) and modifications to lobster traps have also been proposed for lionfish harvest (Pitt and Trott, 2013; Hutchinson *et al.*, 2019). Further research, development, and testing are needed to determine whether such experimental gears could enable profitable fishing with minimal environmental impacts (Harris *et al.*, 2023b).

LESSONS LEARNED AND KEY RECOMMENDATIONS

Although full eradication of invasive lionfish is not feasible, control efforts can mitigate lionfish impacts on invaded ecosystems and the services they support (Savva *et al.*, 2020; Green and Grosholz, 2021). The general scientific consensus is that lionfish removal efforts can decrease local lionfish densities (support: Frazer *et al.*, 2012; De León *et al.*, 2013; Dahl *et al.*, 2016; Harms-Tuohy *et al.*, 2018; Harris *et al.*, 2019; counter: Bayraktarov *et al.*, 2014; Smith *et al.*, 2017). Successful approaches have included: 1) conducting routine removals by spearfishing with scuba; 2) encouraging the development of recreational and commercial lionfish fisheries; and 3) engaging local communities in market development, research, and public education (Ulman *et al.*, 2022; summarized by the infographic in Figure 2). Two failed approaches include feeding lionfish to native fish to promote predation, and implementing bounty programmes (ibid). Attempts to train native marine predators to prey on invasive lionfish by feeding them speared fish have been largely unsuccessful and have inadvertently led to increased risk for divers due to large predators (e.g. sharks and eels) associating humans with food. Bounty programmes, offering a financial reward per lionfish collected, quickly depleted their funds and failed to foster sustainable harvesting.

Most marine jurisdictions in the Western Atlantic have implemented policies for encouraging lionfish harvest using spearfishing (Candelmo *et al.*, 2022). In Florida, United States of America, for example, management changes were made early in the invasion to allow for unlimited recreational harvest (i.e. without a licence, bag limit, or seasonal restrictions) and inexpensive licences for commercial harvest. To prevent potential abuse of spearfishing with scuba (e.g. hunting native fishes in no-take zones), short pole spears were mandated for lionfish culling. These are suitable for lionfish harvest but impossible or inefficient for harvesting other fishes. Some marine parks (e.g. in Florida, and Roatan, Honduras) and islands (e.g. Cayman Islands, Bonaire) distribute a specific pole spear for hunting lionfish (Candelmo *et al.*, 2022). A recent programme in Cyprus trained divers as citizen scientists and successfully reduced lionfish densities in marine protected areas (Kleitou et al., 2021). As of Kleitou *et al.* (2022), authorities had not accepted this a a longer-term management plan.

FIGURE 2
Summary of management recommendations for invasive lionfish



Lessons from the Western Atlantic Lionfish Invasion to Inform Management in the Mediterranean
Ulman, Ali, Harris et al. (2022), *Frontiers in Marine Science*
doi.org/10.3389/fmars.2022.865162

Source: Ulman, A., Ali, F.Z., Harris, H.E., Adel, M., Al Mabruk, S.A.A., Bariche, M., Candelmo, A.C., Chapman, J.K., Çiçek, B.A., Clements, K.R., Fogg, A.Q., Frank, S., Gittings, S.R., Green, S.J., Hall-Spencer, J.M., Hart, J., Huber, S., Karp, P.E., Kyne, F.C., Kletou, D., Magno, L., Rothman, S.B.S., Solomon, J.N., Stern, N. & Yildiz, T. 2022. Lessons from the Western Atlantic lionfish invasion to inform management in the Mediterranean. *Frontiers in Marine Science* 9: 526.

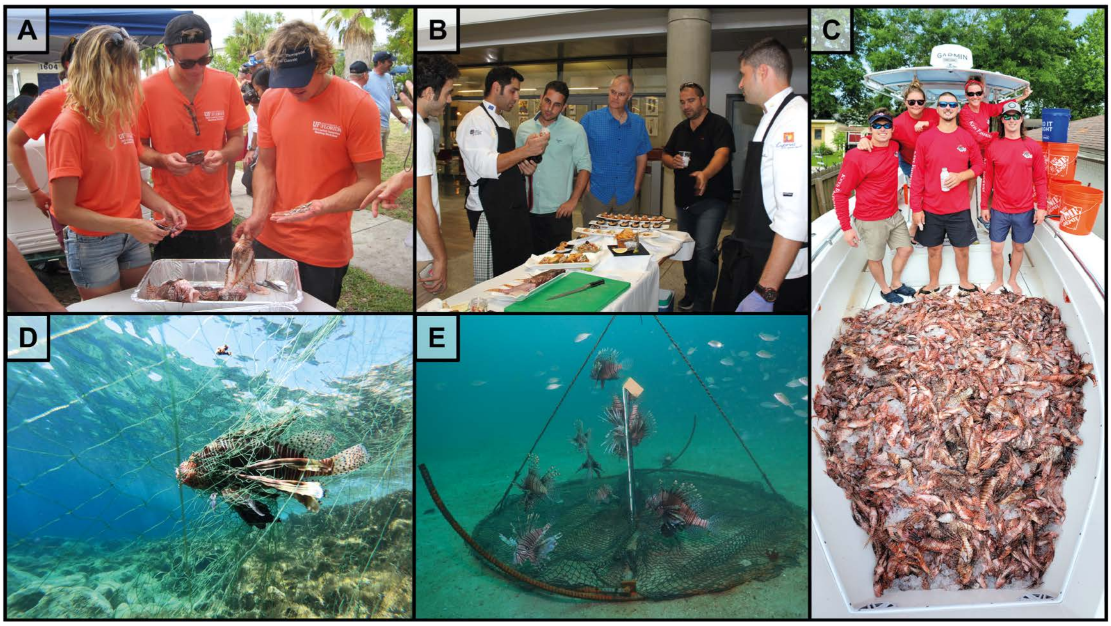
In many areas, managers support or cooperatively coordinate publicly organized spearfishing removal events, sometimes called "tournaments," "derbies," or "rodeos." Removal events can achieve concurrent objectives toward participatory management (Clements *et al.*, 2022; Ulman *et al.*, 2022). Beyond incentivizing removal efforts, removal tournaments can be used to collect life history data (Figure 3A; Fogg *et al.*, 2017) and monitor lionfish populations (Harris *et al.*, 2020a). The events – and their associated media attention – deliver key messaging points that lionfish are non-native and environmentally damaging, while also being safe and appetizing to eat (Figure 3B-C).

Efforts to overfish lionfish populations could be incentivized with price subsidies or value-added by-production of lionfish fins for jewellery or skin for leather products. In Cyprus, for example, fishers often discarded lionfish during the early stages of the invasion (Kleitou *et al.*, 2022). However, public education campaigns have promoted lionfish as a safe and environmentally-friendly seafood choice and raised the price of lionfish in many parts of their invaded range (Huth *et al.*, 2018; Simnitt *et al.*, 2020; Blakeway *et al.*, 2021; Kleitou *et al.*, 2022). In the northern Gulf of Mexico, for example, the price of lionfish is now similar to other high-value reef fishes like grouper and snapper (approximately USD 13 per kg in 2023), and commercial harvest via spearfishing with scuba now lands tens of thousands of kilograms of lionfish per year (Harris *et al.*, 2023a). In the Mediterranean Sea, the price of lionfish generally varies between countries and can depend on the availability of the fish and the public's familiarity with the product. For example, the value of lionfish in Cyprus has increased substantially over the past five years and, for larger individuals, is now similar to mid- to high-priced fish (EUR 12–17 per kg) (Kleitou *et al.*, 2022).

FIGURE 3

Lionfish harvest and outreach events and lionfish fisheries

A) Researchers sampling lionfish diet data from a lionfish harvest tournament in southwest Florida, United States of America. B) Lionfish taste-testing and education with the collaboration of chefs in Cyprus. C) Commercial lionfish harvest from a lionfish spearfishing tournament in the northern Gulf of Mexico. D) Lionfish captured in a fishing trammel net in the Kavo Gkreko marine protected area of Cyprus, Mediterranean. E) Experimental testing of the 'Gittings trap' near high-density artificial reefs in northwest Florida (adapted from Harris *et al*., 2020b).



Source: Photos were taken by the authors or given express permission to use.

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Chapter 9
The red king crab invasion in the Barents Sea

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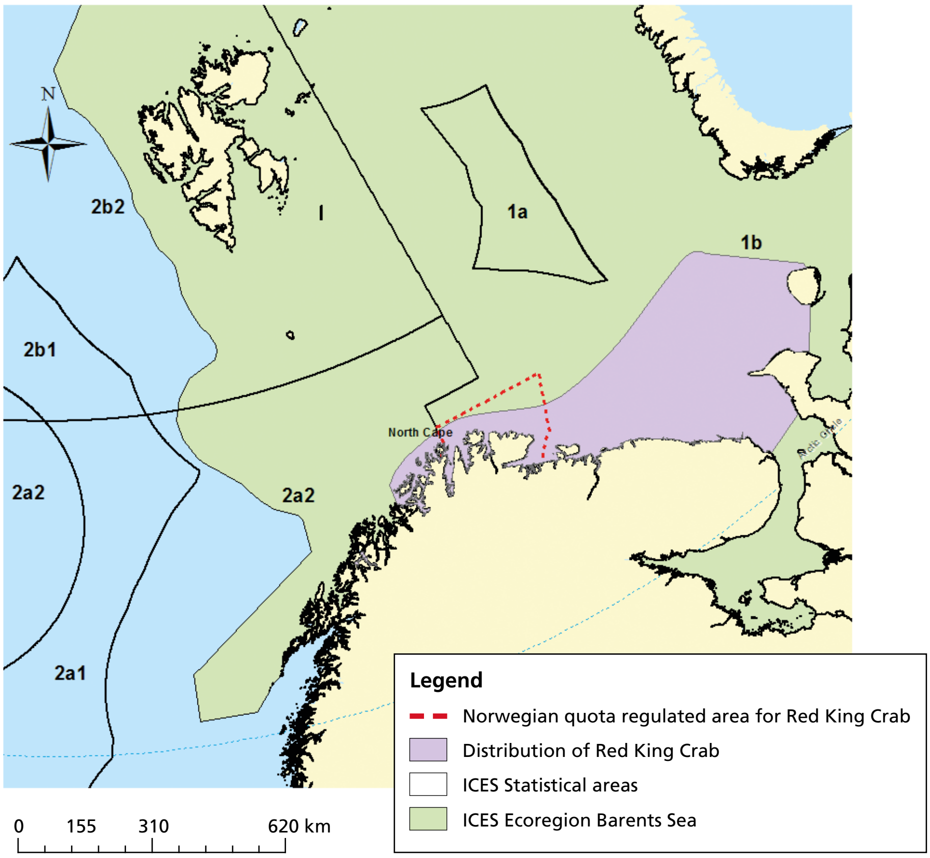
SUMMARY
The Barents Sea ecoregion supports important fisheries and contributes significantly to the export value of Norway. The Norwegian fisheries consist of an oceangoing fleet, along with a coastal fleet of smaller vessels. Quotas are shared between these two vessel types, as well as at the fleet level, through fisheries licences and permits. Since the introduction of the red king crab (*Paralithodes camtschaticus*) from the Pacific to the Eastern Barents Sea in the 1960s, the population has expanded and is now the foundation of an important fishery. To balance commercial interests and the potential negative impact of this alien invasive species, a dual management system has been put in place in Norway. In the east, it is managed as a commercial stock with quotas allocated to local fishers who were negatively affected by red king crab bycatch in traditional fisheries. West of 26°E there is an open-access fishery that aims to limit the further spread of the red king crab. The open-access fishery has generally been effective, although the red king crab has been observed in some locations further south and west. While the commercial opportunities related to red king crab are valuable, there are also concerns regarding the potential negative impact of the invasion on local ecosystems. The crab is an opportunistic predator that forages heavily on larger and slow-moving benthic organisms, leading to increased abundances of smaller organisms and reduced total production in benthic ecosystems.

1. FISHERY CONTEXT
The Barents Sea ecoregion covers the shelf sea areas north of Norway and Russia (Figure 1). It is a highly productive sea, supporting fisheries of key importance and value. Currently, the Barents Sea cod is the most important species in terms of commercial value (Sakshaug *et al.*, 2009). Norway is a net exporter of fish and fish products, and in 2022 the export value of the Norwegian seafood sector was 14 USD billions, with farmed salmon making up 70 percent of the total value, followed by cod (8 percent) (NSC, 2023). This article focuses on the Norwegian part of the Barents Sea.

FIGURE 1
The Barents Sea ecoregion and ICES statistical areas, showing the distribution of red king crab and the Norwegian quota-regulated area for the species (red stippled line). North Cape marks the management line at 26°E



Source: produced by Norwegian Institute for Water Research (NIVA) based on ICES statistical areas.

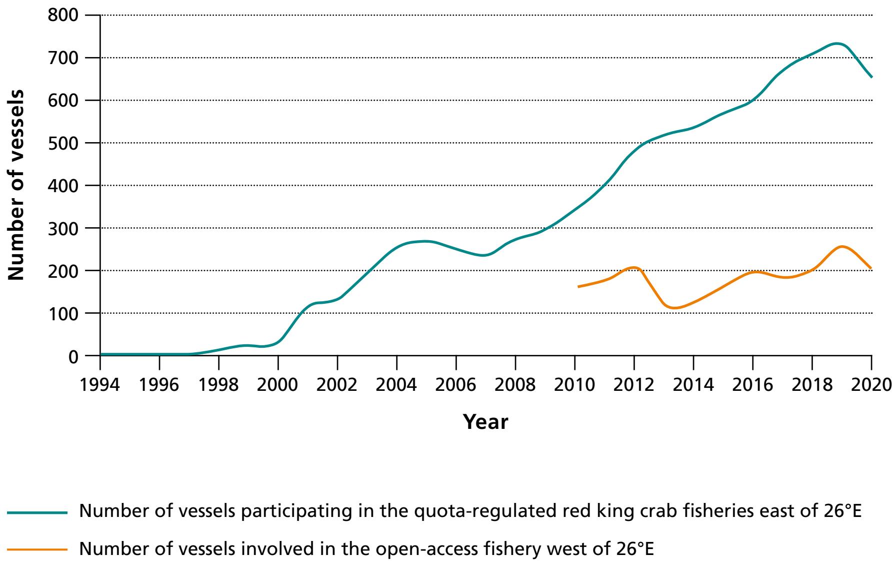
In 2022, the number of people in Norway with fisheries as their main occupation was 9 591, with 1 226 people deriving their income partly from fisheries. Of these, almost half the full-time fishers (45 percent) and 72 percent of the part-time fishers are in Finnmark, Troms, and Nordland counties (DF, 2019). The fishing fleet consists of a coastal fleet of vessels below 28 m in length, and a seagoing fleet of trawlers, ring net vessels and large longliners above 28 m in length. The small coastal vessels make up around 94 percent of the total fleet and fish with gillnets, handlines and pots. Norwegian commercial stocks are regulated through quota systems, fishery licences and permits. Advice from ICES forms the basis for setting quotas, and international negotiations are based on this advice (BarentsWatch, 2013; MFCA, 2011; Henriksen, 2014).

Since the introduction of the non-indigenous red king crab (*Paralithodes camtschaticus*; hereafter king crab) to the eastern Barents Sea in the 1960s, its abundance has increased to support a new coastal fishery in northern Norway. The fishery is managed by area. Registered vessels, primarily based in Finnmark, participate in a quota-regulated fishery east of approximately 26°E and south of approximately 71.5°N (Lovdata, 2023) (Figure 1). Outside of the quota-regulated area the fishery is open-access and anyone, including vessels from the regulated area, can fish for red king crab. As the migration is mostly westwards, the stock size in the regulated area is not believed to be affected by the open-access fishery. Up to 200 vessels were involved in the open-access fishery in the west from 2010 to 2020 (Hvingel *et al.*, 2019) (Figure 2), but in 2021 and 2022 this number doubled with more than 400 vessels operating in the area (Hvingel *et al.*, 2022). ICES is not involved in advice on management of the king crab. King crab is monitored by the Norwegian Institute of Marine Research, which annually assesses the stock to facilitate decisions on the TAC and management regulations. Stock estimates in the eastern management zone are based on information from annual research cruises using video transects, trawls and pots to assess the number of crabs. Crabs caught by the two latter methods are measured to get data on size and sex composition. An index for stock size is estimated based on this information, which then feeds into a model that estimates the stock development, status, and prognosis. Reference points used are MSY, B_{msy}, carrying capacity, B_{lim}, F_{msy} and F_{lim}. A research cruise using pots is the basis for evaluating if the open-access fishery is limiting the spread of the crab and whether the density of the crabs is at a low level (Hvingel *et al.*, 2022).

FIGURE 2

The number of vessels participating in the quota-regulated (blue) and open-access (orange) fisheries from 1994 to 2020

Note that the blue line may also include vessels from west of the management line in the years prior to the establishment of the dual management regime. In the open-access fishery there is no obligation to report, thus information from this area is limited



Source: produced by Xuan Bui Bich, based on data from Hvingel, C., Sundet, J. H., & Hjelset, A. M. 2020. Kongekrabbe i norsk sone. *Havforskningsinstituttet*, 1–17. https://www.hi.no/resources/Bestandsvurderinger-av-kongekrabbe-for-2020-2.pdf

Climate shifts are a key component of expected change in Norway's fisheries. Patterns of migration and distribution of fish stocks are expected to change, with impacts on catches in different locations. However, there are major uncertainties relating to how climate change will affect the Barents Sea (Kvamsdal, 2023). An assessment of 39 fisheries resources in the Northeast Atlantic found that most stocks in the region would respond positively to climate change (Kjesbu *et al.*, 2022). King crab may be sensitive to ocean acidification, but there is insufficient knowledge to predict how this will affect it and other marine species (André, 2014; Sundet and Hjelset, 2019).

2. HISTORY AND IMPACTS OF THE RED KING CRAB ON LOCAL FISHERIES AND ECOSYSTEMS

The king crab was introduced by Soviet Union scientists to the Barents Sea from the northern Pacific in the 1960s to establish a new commercial fishery in the region (Orlov and Ivanov, 1978). Since then, it has spread westwards and established large populations along the Norwegian coast and northeast of the Kola Peninsula (Figure 1). There have also been individual observations of king crab outside its area of distribution. The king crab is a highly valued species on the international market and has become an important source of income for fishers in the region. At the same time, as a large top predator in a new system, the king crab represents a threat to the local ecosystem (Falk-Petersen *et al.*, 2011). The king crab is also a nuisance to local fishers in Finnmark's traditional fishery as it gets entangled in the fishing gear and eats the bait as well as the catch. The entanglement of king crabs in gillnets results in losses both in terms of the time needed to disentangle them and the damage caused to the nets. Sometimes fishers have to use extra fuel to get to king crab-free areas to carry out their fishing activities. In the longline fishery, king crabs eat baits, thereby reducing the efficiency of the fishery (MFC, 2007).

The king crab is classified in Norwegian risk assessments of alien species as a "severe impact" species with a high invasion potential and significant ecological impact (Artsdatabanken, 2018). It can grow to 10 kg with a carapace length (CL) of 22 cm (Pedersen *et al.*, 2006). It is a coldwater species and can handle temperatures from -1.6 to 18 °C, with its optimal temperature being between 2 to 7 °C. It is found in depths of a couple of metres down to 500 m, depending on age, sex, and the time of year. Juveniles prefer pebbles and rocky habitats, while adults prefer sand and muddy bottoms. A female king crab can spawn between 100 000 and 700 000 eggs depending on its size. After hatching, king crab larvae live in the upper water layers where they can be transported over large distances by ocean currents. While they have a high site fidelity, king crabs have also been observed to move long distances (Artsdatabanken, 2018; Sundet and Hjelset, 2019; Windsland *et al.*, 2013; Pedersen *et al.*, 2006).

The king crab is an opportunistic omnivore predator which forages for the most abundant food. Marine bristle worms and bivalves are the most commonly found prey groups in the area (Falk-Petersen *et al.*, 2011; Jørgensen and Nilssen, 2011; Windsland *et al.*, 2014). Its larvae feed on planktonic organisms. Post-larval king crabs feed on sediment-associated organisms. Juvenile and adult king crabs feed on benthic organisms, attacking and tearing apart larger animals and filtering small invertebrates from the substratum (Falk-Petersen *et al.*, 2011). Sessile or slow-moving benthic organisms are the most vulnerable. Initially, large mussels and echinoderms were reported to have disappeared from areas of high king crab density in the Varanger fjord (Finnmark). However, repeated studies have indicated that after a strong reduction during the first invasion period, parts of the seabed fauna has recovered (Oug *et al.*, 2011; Oug *et al.*, 2018). Nevertheless, much of the benthic production has changed from large slow-growing species to small rapid-growing organisms, resulting in a lower total production (Fuhrmann *et al.*, 2015). Food-web models estimate that king crab consume 1–18 percent of the benthic invertebrate production, depending on local habitats (Pedersen *et al.*, 2018). But while the benthic community composition and diversity have changed, there has not been a complete loss of species and the total biomass remains the same. Due to various increases or reductions of smaller species, the observed shifts in overall abundances have sometimes been up and sometimes been down, depending on the timing and location sampled (Oug *et al.*, 2011; Oug *et al.*, 2018). Ongoing monitoring of larger bottom fauna in the quota-regulated area has not indicated any recent changes, but the time series (seven years) is probably too short to reveal significant variations (Sundet *et al.*, 2019). As such, the continued crab fishery in the quota-regulated area implies that the food resources are sufficient for the king crab stock at its present level.

The king crab affects the architecture of both soft-bottom and rocky substrate habitats. Examples include declines in structurally complex scallop beds in invaded areas, and removal of sedimentary organisms leading to a degradation of the sedimentary environment (Falk-Petersen *et al.*, 2011; Oug *et al.*, 2018). Sea urchin numbers have also seen a reduction after the invasion. The urchins have been associated with the decimation of kelp forests along the Norwegian coastline which provide important habitats, nursery grounds and food for commercial species (Sivertsen, 2006; Kvile *et al.*, 2022). A potential positive impact of the king crab invasion could be the recovery of the kelp forest, and thereby the coastal cod population (Falk-Petersen *et al.*, 2011; Christie *et al.*, 2019).

The king crabs may also affect native populations through competition, alteration of food-webs, and restriction of native organisms to less favourable habitats (Falk-Petersen *et al.*, 2011), as well as through the introduction of parasites. King crab are likely competing for food with bottom-feeding fish and birds, but food-web simulations indicate that the dominant commercial fish species, the Atlantic cod, is not heavily affected (Pedersen *et al.*, 2018). King crabs predate upon the eggs of native species. While this is unlikely to have population-level effects on capelin, it may affect local lumpsucker populations (Mikkelsen, 2013). King crab is also prey to fish, octopuses and marine mammals at different stages of its life cycle. In the Bering Sea its larvae are subject to predation by several fish species, and during moulting it can be preyed upon by cod and other groundfish (Falk-Petersen *et al.*, 2011).

3. ADAPTIVE RESPONSES

Management of the king crab was considered and discussed by the Joint Norway-Russia Fisheries Commission (JNRFC) starting in 1992 up until the early to mid-2000s. However, owing to the countries having different aspirations for the fishery, the king crab became the only shared commercial stock in the Barents Sea on the management of which they essentially agreed to disagree. In the 1990s and early 2000s Russia and Norway cooperated on research and management of the crab, mostly with a view to building a commercial fishery (MFC, 2007). While Russia has had a purely commercial focus from the outset, Norwegian management has also acknowledged that there are negative impacts associated with the presence of the king crabs. Despite the agreements in place for cooperation, research and management, in 2006 Russia, without consulting Norway, set a quota for 3 million red king crabs, which was above the 20 percent fishing mortality rate (F_{msy}) agreed on in 2002. This was because a strong year-class had reached commercial size and Russia wanted to harvest the excess biomass more intensely, as it would otherwise be lost due to natural causes. Norway then followed, doubling the quota for the 2006/2007 season without consulting Russia, resulting in an F_{msy} of 37 percent. The 2006 agreement to manage the king crab populations separately stated that, while the two parties were not bound to agree on mutual management measures, they would still inform each other on technical regulatory measures and discuss the results of their research on stock size estimates, migration, and the king crab's impact on the ecosystem (MFC, 2007).

In Norway, a quota system allowing for small-scale fishers in eastern Finnmark to catch and sell king crabs was implemented in 2002, to compensate them for bycatch damages the king crabs had caused (MFC, 2007). While the fishers were initially afraid of the impact of the king crab on traditional fisheries and the ecosystem, their attitude changed when the king crab became an important source of income (Eldorhagen, 2008). Concerns regarding potential negative impacts on the local ecosystem and fisheries resulted in Norwegian authorities implementing an open-access fishery west of 26°E in 2004 to limit king crab expansion. East of 26°E, the king crab is managed as a commercial resource through quota regulations (Kourantidou and Kaiser, 2021; Skonhoft and Kourantidou, 2021). In the open access area west of 26°E, subsidies were introduced in 2010 for under-market-sized crabs (and females in some years) to further incentivize fishers to continue harvesting and contribute to limiting the expansion. Small crabs represent a cost to the fishers, as handling them requires a lot of work and the price is low. Thus they were often discarded, despite a discard ban (Ivertorp, 2008; DF, 2014). The effect of the subsidies has been evaluated annually, and they have been adjusted accordingly (DF, 2014). However, no formal evaluation of the subsidies has been made, so it is not clear why there have been no further subsidies since 2018. The open-access fishery is regarded by management authorities as successful in keeping the king crab population at a low level and limiting its establishment further west and south along the Norwegian coast (Sundet *et al.*, 2019).

Since the opening of the commercial fishery in Norway in 2002, it has expanded and become valuable. The first-hand value of the king crab catch in 2021 was USD 51.25 million. A significant quantity is exported, with the export value being USD 92.5 million in 2021 (Hvingel *et al.*, 2022). Fishers were paid up to USD 46.3/kg for the crabs in 2022.[1] To ensure that the benefits from the fishery stay within the affected communities, quotas are allocated only to locals who complete a minimum income requirement from other fisheries (MFC, 2007) (see Figure 2 for the number of vessels involved in the fishery). The TAC now includes a quota not only for commercial fishers but also for tourism, recreation, research, bycatch, and a youth-fishing initiative (Husa *et al.*, 2022). For 2023, the king crab TAC is set at 2 375 tonnes for males and 120 tonnes for females (Regjeringen, 2022). Prior to approval of the king crab management plan in 2007, the political debate was polarized between those regarding the species as a potentially important source of income and those concerned about its negative impacts (MFC, 2007). Generally, though, there was agreement that biodiversity concerns should be central and that further invasion was undesirable due to concerns about negative ecosystem impacts (Falk-Petersen, 2014).

4. OUTCOMES

The king crab fishery has grown to become an important source of income to local fishers in northern Norway and has resulted in changes in the socioeconomic landscape, including in on-land infrastructure for the delivery of the king crab as well as for exports. The king crab has transitioned from being a nuisance to coastal cod fishers, to a valuable and indispensable resource that supports their communities. In fact, the high value of the fishery and the high price king crab fetches in the market have also led to some illegal harvesting with an estimated annual value in the range of USD 13.9-16.7 million, along with illegal transportation, as has been evidenced by recent arrests of poachers and transporters in Norway.

The Directorate of Fisheries organizes annual dialogue meetings with stakeholders to get feedback on the regulation of the king crab fishery. The 2022 dialogue meeting[2] largely showed that stakeholders were in general terms happy with the current management, although some stakeholders would like it to be more thoroughly evaluated. Previous meetings heard stakeholders' views on how king crab could be better managed to serve fishers' interests and benefit certain communities or groups of beneficiaries.

As part of a research project (PICO - NIVA), stakeholder workshops have recently been organized to capture views on the governance and management dimensions of the king crab fishery (Ramirez-Monsalve *et al.*, 2022). The results reflect hopes and concerns associated with the fishery, along with its local importance, but also reveal potential conflicts between different stakeholders, traditional fishery values, and concerns regarding a lack of understanding of the impact of the king crab on the ecosystem.

[1] Statistikk Norges Råfisklag (rafisklaget.no)
[2] Åpent dialogmøte om forvaltning av kongekrabbe (fiskeridir.no)

5. CHALLENGES

The management of the king crab was evaluated in 2007 in a White Paper produced by the Ministry of Fisheries and Coastal Affairs (MFC, 2007). This shows how evaluation of the risk the king crab represented was important when assessing Norway's obligations with respect to international law. The Convention on Biological Diversity (CBD, n.d.) and the precautionary principle were taken into consideration. The duty to remove or control the king crab population would only come into effect if the species was proven to represent an unacceptable risk to an ecosystem (MFC, 2007). For the king crab, its long-term effects on the ecosystem remain largely unknown (ICES, 2016; Kourantidou and Kaiser, 2019a). Furthermore, the monitoring systems in use for environmental quality assessments, EU's water framework directive, do not seem to capture the impacts of the crab on seabed ecosystems. A new method is therefore under development (Oug and Borgersen, 2022). At the same time, Norwegian authorities recognize and consider the precautionary principle in the management of the king crab, according to which lack of knowledge should not limit measures that prevent environmental degradation (Post, 2004; MFC, 2007).

However, solely focusing on reducing the ecological risk would be costly and would deprive local communities of the economic opportunities the king crab represents (Falk-Petersen, 2014). Furthermore, continuous migration from the eastern part of the Barents Sea could be expected as the Russian strategy is to secure a viable king crab stock that can support a valuable fishery (Sundet and Hoel, 2016). Nevertheless, it is worth noting that the spatially differentiated management implemented in Norway has resulted in stakeholder conflict in the past, with some fishers right on the border of the 26°E line, or slightly west of it, arguing over the need to be included in the quota area (TCG, 2018). Finally, impacts on the ecosystem remain uncertain, and efforts to sustain a sustainable king crab fishery versus effectively addressing the invasion have been debated, especially when it comes to certification of the king crab fishery (Kourantidou and Kaiser, 2019b).

6. LESSON LEARNED AND KEY RECOMMENDATIONS

1. Commercial exploitation provides opportunities for population control in the case of invasion by a high-value species, but it may risk making harvesters reliant for their livelihoods on the invasive species – which perpetuates its presence.
2. Allocating fisheries rights to those negatively affected by the invasion have benefited local fisheries and coastal communities.
3. Despite some controversy over the management of the valuable invasion, close dialogue between management and stakeholders has helped reduce conflicts concerning resource management.
4. Stakeholders are concerned about the ecosystem impacts of the invasion, but its long-term effects remain poorly understood to date.

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Chapter 10

The response of governments and fishers to the expansion of tropical organisms along the temperate coasts of Japan

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SUMMARY

Since the 1990s, a decline in native seaweed beds and an increase in reef-building corals have been observed on the temperate coasts of western Japan, where sea surface temperatures are rising at roughly twice the global average rate. At the same time, climate warming has caused the species composition of *Sargassum* to shift from temperate to tropical; while abalone fishing has ceased due to the loss of kelp beds. These changes, although not related to non-indigenous species, are similar to the ones caused by many biological invasions and deserve appropriate responses.

In addition to efforts to control herbivorous species, there are projects underway to create seaweed beds from tropical *Sargassum* species and to promote the use of coral communities for the tourism industry. The majority of these projects are experimental, with limited results. Coastal fishers who have played key roles in these projects are ageing and lack successors, and securing human and financial resources to sustain operations has become a major issue. The management of range-expanding species should be carried out not only by fishers and the government but also by local residents and non-governmental organizations, in order to create a system that allows the entire community to participate in management actions.

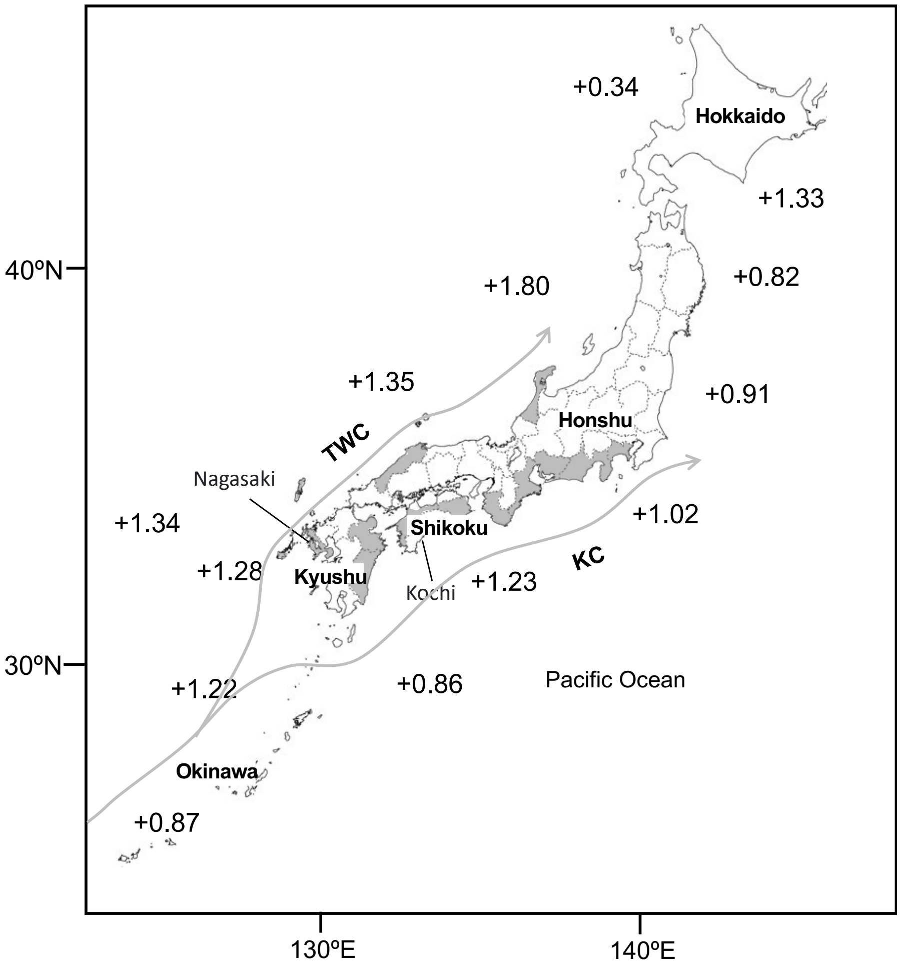
1.FISHERY CONTEXT

Japan's marine food production is comprised of pelagic fisheries, offshore fisheries, coastal fisheries and aquaculture. Coastal fisheries account for approximately 20 percent (1 million tonnes) of the total (Fisheries Agency of Japan, 2019). However, set-net fisheries for migratory fish and small-scale coastal fisheries that use gillnets and diving to catch fish, shellfish, spiny lobster and squid are both being affected by climate change. The average annual sea surface temperature (SST) around Japan has risen by 1.19 °C over the last 100 years, according to the Japan Meteorological Agency (Figure 1). The rate is roughly twice that of the global average (0.56 °C/100 years). The rise in water temperature has been notable since the 1980s, following which the appearance of range-expanding species has become prominent in Japan's coastal areas. For example, yellowtail (*Seriola quinqueradiata*), a migratory fish, has moved northward along its migration route, and the catch in northern Japan (Hokkaido) from 2017 to 2019 was six times greater than it had been 10 years ago (Fisheries Agency of Japan, 2020). The progressive decline of temperate seaweed species and the establishment of tropical corals have negatively impacted the gillnet lobster fishery.

This section focuses on small-scale fisheries in coastal areas, for which administrative measures are being implemented. The region studied is western Japan, a temperate

FIGURE 1
Increase rates of area-averaged annual mean SSTs around Japan from 1900 to 2019 (°C per century)

Prefectures in grey indicate those that responded in the 2005 survey that their seaweed beds were in decline due to excessive feeding from *Siganus fuscescens, Calotomus japonicus* and *Kyphosus* spp. (Fujita *et al.*, 2006). KC = Kuroshio Current, TWC = Tsushima Warm Current.



Source: Japan Metrological Agency. 2022. State of the ocean climate: Sea surface temperature (around Japan) [Online]. Available: https://www.data.jma.go.jp/gmd/kaiyou/shindan/index_gw.html (Accessed 28/12/2022)

region where changes in coastal ecosystems due to climate change are significant. Here, tropical organisms, transported from further south by the Kuroshio Current and the Tsushima Warm Current, appear abundantly during summer. Although the rate of ocean acidification in western Japan is the same as the national average (pH –0.02/10 years), the increased rate of area-averaged annual mean SSTs from 1900 to 2019 is 1.23–1.28 °C (Figure 1), which is higher than the national average, and this has led to the overwintering and establishment of non-indigenous tropical organisms. Simultaneously, extreme weather events such as heavy rains and extreme hot days associated with climate change have been increasing since the 1990s (Japan Metrological Agency, 2023), and these events also affect coastal ecosystems. The organisms covered in this section cannot be defined as non-indigenous species (NIS), rather they are range-expanding species under the growing influence of climate change. Nevertheless, management responses undertaken to deal with this phenomenon can provide useful lessons for this technical paper.

2. HISTORY AND IMPACTS OF FISH HERBIVORY, TROPICAL SEAWEEDS AND CORALS ON LOCAL FISHERIES AND ECOSYSTEMS

According to a nationwide seaweed bed survey conducted in Japan between 2000 and 2008, 44.7 percent of the 26.9 ha of seaweed bed area identified in a 1989–1991 survey on Kyushu's west coast, Shikoku and southern Honshu's Pacific coast has been lost (Fujita *et al.*, 2010). This loss is partly due to increased silt and sediments caused by heavy rainfall and marine pollution caused by eutrophication; however, the main factors causing losses over a wide area are physiological damage to seaweeds due to high water temperatures and increased feeding activity of herbivorous fish and sea urchins during autumn and winter (Fujita, 2010; Fujita *et al.*, 2010; Vergés *et al.*, 2022) (Figure 1). As the water temperature rises the distribution of herbivorous fish species expands to higher latitudes, which leads to overgrazing in new areas (Kumagai *et al.*, 2018). Abalone fishing in Kochi Prefecture has ceased due to the loss of kelp beds caused by rising water temperatures and damage from herbivorous animals (Serisawa *et al.*, 2004). Climate warming has also caused the component species of *Sargassum* to shift from temperate to tropical. Temperate species, such as *Sargassum yamamotoi* and *S. piluliferum*, were dominant in western Japan until the 1980s, but tropical species (e.g. *Sargassum ilicifolium*) have become established and have flourished in many areas since the 2000s (Tanaka *et al.*, 2012; Tanaka *et al.*, 2013). Because tropical *Sargassum* species have shorter flourishing seasons than temperate ones, there is concern that the decline of temperate *Sargassum* beds will affect fish populations that use them as nurseries (Terazono *et al.*, 2012). There has also been a northward range expansion of reef-building corals along the temperate coast of Japan (Yamano *et al.*, 2011; Mezaki and Kubota, 2012). Temperate coral communities attract tropical fish, including valuable commercial species such as *Scarus ghobban* (Nakamura *et al.*, 2013), but they are not targeted for fishing due to a lack of large individuals and insufficient local demand. For the lobster fishery in western Japan, gillnets are set in the evening and left overnight before being retrieved the next morning. The appearance of corals negatively affects the lobster fishery because the nets get caught on or torn by corals (Figure 2).

FIGURE 2

(a) Gillnets used in lobster fishing. (b) Reef-building corals have begun to appear in the fishing grounds in Kochi Prefecture, western Japan.

3. ADAPTIVE RESPONSES

Based on expert advice, the Fisheries Agency of Japan published guidelines for promoting seaweed restoration, including anti-grazer measures (Kuwahara *et al.*, 2010); and national and local government subsidies were provided to entities (primarily fishery cooperatives) to implement these measures. To combat herbivore overgrazing on seaweed beds, fishers with scuba diving gear were engaged to remove sea urchins (*Mesocentrotus nudus*, *Heliocidaris crassispina*, *Diadema* spp. and *Echinometra* spp.) and seaweed bed protection nets were installed, while gillnets were used to remove herbivorous fish responsible for overgrazing (Fisheries Agency of Japan, 2021). These fish – mainly *Siganus fuscescens*, *Calotomus japonicus* and *Kyphosus* spp. – have a low commercial value in temperate regions, so events including cookery demonstrations were organized to promote their consumption and to increase fishing pressure by creating higher demand (Fisheries Agency of Japan, 2021).

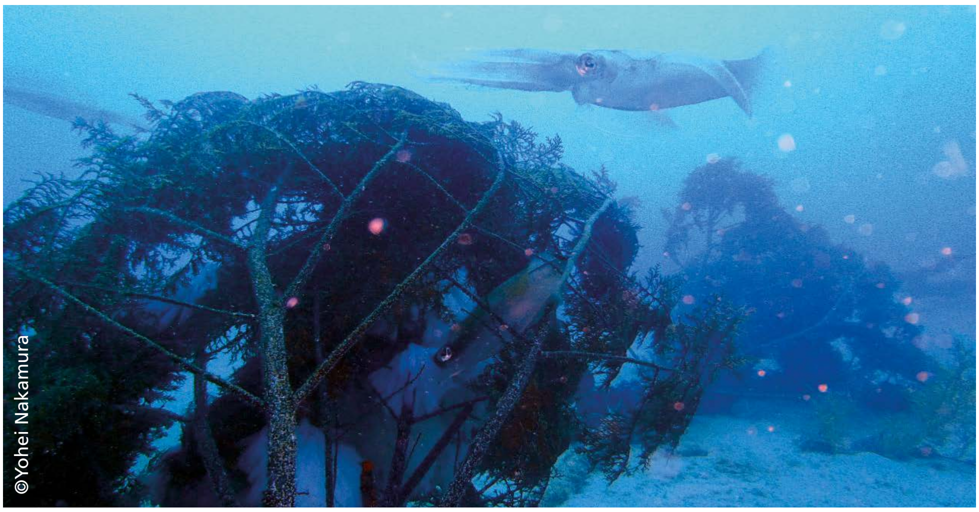
Herbivore population control aims to restore the balance between seaweed productivity and herbivore feeding pressure to its original state. The removal of sea urchins was successful in restoring seaweed beds; however, the effect of herbivorous fish removal on the restoration of seaweed beds remains unclear (probably because of their wide home range). Moreover, the population of sea urchins will quickly increase if they are not continuously removed.

The Fisheries Agency discusses the activities of each entity involved in seaweed restoration measures at the annual council meeting in order to seek better approaches and share information among stakeholders. Along with the control of herbivore species, the restoration of seaweed beds was planned. In light of the challenge of restoring seaweed beds with native temperate species in a warming ocean (temperate seaweed species do not tolerate rising water temperatures), experimental seaweed beds were created in Nagasaki Prefecture using non-indigenous tropical *Sargassum* species more adapted to the current temperature regime (Nagasaki Prefecture, 2018). Another project is being carried out on Kashiwa-jima Island in Kochi Prefecture in collaboration with non-profit organizations (NPOs), fishers, the forestry sector, the diving industry, and local residents including children: all are engaged in securing spawning beds for bluefin reef squid (*Sepioteuthis lessoniana)* by sinking thinned cedar and cypress trees to replace lost seaweed beds (Figure 3). Finally, a reef-building coral community developed on breakwaters in Nahari

FIGURE 3

Eggs of a bluefin squid laid on thinned wood

Local children participate in this project as part of their environmental studies to learn about forest and marine ecosystems.



Town, Kochi Prefecture, is being used as a tourist resource for snorkelling. Public awareness raising about activities related to the natural environment can be targeted at schools, local residents and tourists. NPOs, rather than fishers, often conduct this activity.

Regular monitoring is necessary to determine ecosystem changes, including the establishment of new species. In Japan, two types of monitoring have been practised: monitoring led by a national research institute with the cooperation of scientists and local NPOs to regularly collect data (e.g. Monitoring 1000), and monitoring by local fishers and NPOs to understand the local environment. For the latter, the Ministry of the Environment is promoting the development of an online platform to consolidate and disseminate monitoring data from each research site, thereby creating a stakeholder network (Ministry of the Environment, 2023).

4. OUTCOMES

Although there have been many cases of seaweed beds recovering as a result of herbivorous animal removal, recovery is often on a small scale, or the seaweed beds disappear again when the project is terminated after recovery (Fisheries Agency of Japan, 2021). Projects typically end due to a cessation of subsidies and a lack of human resources. In some fishing villages, management actions have been carried out with the help of local university students, members of diving clubs, and volunteer divers. Although the commercialization of herbivorous fish has been successful in short-term events, unfamiliar fishes tend not to be in demand and thus do not become part of the local food culture. Local subsidies have supported ongoing catches of herbivorous fish (*Kyphosus* spp.) and its successful commercialization in Iki City, Nagasaki Prefecture (although only a small percentage is commercialized, while the majority is disposed of) (Fisheries Agency of Japan, 2021). The bluefin reef squid project has not only led to an increase in bluefin reef squid spawning in thinned wood (Figure 3), but has also increased environmental awareness and interaction among local residents (Kanda, 2008). Since tropical *Sargassum* species have shorter flourishing seasons than temperate ones (which have almost year-round vegetation), seaweed bed creation using tropical *Sargassum* species requires attention to the seasonality of the target animal resource, and in some cases will lead to changes in the quality of ecosystem services derived from the new seaweed beds (Ministry of the Environment, 2023).

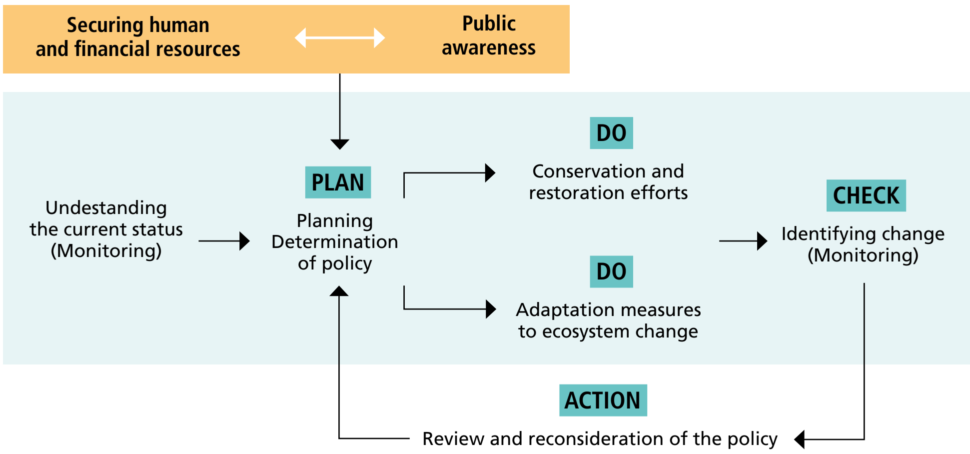
In terms of coral tourism resources, few fishing communities are able to benefit from them, because developing the infrastructure to convert coral colonies into tourism resources is difficult and stable income cannot be expected. Furthermore, this is a method of using coral which does not directly address the problem of lobster fishing gear. In Okinawa (a coral reef-dominated subtropical region), lobster fishing is carried out by divers; but due to an ageing fisher workforce in the temperate region, switching from gillnet fishing to diving is unrealistic. Using traps may be one alternative; however, their fishing efficiency is very low. Since it takes time to change from a seaweed bed ecosystem to a highly productive coral ecosystem, immediate action is not required. However, fishing methods should be developed to allow fishers, especially elderly fishers, to fish in areas where coral has been developed.

5. CHALLENGES

The major challenges for environmental restoration projects, including anti-grazer measures, are to secure human and financial resources in the long term. Coastal fishers who have led environmental restoration projects are facing ageing issues and a lack of successors. There are two kinds of subsidies that support environmental restoration projects: those provided by the national government and related agencies, and those offered by companies and private organizations. The former may have restrictions such as requiring cooperation with local government during application, whereas the latter often only allow private organizations such as NPOs to apply, and in many cases are time-limited and are not widely applied for. While anti-grazer measures may require a large budget, alternative methods could be developed for long-term activities, including a change in fishing gears.

The Fisheries Agency and the Ministry of the Environment recommend an adaptive management approach in which the policy of conservation and restoration is revised in accordance with current environmental changes (Figure 4). Continuous monitoring is required to detect environmental changes and plan countermeasures, but obtaining technical capacity for scuba diving and aerial photo analysis is challenging. A monitoring manual with simple methods and indicators that non-specialists (e.g. fishers and local volunteers) can use is required. The degree to which fishers and local residents are aware of changes in coastal ecosystems, including the arrival of new species, varies according to their direct use of coastal resources. Those with little involvement in coastal resources need a strong motivation (or incentive) to participate in monitoring projects. The decline of seaweed beds is frequently caused by multiple factors, including rising water temperatures and the effects of anthropogenic factors (e.g. water pollution and sedimentation). Depending on the situation, it is necessary to effectively combine multiple technologies and management measures.

FIGURE 4
Flowchart of processes in adaptive management of coastal ecosystem changes



Source: Ministry of the Environment, Japan. 2023. *Climate Change Adaptation Manual for Coastal Ecosystems in Regional Action Plans for Climate Change Adaptation (Kyushu and Okinawa region).*

6. LESSON LEARNED AND KEY RECOMMENDATIONS

- To address the shortage of human resources, environmental restoration projects should be implemented not only by fishers and the government but also by local residents and non-profit organizations, by creating a system that allows the entire community to participate.
- The benefits of coastal ecosystem services and the effects of climate change should be made widely known to all stakeholders, including local residents, in order to increase their interest in the local environment and encourage them to consider what they can do to help it.
- The establishment of platforms (e.g. councils and websites) for the exchange of knowledge and technology gained through activities will aid in technological innovation and help to counter financial shortfalls.
- The impacts of climate change on natural ecosystems are coupled with other anthropogenic stressors. Both climatic and non-climatic drivers should be addressed in order to effectively manage fishery resources and increase ecosystem resilience.

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Chapter 11

Subsidizing the overharvest of an overgrazing, range-extending sea urchin for kelp restoration and abalone habitat protection

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SUMMARY

The commercial harvest of the range-extending longspined sea urchin (*Centrostephanus rodgersii*) in Tasmania, Australia, was rapidly accelerated by catch subsidies initiated by the abalone industry, which it threatened. The 650 km climate-driven extension of the urchin distribution, and subsequent extensive overgrazing of kelp reef ecosystems, represents one of the largest and most immediate threats to the USD 52 million abalone industry. This threat also extends to hundreds of kelp-associated species, and in turn results in the downgrading of social, cultural, ecological and economic values. The response of the abalone industry – to both initiate subsidy payments for urchin removals and to lobby for political support – was fundamental to securing timely and effective management intervention on this locally non-indigenous species (NIS). Harvest subsidies provided the urchin industry with financial reassurance to overcome barriers associated with infrastructure, intellectual knowledge on urchin processing, and international market development. After a decade of urchin industry fluctuations pre-subsidy, harvests of urchins quickly rose to 500 tonnes per annum after its inception, resulting in extensive kelp protection and localized kelp restoration in areas of intense urchin fishing. The early action to prevent extensive urchin overgrazing along the 250 km Tasmanian east coast has been both effective and affordable, as rehabilitating hyper-stable, extensive barren grounds would inevitably involve substantially higher effort and cost. Financial support from the Tasmanian State Government and the introduction of spatially variable harvest subsidies has seen the urchin control redistributed to regions of high importance for the abalone industry. Additional urchin control actions, such as "take-all" (all urchin size classes) harvesting and culling, have been trialled to supplement the commercial harvest, further reducing urchin abundances on high-value reefs. Marine spatial planning and associated decision tools are under construction to facilitate spatial prioritization of harvesting, subsidy allocation, and control method application. Here we document that with support and prioritization, commercial harvest can be an affordable and effective management strategy of aquatic NIS over large scales.

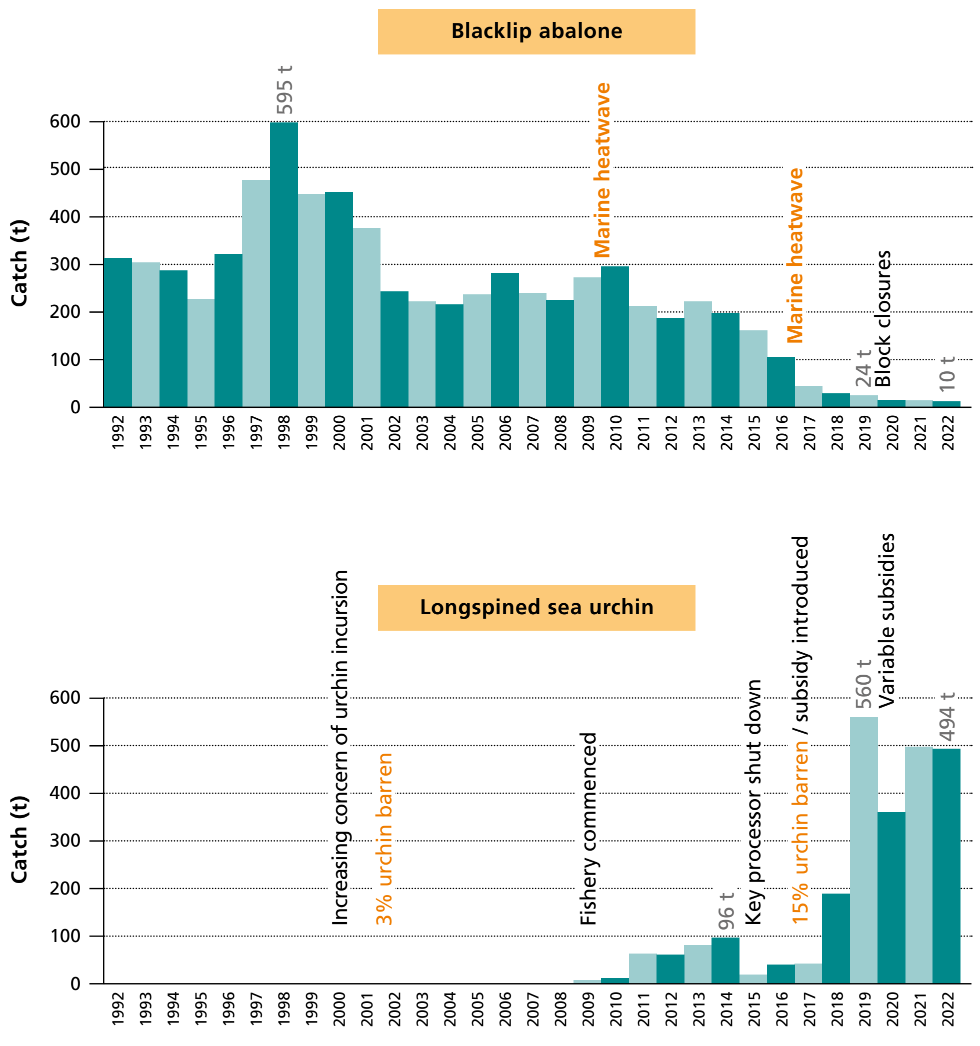
1. FISHERY CONTEXT

The Tasmanian wild abalone fishery is one of the largest in the world, historically producing up to 25 percent of the annual global wild harvest. Commercial abalone fishing commenced in the late 1950s with annual catches in the order of 2 000 tonnes being landed by the mid-1960s. The fishery has primarily focused on the hand-harvesting of blacklip abalone (*Haliotis rubra rubra*) by divers, with greenlip abalone (*H. laevigata*) typically accounting for around 5 percent of the annual wild harvest in Tasmania. The fishery has limited entry with a maximum of 121 dive licence entitlements, is managed with an annual Total Allowable Commercial Catch (TACC), and has region-specific size limits. Abalone are distributed around the coast of Tasmania, the fishery comprising five regional zones each with its own TACC which is equally divided among 3 500 individual quota units held across approximately 450 quota-holding entities, 70 percent of which are held in Tasmania. About 95 percent of Tasmanian abalone is exported to a range of

FIGURE 1

Changes in catches of blacklip abalone (since 1992) and longspined sea urchin off eastern Tasmania through time

Key impacts and major management actions are indicated, as well as urchin barren assessment surveys



Source: Authors' own elaboration.

destinations in Asia, the vast majority live. The Gross Value Added (GVA) of the fishery was estimated to be USD 52 million in 2019, from a total catch of 1 267 tonnes, but it has likely declined since then with further TACC reductions and area closures (Rust and Ogier, 2021; Mundy and McAllister, 2022).

Production in the Tasmanian abalone fishery has contracted since the late 2000s, due to declining stocks following persistent overfishing, insufficient conservative management, variable recruitment, and the increasing frequency and magnitude of warm water events, particularly off eastern Tasmania (Figure 1; Mundy and McAllister, 2022). The east coast has experienced several minor and two major climate-enhanced marine heat wave (MHW) events over the past two decades (2009/2010 and 2015/2016) resulting in wild abalone mortalities in late summer across most of the Tasmanian east coast (Bicheno south to the Actaeon region) (Oliver *et al.*, 2017). The 2015/16 heatwave lasted 251 days and reached a maximum intensity of 2.9 °C, and global climate models indicate the likelihood of the occurrence of an extreme warming event of this duration or intensity is ≥330 times (duration) and ≥6.8 times (intensity) more likely compared to historical baselines due to the influence of anthropogenic climate change (Oliver *et al.,* 2017). Habitat loss resulting from extensive kelp overgrazing by the range-extending longspined sea urchin (*Centrostephanus rodgersii*) has continued to exert negative pressure on abalone stocks (Ling and Keane, 2018). Subsequently, there have been significant TACC reductions and area closures over numerous years in an effort to rebuild heavily depleted abalone stocks (Mundy and McAllister, 2022). Approximately half of the Tasmanian East Coast has been closed to commercial abalone fishing since 2020.

2. HISTORY AND IMPACTS OF LONGSPINED SEA URCHINS ON LOCAL FISHERIES AND ECOSYSTEMS

South-eastern Australia is a global hotspot for marine climate change, with waters warming at a rate four times the global average; 86 species have been observed undergoing range-shifts in Tasmania alone (Hobday *et al.*, 2014; Gervais *et al.*, 2021). Of these, the 650 km range extension of the longspined sea urchin (*Centrostephanus rodgersii*) represents the single largest and most immediate marine environmental threat to kelp-dominated reef ecosystems in eastern Tasmania (Johnson *et al.*, 2011; Ling *et al.*, 2015). Oceanic warming coupled with the strengthening of the East Australian Current (EAC), both resulting from anthropogenic climate change, is increasing water temperature off eastern Tasmania at a rate of 0.4 °C/decade, with temperatures during the urchin's spawning period (late winter) now regularly above its larval survival limit of 12 °C (Figure 2; Ling *et al.*, 2008; Ridgway and Ling, 2023). The poleward flow of the EAC has enabled the transportation of larvae (three-month larval phase) from mainland Australia south to the island state of Tasmania (Ling *et al.*, 2008).

First reported in Tasmania in 1978 (Edgar, 1997), populations of the longspined sea urchin grew to an estimated 11 million individuals in 2002, and to ~20 million in 2017 (Johnson *et al.*, 2005; Ling and Keane, 2018). During this period, the overgrazing of kelp bed habitats and the formation of barrens has rapidly expanded to constitute 15 percent of reef along Tasmania's east coast. Projections of observed rates of population increase and overgrazing have indicated that unless there is a meaningful response to this threat, half of all reefs in eastern Tasmania might become urchin barren grounds by the mid-2030s (Ling and Keane, 2018; Keane and Ling, 2022).

The presence of longspined sea urchins in low abundance and/or the presence of small barren patches (1–10 m^2) within kelp beds is not problematic for fisheries production or biodiversity more generally. However, it becomes problematic when abundance builds towards the tipping-point of overgrazing (approximately 2.0 urchins per m^2) across hectares to hundreds of hectares of the reef, and collapse to extensive barrens occurs (Ling *et al.*, 2015; Ling and Keane, 2018). The flow-on impacts of kelp bed overgrazing by this urchin are dramatic for biodiversity, with the local loss of more than 150 species that live among Tasmanian kelp beds (Ling, 2008).

Observations of overgrazing by longspined sea urchins and habitat displacement of abalone in Australian waters were first documented in the 1960s (Shepherd, 1973). Off eastern Tasmania, abalone abundances are markedly lower in once-productive abalone habitats subject to extensive overgrazing where urchin barrens have formed, and almost non-existent in extensive barrens (Johnson *et al.*, 2005; Ling, 2008; Johnson *et al.*, 2011; Ling and Keane 2018). While the proportional impacts of historical overfishing, marine heatwaves and urchin-derived habitat loss have not been quantified in Tasmania, extensive urchin barrens unequivocally have a negative impact on abalone production.

Conversely, the range extension of longspined sea urchins and their commercial value have provided some commercial abalone divers with an alternative harvest species in the wake of abalone TACC and quota reductions, creating additional socioeconomic benefits for coastal communities. Similarly, the expansion of the commercial urchin fishery has created a parallel economic incentive for abalone processing facilities to expand, invest, and diversify their business into the processing of urchins, as the availability of abalone quota has reduced and lower volumes have passed through once-thriving abalone factories (Cresswell *et al.*, 2019, 2022).

A poorly understood aspect of the impact of abalone fishing on ecosystems is whether there is potential for a competitive release effect on other coexisting grazing species. Anecdotal information from abalone fishers in other states suggests significant depletion of abalone populations allows more rapid expansion and dominance by the longspined sea urchin. It is theorized that high densities of abalone in crevices and depressions prevent the progression of urchin barrens (Gorfine *et al.*, 2012), however experimental manipulations of these interactions between blacklip abalone and longspined sea urchin to date are not conclusive (Strain and Johnson, 2009). In New Zealand, high densities of the abalone *Haliotis iris* have displaced the endemic sea urchin *Evechinus chloroticus* (Wing *et al.*, 2015).

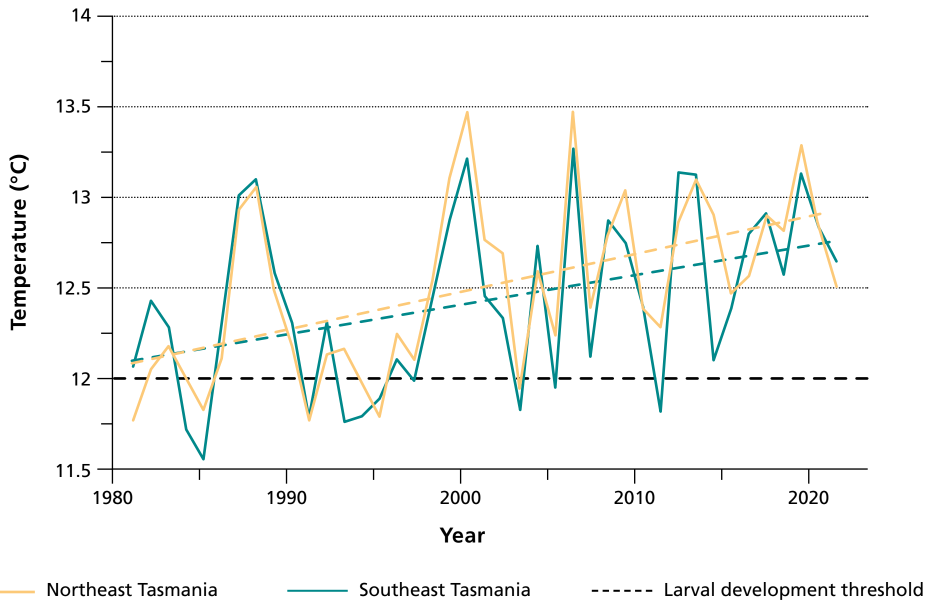
3. ADAPTIVE RESPONSES

Commercial harvesting of longspined sea urchin began in 2009, with catches increasing to 96 tonnes by the 2013/14 season (Figure 1; Keane *et al.*, 2019). The closure of the key urchin processor in 2015 saw catches drop to 40 tonnes and resulted in heightened concern for the abalone industry as urchin barrens were being increasingly observed along the coastline. It was at this time that discussions, led by the Tasmanian Abalone Council Ltd (TACL), began about how to encourage and support urchin harvesting in an effort to rekindle the urchin industry and remove urchins from reefs. The TACL met in February 2015 to discuss options for supporting commercial harvesting, with a subsidy from TACL agreed upon for the 2016/17 season at USD 0.48/kg paid to urchin divers (DPIPWE, 2018). The subsidy provided direct assistance for urchin control as well as a means of providing start-up funding to the fledgling Tasmanian urchin processing sector.

In 2018, the Abalone Industry Reinvestment Fund (AIRF) committee was formed as a joint commitment between the Tasmanian state government and abalone industry. The AIRF contained funds of USD 3.3 million, a partial redirection of royalties paid by the abalone industry to the government, to be paid over 5 years to support and increase the sustainability and productivity of the Tasmanian abalone fishery, as well as to support projects to reduce the longspined sea urchin population on the east coast. The main goals of the AIRF in relation to urchins were to:

- Stop the growth of existing barrens
- Prevent the establishment of new barrens
- Promote the recovery of extensive barrens.

FIGURE 2
Mean annual SST during the key spawning period (August) of longspined sea urchins from northeast and southeast Tasmania from 1982 to 2022
Trendlines are shown (dashed lines), as is the 12 °C longspined sea urchin larval development threshold (Ling, 2008).



Source: NOAA www.ncei.noaa.gov/products/optimum-interpolation-sst. Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., Smith, T. & Zhang, H.-M. 2020. Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1. *Journal of Climate*, 34: 2923–2939. https://doi.org/10.1175/JCLI-D-20-0166.1

Significant investment in urchin processing facilities by a key abalone processor resulted in increased catches from 2018. However, much of the urchin harvest was coming from a small section of coastline and not from key abalone fishing grounds under increasing threat. In March 2019, the subsidy was adjusted to a spatially explicit structure with the price/kg varying depending on latitudinal zones defined down the east coast of Tasmania (Figure 3; Cresswell *et al.*, 2019). The latitudinal structure of the subsidy was further adjusted in March 2020 and December 2021, with the main aim of spreading effort into areas of higher value to the abalone industry, often where urchin density was lower but increasing, to prevent extensive barren formation (Cresswell *et al.*, 2022). The spatial subsidies quickly saw effort spread into regions where minimal to no catch was recorded beforehand. Some urchin harvest persists in unsubsidized areas due to the high-catch, low-cost nature of these fishing grounds. Regular review of the subsidy strategy is undertaken to ensure its effectiveness, and it will likely continue to be used as a tool to direct effort into high value areas while funding is available. At present, no long-term funding stream has been secured. The large urchin harvests have resulted in large quantities of urchin processing waste, and this is being addressed by developing organic fertilizers (Campus *et al.*, 2022).

Near the southern and northern extent of the range of this urchin in Tasmania, further measures have been taken in addition to harvest subsidies. A "take-all" harvest has twice been trialled as a method to harvest all visible urchins (an alternative culling) in productive areas. In a take-all harvest, all detectable size classes of urchins are harvested from target sites and transported to the processing facility; all commercial-sized urchins are processed, while the remainder (i.e. non-viable, small and immature urchins) are discarded. A take-all harvest funded by the AIRF was conducted in 2020 in southeast Tasmania (Larby, 2020), removing 34.9 tonnes, while a second take-all removed 3.4 tonnes from offshore islands in northeastern Tasmania in 2021 (Larby, 2021). Two urchin culls, where all visible urchins are killed in situ without utilization of their products, have also been conducted at the southern range extent, killing an estimated 48 000 urchins of all sizes (Huddlestone, 2019, 2020).

In addition to urchin harvesting and culling, a programme to rebuild southern rock lobster (*Jasus edwardsii*) stocks was introduced in 2013 for both lobster fishery enhancement and predatory control on urchins: The Tasmanian East Coast Rock Lobster Stock Rebuilding Strategy 2013-2023 (Johnson, *et al.*, 2005, 2013; Ling *et al.*, 2009 DPIPWE, 2018). The strategy involved lobster TACC reductions and lobster translocations, with the aim of rebuilding populations to 20 percent of historical stock levels by 2023. In total 229 500 individual lobsters have been translocated from southern Tasmania to areas along the east coast (Rafael Leon, personal communication). However, recent research has shown that abalone are the preferred prey (over longspined sea urchins) of southern rock lobster, and the translocation of lobsters has been directed away from key abalone habitat (Smith *et al.*, 2022).

4. OUTCOMES

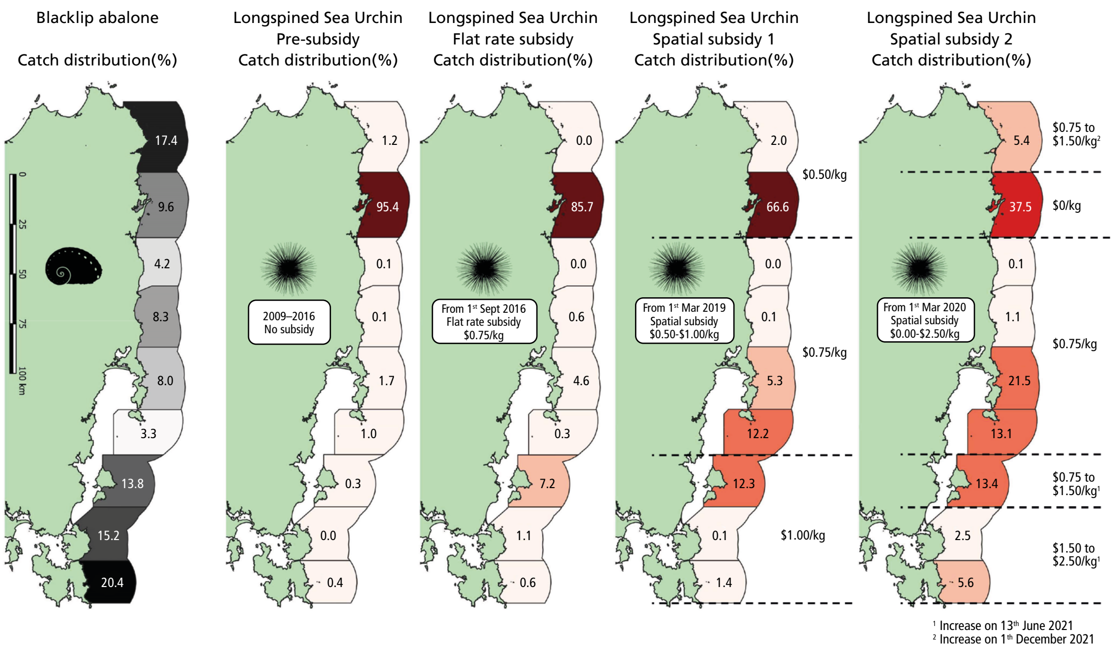
The introduction of urchin harvest subsidies accelerated the development of the harvest industry by providing financial support while processor infrastructure was upgraded, processing practices streamlined, and international markets developed. The outcome of urchin harvest subsidies is clearly evident, with annual catches rapidly increasing from 40 tonnes in 2016/17, to 180 tonnes in 2018, and 560 tonnes in 2019 (Figure 1; Creswell, 2022). Restructuring of the processing sector for efficiency gains saw catches dip to 360 tonnes in 2020, before harvests of almost 500 tonnes in 2021/22.

The harvest subsidies for longspined sea urchin have resulted in the fishery growing to be Tasmania’s third largest wild harvest fishery, behind southern rock lobster and abalone. This has generated significant employment and economic activity in the state, and has partially offset employment losses from consistent TACC reductions and closures imposed on the abalone industry. Some abalone divers have invested in urchin dive licences and switched their primary harvest species from abalone to urchin, while key abalone processing facilities have more than 60 staff employed on urchin processing days (personal observation).

The spatially variable subsidies have been instrumental in redirecting fishing effort to target regions of high importance to the abalone industry, reefs further from port, and areas of low but increasing urchin densities with expanding incipient barrens. Such areas were targeted as they are early warning signs for more extensive barren formation, and early action in these areas is effective and affordable (Ling *et al.*, 2009, 2015; Ling and Keane, 2024). Before the introduction of the spatially variable subsidy >95 percent of the total harvest was being removed from the St Helens region in north-eastern Tasmania; the spatially variable subsidy has dispersed approximately 60 percent of this effort along the eastern coastline in recent seasons (Figure 3; Cresswell *et al.*, 2022).

The intense harvesting under subsidy is starting to have observable impacts on the reefs in which it operates (Keane and Ling, unpublished research surveys, 2021–23). Urchin abundances have declined, and kelp loss has stabilised with some kelp recovery occurring in regions where overall fishing mortality is ~10 percent. Kelp recovery is also observed on the edges of extensive barrens, with repetitive harvesting along the kelp edge pushing the kelp-barren interface deeper. A size-structured stock assessment model under development is highlighting how harvesting has further halted urchin population expansions, with current abundances in assessed regions up to 50 percent lower than modelled scenarios without harvest (Cresswell *et al.*, in prep). This contrasts to the pre-subsidy period where urchin harvesting had a limited impact on urchin density and population growth, as annual harvests were 0.7– 1.7 percent of the estimated population (Ling and Keane, 2018; Cresswell *et al.*, 2020).

FIGURE 3
Maps of eastern Tasmania showing the spatial distribution (%) of the blacklip abalone harvest (2010 to 2020; left panel) and the longspined sea urchin harvest pre (2009–2016) and post introduction of flat rate (2016–2019) and spatially variable (2019–2022) subsidies (right panels)



Note: subsidy rate expressed in $AUD.
Source: Authors' own elaboration.

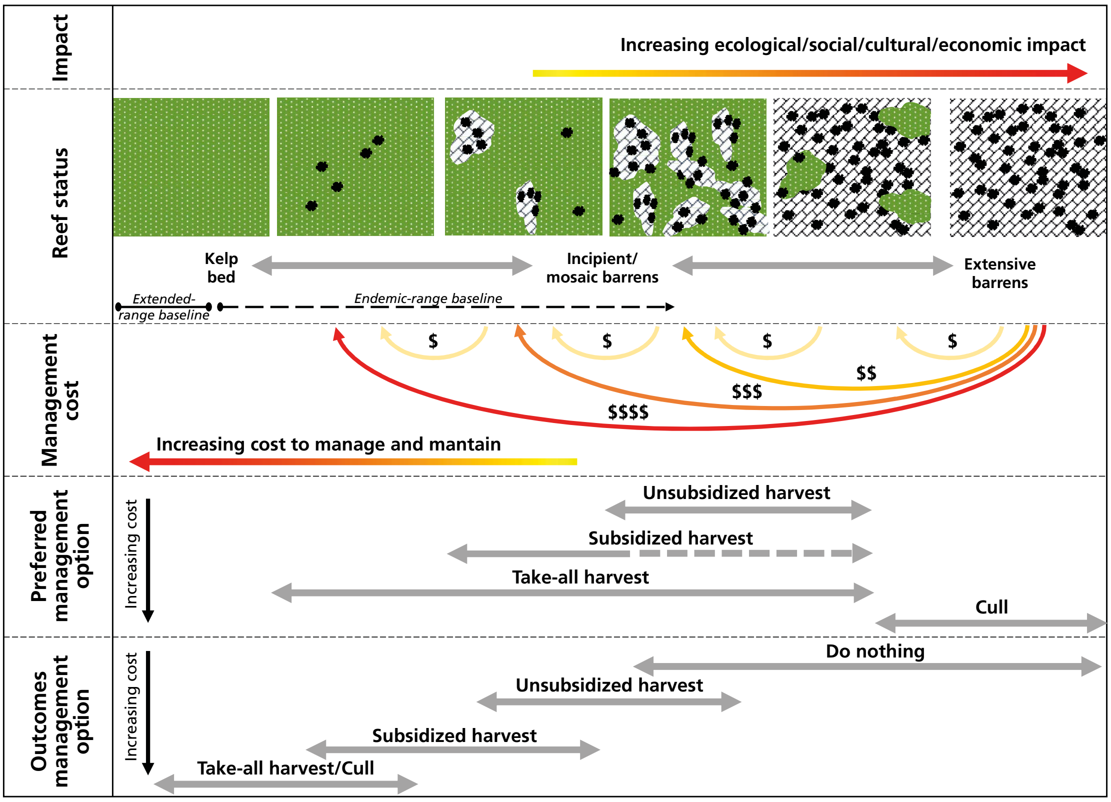
While all management options explored to date may have positive environmental outcomes, the costs and benefits differ considerably. For example, take-all harvests and culling are labour-intensive and expensive exercises for which the costs cannot be fully offset with a marketable product. However, the benefit of using these methods to remove all size-classes of urchin from specific and critically important areas may justify the costs. Urchin numbers have rebounded in the southern take-all harvest area (Charlton, 2021) prompting additional take-all harvests to be conducted in 2023, and urchin harvesting has recommenced in the culled zones, confirming that a long-term and ongoing solution to urchin control is required. Similarly, rebuilding predatory control of urchins can be expensive, may need to be a long-term proposition to become effective, can have economic and social trade-offs (for commercial and recreational fisheries), may impact other species and fisheries (Smith *et al.*, 2022), and may be preventative only (i.e. it may not restore extensive barrens to kelp; Ling and Keane, 2021). After ten years of rock lobster stock rebuilding, large parts of the east coast still have lobster populations at levels <20 percent of the unfished biomass (IMAS, 2023), levels that will likely have a negligible impact on preventing urchin barren formation.

5. CHALLENGES

Raising awareness of the impact of aquatic non-indigenous species (current and potential) is the fundamental challenge to securing timely and effective management intervention and funding, given that much of the marine environment is "out-of-sight, out-of-mind". A further challenge is to secure cooperative action between sectors and even jurisdictions, to manage the threats posed by NIS. The substantial threat posed by urchins to the lucrative abalone fishery motivated the TACL to lobby the Tasmanian state government, and when this was supported by science and resource management, the Tasmanian state government responded by establishing the USD 3.3 million AIRF in partnership with the abalone industry. Without funding, management of the urchin (and NIS species more generally) becomes increasingly difficult, if not impossible. In this case study, we highlight that early cooperative action to prevent extensive overgrazing by sea urchins in the first place can be an affordable and effective strategy, while rehabilitating hyper-stable, extensive barren grounds will inevitably involve substantial effort and cost (Figure 4; Ling *et al.*, 2009; Keane and Ling, 2022).

Cooperative efforts in Tasmania under the AIRF have laid a foundation for interjurisdictional partnership, with a tri-state agreement (with New South Wales and Victoria), supported by key research bodies, having been announced in early 2023 at the National Centrostephanus Workshop (NRE Tas, 2023). The partnership acknowledged that climate-change pressures and resulting impacts differ between states, and developed a national taskforce to tackle the threat of longspined sea urchin along the entire affected Eastern Australian coastline. While management objectives will likely differ between and within each jurisdiction, this is a positive step towards a unified approach. Currently, the management objectives in Tasmania are to build and maintain appropriate harvest pressure on urchins to prevent overgrazing in key habitats, while enabling an ongoing industry for sustained urchin control. Key to this is continuation of funding for harvest subsidies, take-all harvests, research, and addressing spatial challenges.

FIGURE 4
Sea urchin management: interaction of increasing urchin densities on kelps beds with preferred management options and relative cost



As barren size on reefs enlarges away from the baseline, the negative impact on ecological, social, cultural and economic values increases. With increasing impact the associated cost of urchin control to restore kelp habitat increases, with the largest cost being to restore kelp beds from an extensive barren state. Both the relative cost to restore kelp habitat initially (curves), and the cost to maintain the reef status at the target level is shown. The preferred management option is shown for the varied reef states, as is the outcomes of the management option if applied successfully. It should be noted that the outcomes of management options are not permanent, and ongoing monitoring and control will be required

Source: Authors' own elaboration.

Realistic and achievable management objectives (in terms of target urchin abundance and barren extent) over the large scales impacted by longspined sea urchins are yet to be determined, but they will be increasingly difficult to achieve and maintain with the greater the reduction in impact on ecological/cultural/social/economic values desired, due to higher effort and cost (Figure 4). For example, eradication of all urchins from a reef will be significantly more costly than limiting urchin incursion to a reference point of 15 percent urchin barren. However, management objectives can be spatially variable, and high-level suppression (i.e. functional eradication; Green and Grosholz, 2021) objectives may be warranted at localized areas of high value. Marine spatial planning (MSP) to encapsulate values associated with Tasmania's east coast reefs, in relation to longspined sea urchin impacts, is underway, and should be used to underpin a solid management framework. The future development of decision-support tools will address the challenge of assigning appropriate controls to meet biological reference points for reefs (barren extent) with available funding, while simultaneously maximizing fisheries returns.

Assessing, ranking, and implementing various control measures in the absence of adequate data to inform decisions, particularly when the threat of the NIS is increasing rapidly, has been challenging. Diver harvesting (including subsidies and take-all harvests), culling, and predator enhancement (lobsters) were all applied to control urchins in Tasmania without a formal comparative assessment to prioritize methods before funding and implementation transpired. All control measures have limitations, particularly regarding spatial suitability, effectiveness and cost, yet often these were unknown, unrealized or unacknowledged at the time of implementation. Acceptance of the limitations, once known by stakeholders, will fast-track management success through the spatial integration of controls.

Establishing a large-scale, economically successful export industry for longspined sea urchin poses many challenges for the processing sector given the highly technical, labour-intensive nature of roe processing, grading and packing. The lack of intellectual property/knowledge around these procedures, as well as efficiency measures given the very high labour costs incurred, restricted rapid development of the industry. High production costs and infrastructure limitations made the industry initially financially marginal. Subsidies reduced the financial risk of harvesting, facilitated investment in infrastructure, and provided confidence for development and expansion of the industry with all its associated ecological gains. A key challenge is to secure ongoing funding for harvest subsidies, take-all activities and/or culling to supress urchin grazing impacts to low levels, or alternatively increasing the value of the urchin harvest to facilitate harvest to lower urchin densities.

6. LESSONS LEARNED AND KEY RECOMMENDATIONS

- Raising awareness of the impact of aquatic non-indigenous species (current and potential) is the fundamental challenge to securing timely and effective management intervention.
- The commercialization of NIS species (e.g. a harvest industry) should be prioritized, where possible, for long-term control where eradication is physically or economically impossible.
- Strong, early investment by governments and industry in NIS harvest fisheries can be cost-effective in the long term.
- Management objectives can be spatially variable, and high-level suppression (i.e. functional eradication) objectives utilising all available control methods may be warranted at localized areas of high value.
- Marine spatial planning is required to identify areas of high economic/ecological/cultural/social value, and associated decision tools will facilitate prioritization and integration of harvesting and other control methods.

- Intellectual property/knowledge of harvesting and processing NIS, as well as facility/infrastructure development, are key barriers to establishing fisheries for NIS.
- Harvest subsidies can accelerate the development of NIS harvest industries, while spatially variable subsidies can be used to direct harvest of NIS to regions of high value.
- Containment of NIS to non-ecologically significant levels may still be possible in localized areas, but at higher cost.

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Chapter 12

Managing the invasive Nile perch *(Lates niloticus)* in Lake Victoria (East Africa) to maintain species diversity and livelihoods

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SUMMARY

A voracious invasive predator, *Lates niloticus* (Nile perch) was introduced into Lake Victoria (East Africa), the world's largest tropical lake, in the 1950s and 1960s, for socioeconomic reasons. This introduction has been condemned for causing the greatest vertebrate extinction ever observed by scientists, involving the loss of more than 300 fish species (mostly cichlids in the genus *Haplochromis*, commonly called "haplochromines") in less than five years. However, in this paper I discuss instead the contribution of the Nile perch to the maintenance of long-term species biodiversity in Lake Victoria. I argue that in addition to revolutionizing the lake's contribution to human well-being in terms of food and nutritional security and household income, Nile perch also likely prevented a total collapse of fish species diversity from overfishing. The decline in haplochromine abundance, attributed to Nile perch predation, may have allowed the pelagic silver cyprinid (*Rastrineobola argentea*), commonly called "dagaa", to expand and flourish due to reduced competition. This expansion, together with the expansion of Nile perch, diverted fishing pressure away from haplochromines, possibly preventing a total collapse in the local population. At present Lake Victoria is in a dynamic equilibrium, with the surviving native species, especially haplochromines, adapted to the changed environmental conditions and predation pressure from the Nile perch. The Nile perch fishery is still resilient despite increasing fishing pressure, but it faces two imminent management challenges. First, there is a lack of consensus on the status of the fishery, leading to precautionary management measures that are largely "top-down" but ineffective. Second, there is a desire to achieve multiple objectives which are conflicting and hard to implement, leading to management measures with high social costs for fishing communities due to limited livelihood options. Conserving the remaining biodiversity will require a management regime that enables fishers to diversify their gears and exploit the highly productive components of the Nile perch fishery, thus shifting fishing pressure away from the vulnerable and less resilient species, especially haplochromines. Whereas Nile perch is highly productive and can support increased catches, expansion of the fishery is not a question of adding more fishers or more gear. Instead, the fishery could be expanded by shifting focus from large and less productive stocks to smaller highly productive stocks. This would require changes in legislation to relax gear sizes and allow the harvest of all fish sizes in proportion to their productivity. Such a paradigm shift would (i) support a limited export industry for large Nile perch (fulfilling the economic objective), (ii) provide riparian communities with small and intermediate sizes of fish to alleviate malnutrition, and (iii) reduce friction between fishers and the state.

1. FISHERY CONTEXT

Lake Victoria (East Africa) is the world's largest freshwater tropical lake, with a surface area of about 688 000 km². The lake is shared by three countries (Uganda, Kenya and Tanzania), and its catchment has one of the highest population densities in Africa, approaching 500 people per square kilometre (Ogutu-Ohwayo *et al.*, 2021). The lake is famous for being home to one of the world's largest assemblages of fish diversity – and this has also registered the greatest extinction of vertebrates ever observed by scientists (Kaufman, 1992). Before the 1980s, Lake Victoria hosted more than 500 fish species, mainly cichlids of the genus *Haplochromis* (commonly called "haplochromines"), distributed across more than 15 trophic guilds (Witte *et al.*, 2007a, b). By the mid-1980s, and after the introduction of the Nile perch (*Lates niloticus*), more than 300 of these haplochromine species had disappeared from the lake, a fact mainly attributed to predation by the invasive species (Kaufman, 1992; Witte *et al.*, 2007b).

Before the introduction of the invasive Nile perch, the fishery in Lake Victoria was dominated by demersal and benthopelagic species, notably the native oreochromines (*Oreochromis esculentus* and *O. variabilis*), catfishes (in several families), marbled lungfish and haplochromines, with annual landings of little more than 100 000 tonnes (Natugonza *et al.*, 2020, 2022). Today, by contrast, the lake supports a highly productive fishery with total annual landings of approximately 1 million tonnes, worth USD 600-900 million (LVFO, 2016a). Catches are dominated by just three species: the introduced Nile perch and Nile tilapia (*Oreochromis niloticus*) and the native silver cyprinid (*Rastrineobola argentea*). The silver cyprinid constitutes the largest proportion of the catch by volume (about 50 percent), followed by Nile perch (about 25 percent), although more than half of the fishery revenues come from Nile perch (LVFO, 2016a). The main fishing gears used are longlines (especially for Nile perch), gillnets (for both Nile perch and Nile tilapia and other species), and small seines (for the silver cyprinid). The mode of operation of the fishing gears differs by region and water depth: in shallow inshore waters (<20 m) gillnets and longlines are operated with small to medium-sized paddled canoes; in coastal (20–40 m) and deep (>40 m) waters both gears are operated with large Sesse boats powered by sail or outboard engine (LVFO, 2016a).

2. HISTORY AND IMPACTS OF NILE PERCH ON LOCAL FISHERIES AND ECOSYSTEMS

The Nile perch, a voracious invasive predatory fish – considered by the IUCN to be one of the world's worst invasive species (Lowe *et al.*, 2000) – was introduced into Lake Victoria in the 1950s and 1960s for economic reasons: it was hoped individuals would feed on the unfished small bony haplochromine cichlids and grow into large fish of commercial importance (Pringle, 2005), and also that the species would absorb the increasing fishing pressure that had collapsed the native oreochromine fisheries (Ogutu-ohwayo, 1990). Before the introduction and establishment of Nile perch, haplochromines were the most abundant fish taxa, accounting for more than 80 percent of the demersal fish biomass in Lake Victoria (Kudhongania and Cordone, 1974). However, this biomass was largely unexploited because of its low commercial value (Pringle, 2005). The only two species targeted in the fishery were *O. esculentus* and *O. variabilis*, which were eventually overfished and had collapsed by the 1940s (Natugonza *et al.*, 2021). The Nile perch population became fully established in the whole lake in the late 1970s through to the early 1980s; during the same period, trawl surveys showed that the relative biomass of haplochromines declined almost to zero (Taabu-Munyaho *et al.*, 2016). Because of the correlation between the decline in haplochromine diversity and abundance and the expansion of Nile perch, almost all studies from the late 1980s through to the mid-1990s attributed the decline to predation by Nile perch (Ogutu-ohwayo, 1990; Kaufman, 1992; Witte *et al.*, 1992a, b). Recent studies, however, have suggested that limnological changes associated with a warmer climate and eutrophication likely played a major role in the haplochromine decline, and at the same time created favourable conditions for the establishment of Nile perch (Hecky *et al.*, 2010; van Zwieten *et al.*, 2015).

Despite the diminished fish species diversity and the associated ecosystem changes that were attributed to its introduction, Nile perch fuelled a lucrative fishery that revolutionized the lake's contribution to human well-being in terms of food security and nutrition, as well as household income. Figure 1 shows changes in two simple fishing effort indicators (numbers of fishers and boats) and total landed catches over time alongside changes in population density around the lake. The population around the lake had been increasing steadily since 1960, but the number of fishers doubled between 1984 and 1990, a period that coincided with the establishment of Nile perch (Taabu-Munyaho *et al.*, 2016). The new entrants were undoubtedly responding to the booming Nile perch stocks, a fact which is also reflected in catch levels: these increased from almost nothing in 1980 to ca. 340 000 tonnes by 1990. The number of fishers remained relatively stable between 1987 and 1995, only increasing slightly by 1999. Between 1999 and 2005, the number of new entrants into the fishery increased threefold – but total catches of Nile perch remained unchanged. However, these new fishers may not have been attracted solely by Nile perch, as the catch rates (catch per unit effort) for the species were at their lowest recorded levels (Natugonza *et al.*, 2022), and surveys showed that its relative abundance was also declining (Getabu *et al.*, 2003; Taabu-Munyaho *et al.*, 2016). Instead, the majority of the new fishers were likely responding to the increase in dagaa stocks, which at the time were expanding – partly as a result of facing less competition from haplochromine species that were declining due in part to predation by Nile perch (Sharpe *et al.*, 2015). During this period, however, dagaa was less preferred than Nile perch for human consumption. The increase in fishing effort, therefore, was likely due to the scarcity of Nile perch relative to the increasing demand for fish from the growing human population around the lake. This suggests that even without the introduction of Nile perch, fishing effort (especially in terms of number of fishers) would still have increased to exploit any abundant fish (in this case haplochromines), as was the case for dagaa. Similar shifts to less preferred but more abundant fisheries have been seen on other African Great Lakes. On Lake Albert (Uganda), fishers have shifted from the declining large commercial fisheries (e.g. *Hydrocynus* spp. and *Alestes* spp.) to small but abundant pelagic species such as *Brycinus nurse* and *Engraulicypris bredoi,* even when the larger species are preferred and would be the most targeted if they were abundant (Nakiyende *et al.*, 2023). Because haplochromines are less resilient to fishing pressure (Natugonza *et al.*, 2021), the high fishing pressure in Lake Victoria shown in Figure 1 could have easily collapsed their populations in the absence of Nile perch and dagaa. The implication of this is that both Nile perch and dagaa are key to the sustenance of livelihoods and fish species diversity in Lake Victoria.

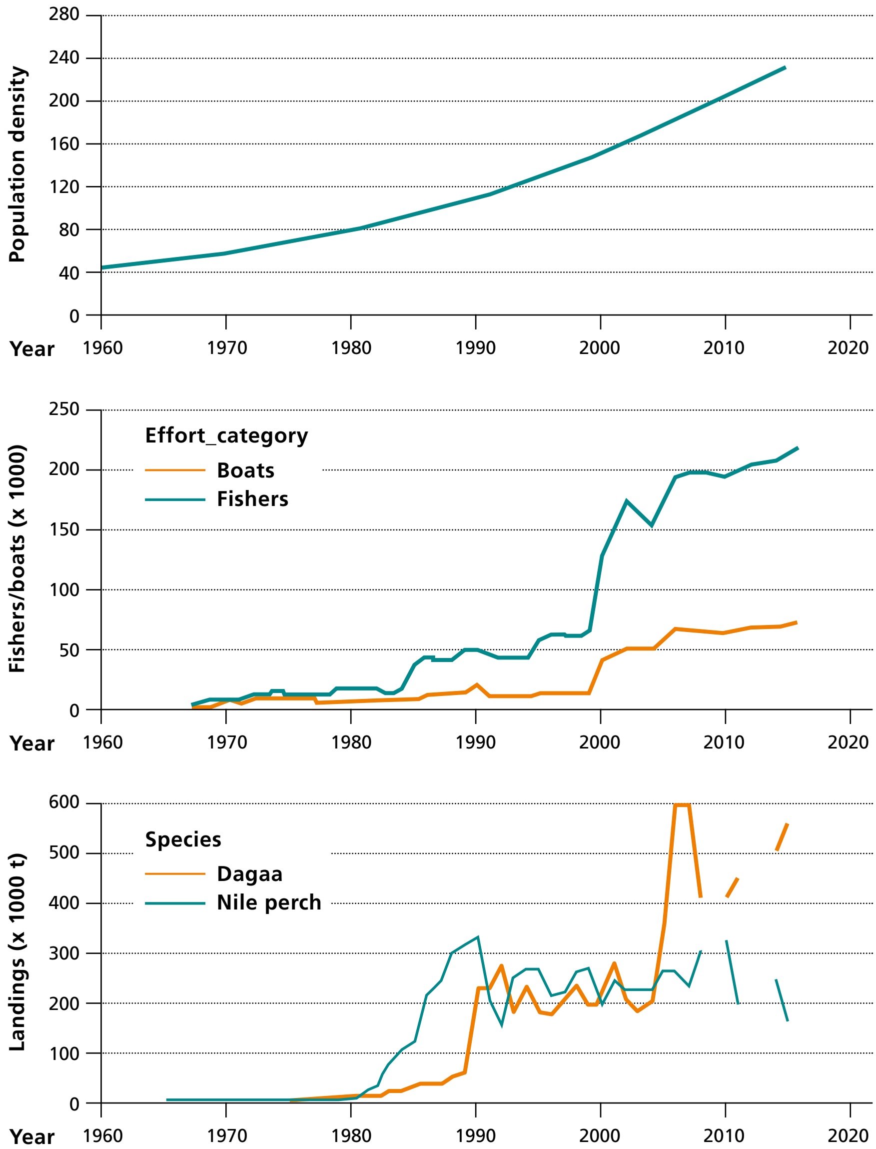
3. ADAPTIVE RESPONSES

The introduction of Nile perch has had both negative and positive consequences for the fisheries of Lake Victoria. Whereas the historical negative impact on biodiversity is visible (Witte *et al.*, 1992a, b), the positive outcomes, associated with increased fish production and transformed livelihoods of fishers and riparian communities, are also well appreciated (Aloo *et al.*, 2017). Consequently, adaptive responses have mainly focused on ensuring that fishing for Nile perch takes place at levels that are sustainable enough for it to remain abundant and commercially viable, mainly to support the export sector. However, this has caused continuous clashes between the state and the fishers, with the latter continuing to exploit all size classes to supply different markets (Mpomwenda *et al.*, 2022).

FIGURE 1

Population density (people per square kilometre), overall fishing effort (numbers of fishers and boats) and landings (thousand tonnes) in Lake Victoria over time

Dotted vertical lines show major shifts in fishing effort. Data sources: fisheries data (Kolding *et al*., 2014; Natugonza *et al*., 2022); population data (Kolding *et al.,* 2008)

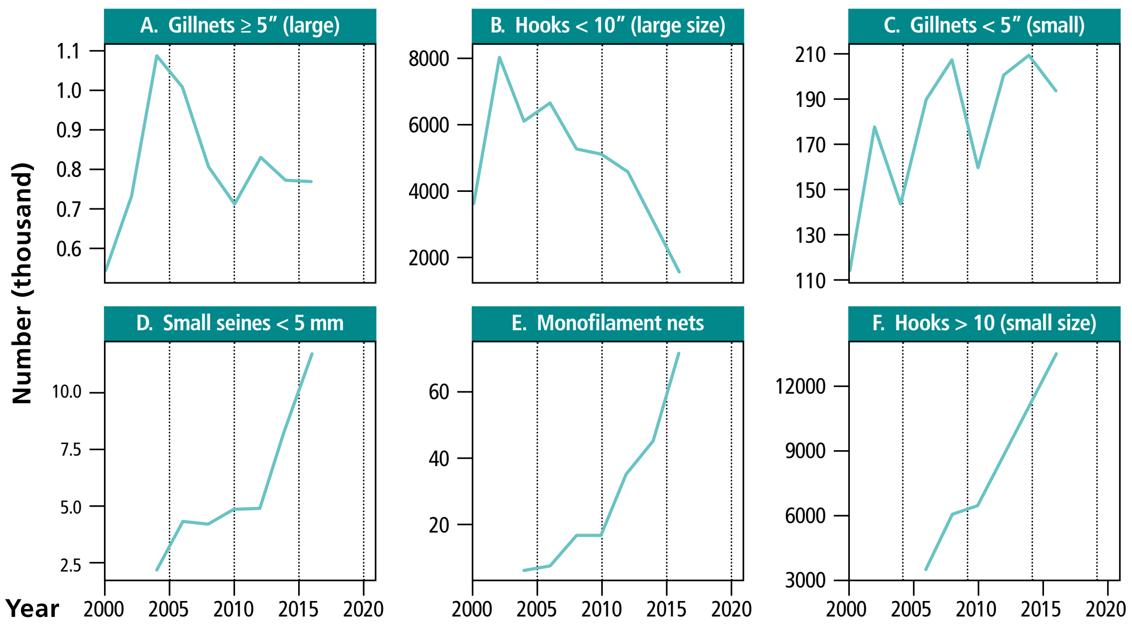


Source: Authors' own elaboration.

In order to maintain viable populations of Nile perch in Lake Victoria, two Regional Plans of Action (RPoA I & II) were prepared. RPoA I aimed to address the capture of undersized fish (LVFO, 2004), while RPoA II aimed to halt any further increases in fishing capacity (LVFO, 2007). To achieve these goals the plans introduced several restrictions to control fishing effort, including minimum mesh size for gillnets, harvest slot size, restricted fishing areas, restricted fishing methods, and restrictions on the number and type of gears permitted (LVFO, 2016b). Consequently, it is illegal to (i) fish using beach/boat seines, monofilament nets, vertically-joined gillnets, gillnets of less than 17.8 cm stretched mesh size, and hooks smaller than size 9, (ii) fish in closed/breeding areas, and (iii) harvest Nile perch of less than 50 cm total length (LVFO, 2016b). Other regulations such as a ban on fishing for haplochromines were primarily aimed at ensuring abundant prey for Nile perch, while also indirectly protecting the vulnerable haplochromines. These measures were in the most part aimed at increasing the biomass of Nile perch to support the export sector (LVFO, 2016b), but this has largely remained unachieved (Nyamweya *et al.*, 2023).

While the above restrictions have been around for nearly two decades, levels of compliance by fishers have been minimal (Mpomwenda *et al.*, 2022). Figure 1 shows that fishing capacity (in terms of the number of fishers and fishing boats) has continued to grow, while Figure 2 suggests that the use of legal gear sizes has decreased (Figure 2A–B) as the amount of illegally sized gear has continued to increase (Figure 2C–F). This progressive increase in the number of gears with small mesh/hook sizes and illegal gear types has been interpreted by some researchers and managers as a sign of depleted fish stocks (e.g. Mkumbo and Marshal, 2015). However, it could also be a response to the increase in abundance of small-sized fishes observed in the past decade (Nyamweya *et al.*, 2023), attributed to high production and recruitment (Kolding *et al.*, 2019). The high number of gears with small mesh/hook sizes could be a diversification strategy to maximize catch of the most abundant stocks and to supply different markets (unpublished market data collected in 2011 on the Ugandan part of Lake Victoria shows that large Nile perch (>50 cm) is mainly destined for export, intermediate sizes (30–50 cm) are largely sold in urban markets, while rural markets are largely dominated by the smallest sizes).

FIGURE 2
Numbers of fishing gears and their sizes in Lake Victoria over time. Data from LFVO (2016c)

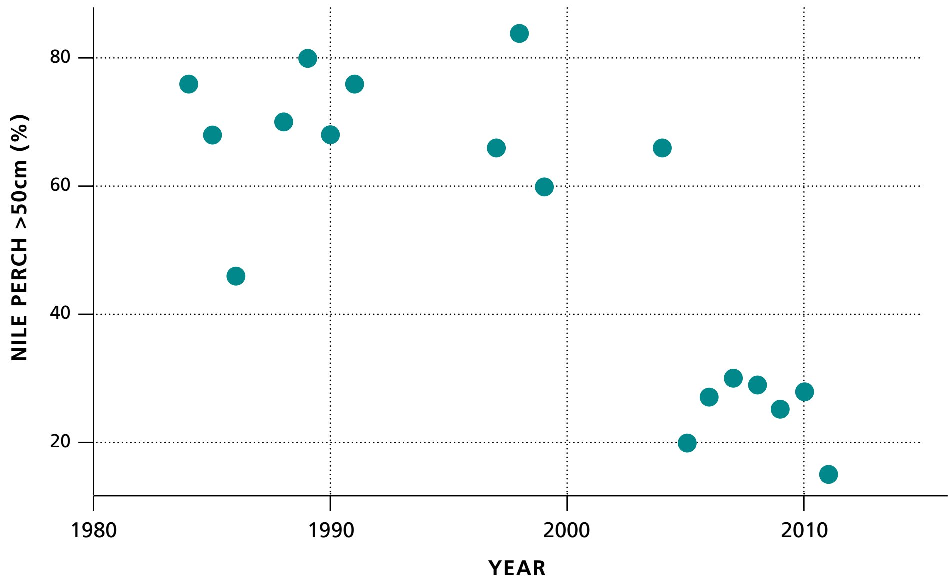


Source: Authors' own elaboration.

4. OUTCOMES

The outcomes of the management responses described above can be assessed in light of the fishery objectives. Since 2005, Lake Victoria fisheries have been managed through three five-year management plans, and in each plan the economic objective of maximizing Nile perch exports has been emphasized (LVFO, 2016b). Data from the industry as well as fishery-independent surveys, however, show that this management objective is yet to be achieved. The biomass of large Nile perch (>50 cm), which dominates the export sector, has not increased, including in parts of the lake with strict enforcement of fishery regulations (Nyamweya *et al.*, 2023). Instead, the volume of exports reduced by almost half between 2005 and 2010 (Aloo *et al.*, 2017). This decline in exports is consistent with a shift to gears with small mesh/hook sizes, resulting in the Nile perch catch being dominated by small sizes that largely serve local markets (Figure 3). Data in Figure 3 show that the proportion of large Nile perch in the catches declined from 60–80 percent during the 1980s and 1990s to 20–30 percent after 2005, a period that has also been marked by continual clashes between fishers and fishery enforcement personnel (Johnson and Bakaaki, 2016; Glaser, 2018).

FIGURE 3
The proportion of large Nile perch (>50 cm total length) in the landed catch over time. Data from Mkumbo and Marshall (2015) and LVFO (2016a)



Source: Authors' own elaboration.

5. CHALLENGES

Lake Victoria faces multiple stressors that also threaten the sustainability of the Nile perch fishery (Hecky *et al.*, 2010). Fisheries managers have two major challenges: (i) a lack of consensus on the status of the fishery and associated management measures; and (ii) conflicting management objectives, leading to management measures that may not be practically feasible to implement. These challenges, which are briefly summarized below, have been widely discussed elsewhere (e.g. Kolding *et al.*, 2008; Natugonza *et al.*, 2022; Nyamweya *et al.*, 2023), and could largely be responsible for the continuous conflict between fishers and managers.

Several studies have been conducted to assess the status of the Lake Victoria Nile perch fishery in order to guide management using various fishery indicators. The commonly used indicators are catch per unit effort (CPUE), biomass, total landings, and average size of fish in the catch. The interpretation of these indicators, however, has been a subject of debate (see Kolding *et al.*, 2008 versus Mkumbo and Marshall, 2015). For instance, fishery data show a remarkable decrease in catch per boat from 35–45 tonnes per year in the early 1990s to less than 15 tonnes per year after 2000 (Kolding et al., 2019), as well as a decline in numbers of large Nile perch (i.e. individual fish greater than 50 cm in total length) in the catches during the same period (Figure 3). These changes have largely been interpreted as a sign of overfishing and collapsing stocks, and to show that strong management actions are needed to ensure the sustainability of Nile perch (Mkumbo and Marshall, 2015; LVFO, 2016b). However, other researchers argue that there is no evidence of declining catches and biomass of Nile perch in Lake Victoria, and that draconian management actions are not justified (Kolding *et al.*, 2019; Nyamweya *et al.*, 2023). Indeed, recent data show that Nile perch size structure has contracted more in parts of the lake that strictly enforce minimum mesh size regulations (e.g. Uganda) than in areas with no strict enforcement (e.g. Kenya) (Nyamweya *et al.*, 2023). In light of these debates managers have chosen to work on a precautionary basis, which could partly explain the deployment of the army in lake since 2017, especially in Uganda, to enforce fishery regulations (Mpomwenda *et al.*, 2022), even when such actions may not be justified (Nyamweya *et al.*, 2023).

Another management challenge concerns the conflicting management objectives. The Lake Victoria Fisheries Organization (LVFO) coordinates the management of Lake Victoria fisheries through five-year phased management plans, which define the management objectives mainly from the national developmental objectives of the three coastal countries (Uganda, Kenya and Tanzania). Generally, management aims to ensure a consistent food supply (mainly through increasing catches), provide increased and diversified fisheries commodities to add value in domestic and international markets, create sufficient employment opportunities in the fisheries value chain, and to conserve native biodiversity (LVFO, 2016b). Achieving these multiple objectives is not only challenging but impossible because of the trade-offs involved (Natugonza *et al.*, 2020). Indeed, the targets and actions defined in the management plans (see LVFO, 2016) primarily have economic objectives, although some of the measures such as the protection of breeding areas and restrictions on the use of indiscriminate gears may indirectly benefit the conservation of native species. For instance, for Nile perch, the objective is to increase stock biomass to support the export sector (by limiting access to the fishery), but catches and employment opportunities are unlikely to be increased by limiting access to the fishery. Also, the economic objective disadvantages poor and vulnerable fishers with limited livelihood options, given that the revenue generated from an export-oriented fishery is not necessarily used to create alternative employment for the affected fishers (Nunan, 2014; Johnson and Bakaaki, 2016). Because the majority of fishers in this category fish for food in nearshore and coastal areas, using gears and methods that have been declared illegal (LVFO 2016a, c), there is always conflict between fishers and the managers, associated with loss of lives and livelihoods.

6. LESSON LEARNED AND KEY RECOMMENDATIONS

- The decline in native species after the introduction of Nile perch, especially the ecologically-important haplochromines, was remarkable – as was the positive socioeconomic transformation of the fishing communities after its successful establishment.
- Some of the fish species that disappeared at the peak of Nile perch establishment reappeared once Nile perch numbers reduced with increasing fishing effort, leading to suggestions that selective harvesting of Nile perch could enhance the

recovery of the haplochromines (Owiti, 2011). However, the data on the evolution of the Lake Victoria fisheries and those of other African Great Lakes suggest otherwise; a reduction in the Nile perch stocks could drive fishers to start targeting haplochromines, which are less resilient to fishing, leading to their collapse.

- The emphasis on economic objectives in the management of Lake Victoria fisheries is inevitable because of lucrative commercial components, involving substantial export earnings (LVFO, 2016b). However, this should be balanced with social considerations by allowing flexibility in fishing gear sizes.
- Although Nile perch is highly productive and resilient to fishing, the fishery will not be further expanded by the addition of more fishers or more gear; instead, the fishery could be expanded by shifting focus from the large and less productive stock to the small and highly productive stocks. This would require adjusting the legislation to relax gear sizes, and the harvest of all fish sizes in proportion to their productivity (see Kolding *et al.*, 2019; Natugonza *et al.*, 2022). Such a paradigm shift would (i) support a limited export industry for large Nile perch (fulfilling economic objectives), (ii) provide riparian communities with small to intermediate sizes of fish to alleviate malnutrition, and (iii) reduce conflicts between state and fishers.

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Appendix 1
Expert opinions around the globe: results of the online survey

In order to collect further information on actions taken to address the impacts of aquatic invasions in both marine and freshwater ecosystems, FAO and CNR-IRBIM created an online survey and disseminated it to a number of selected experts around the globe. The questionnaire was shared with experts during the period from November 2022 to January 2023. The survey consisted of a total of 32 questions related to the introduction of AIS, their impacts, and the outcomes of management actions.

A total of 110 experts from 44 countries completed the questionnaire, reporting actions on 71 different taxa among fish, molluscs, crustaceans, other invertebrates, plants and seaweeds.

Data was analysed using the software R v. 4.2.2 (Core Team, 2022), and the same software was used to create graphs and figures.

DESCRIPTION OF THE SAMPLE

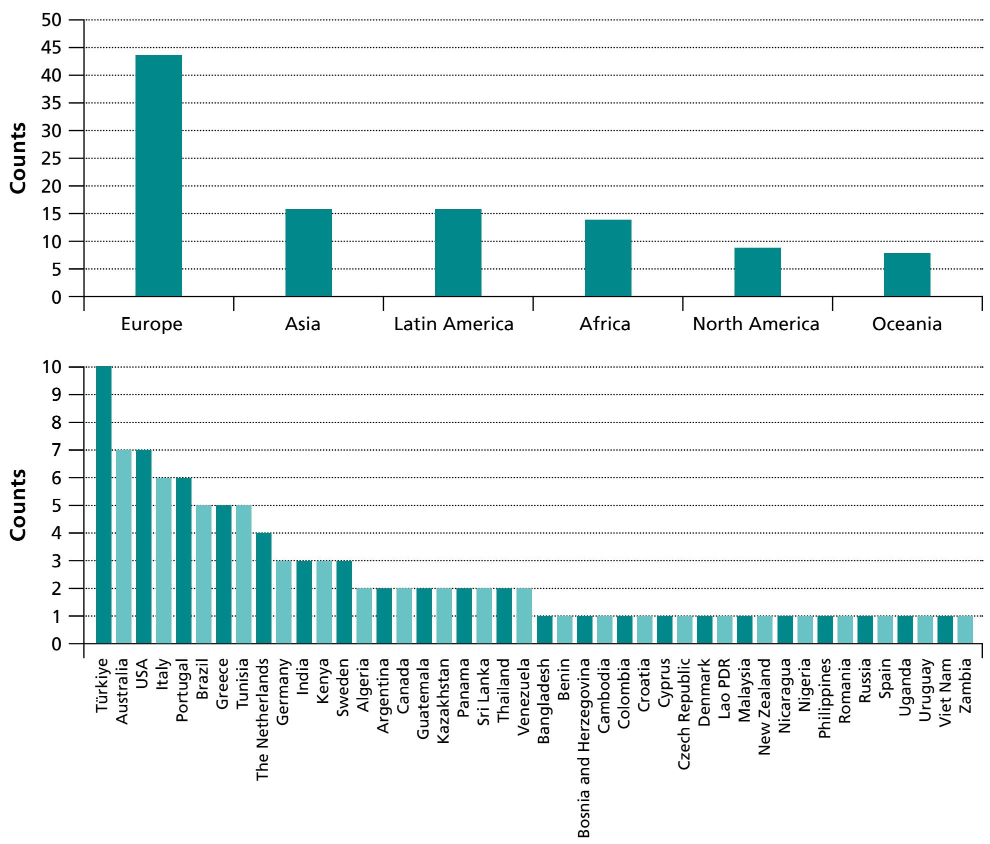

FIGURE A1
Origin of the respondents by continent (A) and by country (B).
Total number of respondents = 110

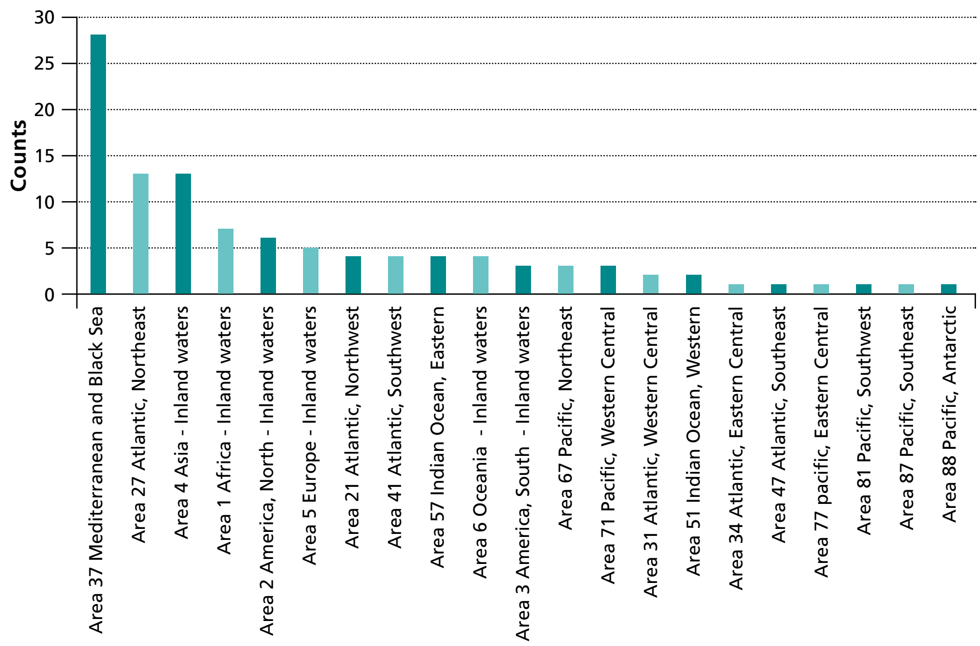

FIGURE A2
Distribution of study areas in marine and inland waters

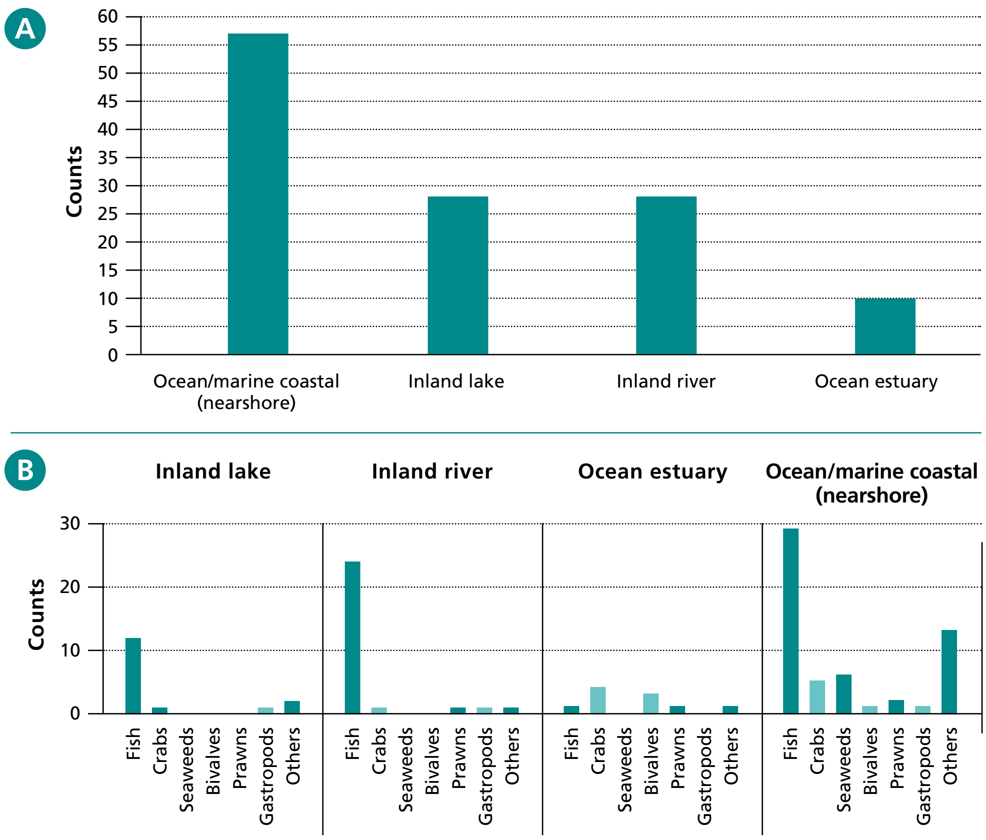

FIGURE A3
Aquatic systems under observation (A) and number of NIS taxa by aquatic system (B)

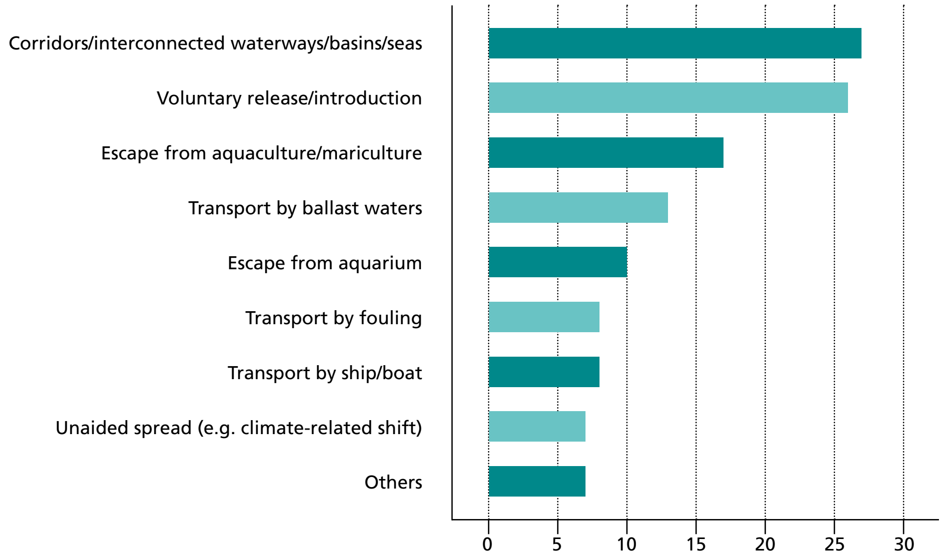

FIGURE A4
Main introduction routes of the reported taxa

TABLE AI

NIS taxa indicated by the respondents, listed in alphabetical order.

NB: scientific names are as reported by the respondents and have not been checked for accuracy.

Taxa	N	Species	N
Arapaima sp	1	*Mytella strigata*	1
Asparagopsis armata	1	*Mytilla* sp	1
Atherina boyeri	1	*Mytilopsis* sp	1
Botryllus schlosseri	1	*Neogobius melanostomus*	2
Callinectes sapidus	3	*Oncorhynchus gorbuscha*	1
Carassius gibelio	2	*Oncorhynchus mykiss*	2
Carcinus maenas	5	*Ophiothela mirabilis*	2
Caulerpa cylindracea	1	*Oreochromis mossambica*	1
Channa argus	2	*Oreochromis niloticus*	7
Cherax quadricarinatus	1	*Oreochromis* sp	3
Clarias gariepinus	2	*Pangasionodon gigas*	1
Crassostrea gigas	1	*Penaeus aztecus*	1
Cynoscion regalis	1	*Perca fluviatilis*	1
Cyprinus carpio	4	*Plotosus lineatus*	2
Eriocheir sinensis	1	*Pomacea canaliculata*	1
Gasterosteus aculeatus	1	*Pomadasys stridens*	1
Generic Acipenseriformes	1	*Pterois miles*	4
Generic Ascidian	1	*Pterois volitans*	2
Generic Asian carp	1	*Pterygoplichthys pardalis*	1
Generic bryozoan	1	*Pterygoplichthys* sp	2
Generic Prawns	1	*Pygocentrus nattereri*	1
Halophila stipulacea	2	*Rapana venosa*	2
Hemigrapsus sanguineus	1	*Rhopilema nomadica*	1
Hypophthalmichthys molitrix	1	*Rugulopteryx okamurae*	3
Hypophthalmichthys spp	1	*Sabella spallanzani*	1
Hypostomus plecostomus	2	*Salix fragilis*	1
Lagocephalus guentheri	1	*Salmo trutta*	1
Lagocephalus sceleratus	6	*Sargassum muticum*	1
Lagocephalus spadiceus	1	*Sarotherodon melanotheron*	1
Lagocephalus suezensis	1	*Siganus luridus*	1
Largemouth bass	1	*Siganus rivulatus*	2
Lates niloticus	3	*Sphoeroides pachygaster*	1
Libinia dubia	1	*Styela clava*	1
Limnothrissa miodon	1	*Tinca tinca*	1
Longspined Sea Urchin	2	*Torquigener flavimaculosus*	1
Macrobrachium rosenbergii	1	*Tubastraea tagusensis*	1
Macrobranchium sp	1	*Tylerius spinosissimus*	1
Micropterus salmoides	1	*Unomia stolonifera*	1
Mnemiopsis leidyi	1		
Morone saxatilis	1		

IMPACTS

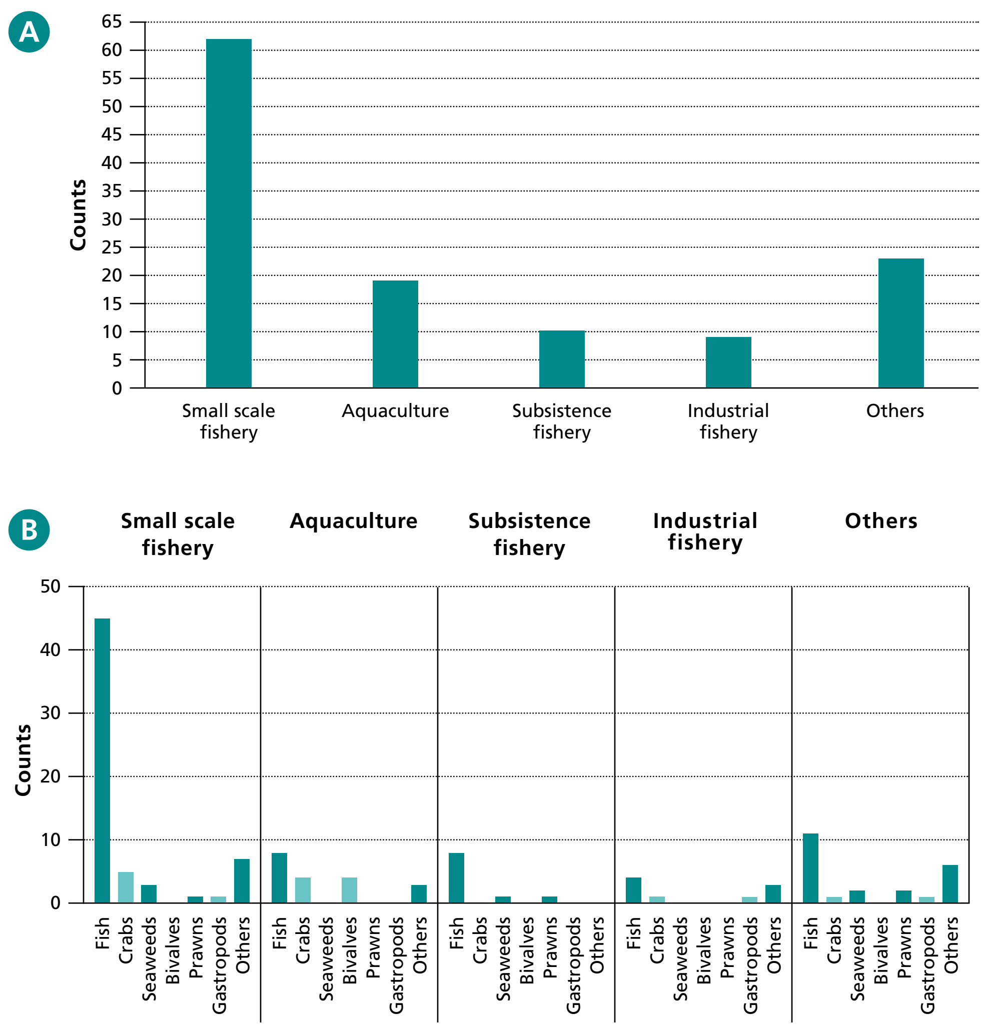

FIGURE A5
Production systems affected by the presence of NIS (A) and distribution of NIS affecting each production system (B)

MANAGEMENT ACTIONS

TABLE AII
Summary of the management actions undertaken by the respondents to deal with aquatic NIS. The category 'Others' includes actions such as research, monitoring, regulatory frameworks and other specific interventions that do not fall into the categories listed in the rest of the table

Which action(s) has been undertaken to manage the invasion?	Frequency
No action	47
Raising public awareness/knowledge	33
Species removal (e.g. governments supporting target fishery to remove the invaders from natural habitat)	33
Training of fishers/workers (including use of new fishing gears, business skills, product development etc.)	20
Early warning (e.g. development of mobile apps for species reporting)	12
Species eradication (e.g. attempts to remove all individuals)	12
Containment (e.g. physical barriers, electric fences and other strategies to limit the geographical spread of the invaders)	11
Technological adaptation in fishery (e.g. replacement of fishing gear/technique)	11
Habitat restoration	10
Biological control (e.g. the use of living organisms to suppress invasive populations)	8
Relocation of landing and processing facilities (including new processing infrastructures)	5
Insurance schemes to protect fishers against loss and damage after biological invasions	4
Certification and product traceability	2
Others	15

	Inland waters			Ocean/marine		
	I DON'T KNOW	NEUTRAL	POSITIVE OUTCOMES	I DON'T KNOW	NEUTRAL	POSITIVE OUTCOMES
Species removal		92	49	2	112	57
Raising public awarness/knowledge		58	28	7	112	60
Training of fishers		44	29	14	70	73
Early warning		15			47	27
Containment of NIS		40	17		20	12
Habitat restoration	8	20	20		20	8
Biological control		2	11		23	22
Relocation of landing		2	9		11	15
Insurance to protect fishers			4		6	9
Product traceability		10		7		3
Others		23	17		41	19

Freq: 100, 75, 50, 25, 0

FIGURE A6
Outcomes of management actions
Numbers inside each cell are effective counts of the answers.
Colours represent the percentage of the answers per management action.

	Inland waters	Ocean/ marine
Lack of awarness/understanding/acceptance/dialogue	4	8
Funding/economic isuues	3	8
Infeasibility of control (abundant populations)	4	3
Conservation of natural habitats/native species	2	4
Enforcement	5	1
Limited efforts/spatial/temporal scale	3	3
Monitoring/scientific knowledge	2	4
Others		2

Freq: 25, 20, 15, 10, 5, 0

FIGURE A7
Challenges related to the management of aquatic NIS
Numbers inside each cell are effective counts of the answers.
Colours represent the percentages of answers per aquatic system.

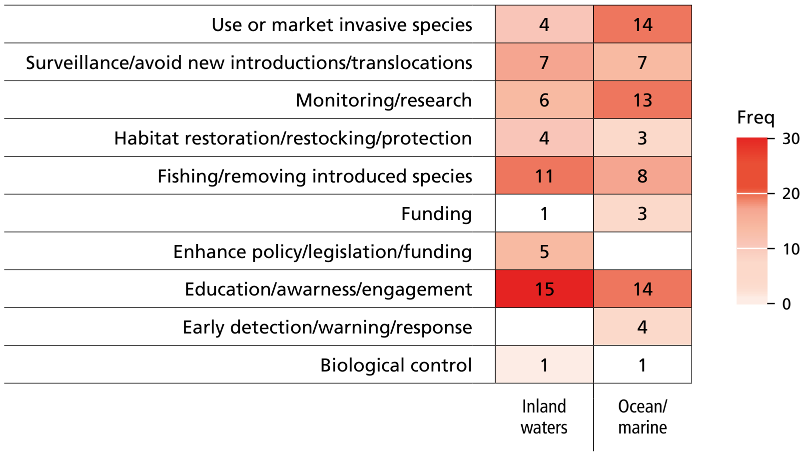

FIGURE A8
Best practices in managing aquatic NIS

Numbers inside each cell are effective counts of the answers.
Colours represent the percentages of answers per aquatic system.

Appendix 2
Useful links and online resources

Code of Conduct for Responsible Fisheries
www.fao.org/fi/agreem/codecond/codecon.asp

FAO Technical Guidelines for Responsible Fisheries
www.fao.org/3/W4493E/w4493e00.htm

Code of Practice on the Introduction and Transfer of Marine Organisms
www.nobanis.org/globalassets/ices-code-of-practice.pdf

Codes of Practice and manual of procedures for consideration of introductions and transfers of marine and freshwater organisms
www.fao.org/3/ae989e/ae989e00.htm

International mechanisms for the control and responsible use of alien species in aquatic ecosystems
www.fao.org/3/a0113e/a0113e00.htm

IPBES Invasive Alien Species Assessment 2023
www.ipbes.net/IASmediarelease

The increasing pressure of a globalized economy and the effects of a changing climate are making biological invasions a frequent feature of marine and freshwater environments. Global fisheries and aquaculture need to adjust to these changes, with the dual aim of reducing the negative ecological consequences caused by these species and making the most of the opportunities they may offer. Capitalizing on a spectrum of management actions from case studies, a global survey and a literature review, this report presents nine measures – grouped as environmental, social or socioeconomic strategies – and explores their potential, main challenges, and enabling factors. These measures, discussed by a group of international experts, may be used as practical resources to aid in the evaluation and identification of appropriate fisheries management responses to aquatic invasive species in the context of climate change. While this report does not attempt to comprehensively address all the complexities of its fast-evolving subject, it provides a starting point for adaptation strategies, recognizing the diverse legal, cultural and socioeconomic conditions of different fisheries, and offering valuable insights to help policymakers, fisheries managers and practitioners deal with aquatic invasions.

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