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Overview Article

Bridging aquatic invasive species threats across multiple sectors through One Biosecurity

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Abstract

Understanding the magnitude of biosecurity risks in aquatic environments is increasingly complex and urgent because increasing volumes of international shipping, rising demand for aquaculture products, and growth in the global aquarium trade, are accelerating invasive alien species spread worldwide. These threats are especially pressing amid climate and biodiversity crises. However, global and national biosecurity systems are poorly prepared to respond because of fragmented research and policy environments, that often fail to account for risks across sectors or across stakeholder needs and fail to recognize similarities in the processes underpinning biological invasions. In the present article, we illustrate the complex network of links between biosecurity threats across human, animal, plant, and environment sectors and propose a universal approach to risk assessment. One Biosecurity is a holistic, interdisciplinary approach that minimizes biosecurity risks across human, animal, plant, algal, and ecosystem health and is critical to reduce redundancy and increase cross-sectoral cohesion to improve policy, management, and research in aquatic biosecurity.

Keywords: ballast, biofouling, fisheries, One Health, zoonoses

Biosecurity is an inherently interdisciplinary topic because it refers to the research, procedures, and policies that cover the exclusion, eradication, and management of alien plant and animal pests, parasites, and pathogens and the release and management of genetically modified organisms and their products (Hulme 2014). Within aquatic environments, alien species have a variety of negative effects across human (Souty-Grosset et al. 2018), animal (Foster et al. 2021), plant (Tasker et al. 2022), algal (Li et al. 2023), and ecosystem health (figure 1; Anton et al. 2019). Irrespective of effects, and whether an aquatic alien organism is a human pathogen, alga, invertebrate, or vertebrate, there are sufficient similarities in the processes of biological invasions that a common framework should be applied to assess and manage risks (Hulme 2020, Hulme 2021). One Biosecurity is a holistic, interdisciplinary approach to minimize biosecurity risks across human, animal, plant, algal, and ecosystem health and aims to reduce redundancy, increase interdisciplinarity, and improve integration across sectors, assisting in global biosecurity management and policy development (Hulme 2021). This approach has relevance across sectors (i.e., human, animal, plant, and ecosystem health) and disciplines, where, for example, the major pathways of aquatic alien species introduction (e.g., via ballast water, biofouling, aquaculture, ornamental aquarium trade; figure 2a–c) to new regions are managed and treated differently, despite each leading to invasions that threaten human, animal, plant, and ecosystem health (Nunes et al. 2015). One Biosecurity has been developed from a terrestrial biosecurity perspective (Hulme 2020), and although issues vary considerably between aquatic and terrestrial ecosystems (box 1), we show how the approach would improve the management of aquatic invasions.

Impacts of aquatic invasive alien species on human, animal, plant, and ecosystem health

In addition to the well-recognized impacts aquatic invasives have on aquatic biodiversity and ecosystems (Molnar et al. 2008), they also have impacts on human health. Lionfish (*Pterois* spp.; figure 2e) are native to the Indo-Pacific but have become increasingly widespread on the Eastern seaboard of the Americas (because of deliberate releases from aquaria), as well as in the Mediterranean Sea (through movement along the Suez Canal), and pose a threat to human health from venomous spines that can cause severe injury to humans and potential anaphylactic shock (Fleming et al. 2023). Invasive alien species can also lead to human health impacts indirectly, where, for instance, invasive shellfish with bioaccumulated toxins produced in harmful algal blooms (HABs) are consumed (Hallegraeff 1998), whereas HAB species also pose more direct risks where they are themselves invasive (Katsanevakis et al. 2018). A wide range of invasive alien pathogens, including microbial eukaryotes (e.g., such as *Entamoeba histolytica*, *Cryptosporidium parvum*), bacteria (e.g., *Vibrio cholera*, *Escherichia coli*), and viruses (e.g., hepatitis A virus, norovirus) have been transported around the world by various vectors, including in ballast water, and can be transmitted to humans through contact with infected waters or infected hosts that have aquatic phases in their life cycles (Havel et al. 2015). Fish and aquatic-derived zoonotic disease agents include bacteria, viruses, fungi, protozoa (e.g., *Cryptosporidium* spp.), and parasitic worms (e.g., roundworms, flukes, and tapeworms) and have caused considerable problems in the aquaculture industry, fisheries, and even in the aquarium trade (Ziarati et al. 2022). Fish handlers'

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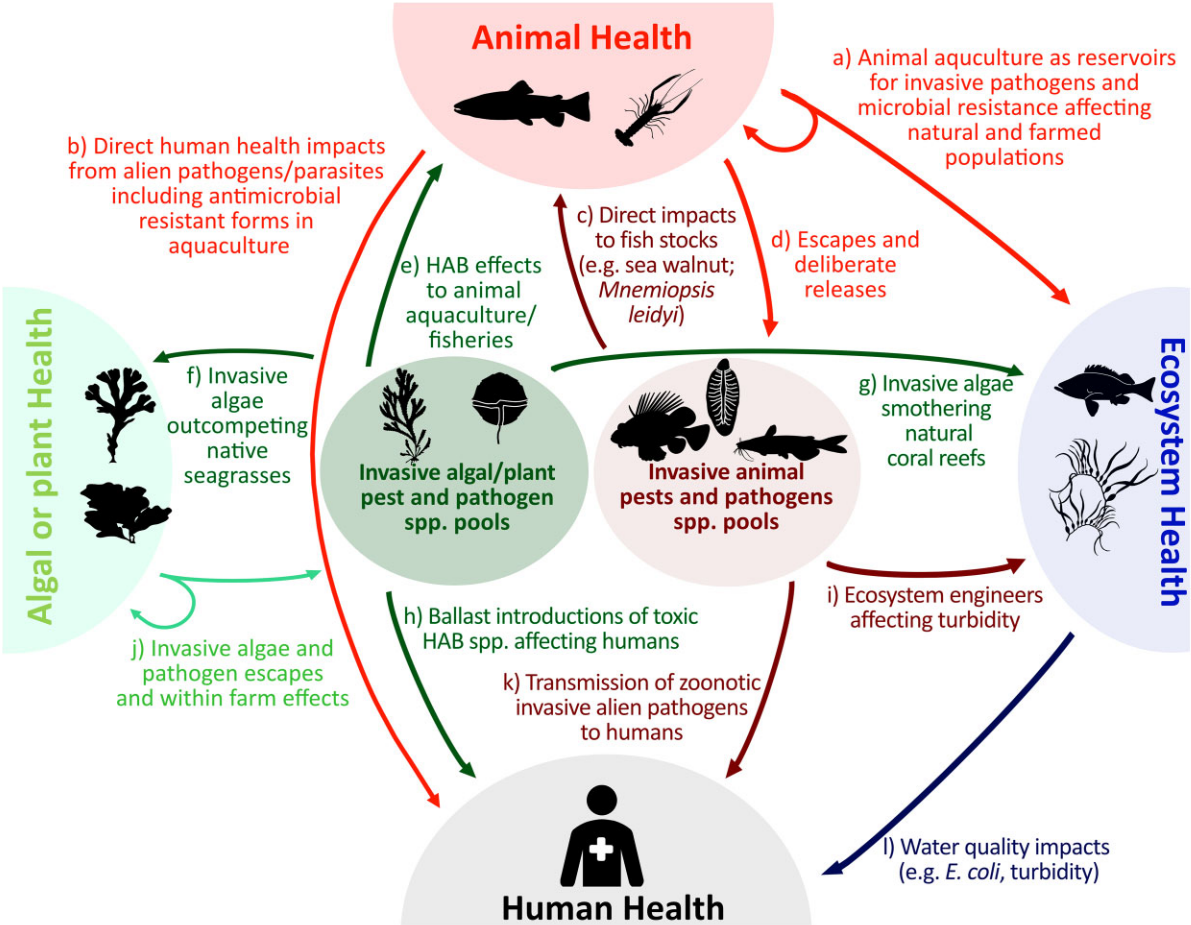

Figure 1. Schematic representation of the multiple links between human, animal, plant, and ecosystem health that are shaped by biological invasions and require a One Biosecurity approach for management (Hulme 2021). Invasive alien species can result from the escape of species from animal or algal aquaculture that subsequently have impacts on human, animal, plant, or ecosystem health (Campbell et al. 2019, Ju et al. 2020). In addition, invasive alien species could be introduced into the environment though other pathways such as ballast water, ornamental escapes, biofouling, etc. and subsequently have impacts across sectors. The arrows (a–l) illustrate examples of the types of interactions arising from invasive alien species arising in one sector but affecting another. For example, alien organisms and pathogens are introduced through ballast water (Bailey 2015), such as harmful algal bloom forming (HAB) species, that have affected fisheries but also (e, h) human health through consumption of affected shellfish (Van Dolah 2000). (d) The introduction of animal species for aquaculture or production fisheries have effects across sectors (Ju et al. 2020, Lins and Rocha 2023), as does (a) the aquarium trade and (b) antimicrobial use and (j) pathogen spill over from aquaculture (Sony et al. 2021). Other examples include (k) invasion of zoonotic schistosomes causing severe disease in humans, associated with the spread of snail host taxa (*Biomphalaria* spp.; Habib et al. 2021). (c) Ballast water likely spread the comb jelly *Mnemiospsis leidyi* into the Black Sea and other locations, which affects fish stocks (Knowler 2005). (i) Invasive ecosystem engineers such the common carp (*Cyprinus carpio*; Mutethya and Yongo 2021) in freshwaters, and polychaete worms in marine environments (e.g., *Marenzelleria* spp.; Kauppi et al. 2018) cause physical state changes as bioturbators and alter ecosystem health, affecting water quality (l), which may also promote HAB formation (Ståhl-Delbanco and Hansson 2002, Welch 2014). Invasive sea grasses (*Halophila stipulacea*) threaten (f) native sea grass meadows (James et al. 2020), whereas (g) algae deliberately introduced to new locations for aquaculture escape and smother coral reefs (Arasamuthu et al. 2023).

disease is relatively common in people that handle fish regularly, occurs worldwide, and is caused by the bacterium *Erysipelothrix rhusiopahiae* (Ziarati et al. 2022). Similarly, geographic range increases of the alien aquatic snail (*Biomphalaria* spp.) are causing increased incidence of the disease schistosomiasis in Africa (Habib et al. 2021), although in some regions of Vietnam, 30%–40% of the human population are infected with fish borne zoonotic trematodes, because of the cultural norm of eating uncooked fish (Phan et al. 2010b), with farmed introduced species vectoring these trematodes (Phan et al. 2010a).

HAB-forming species are invasive in both marine and freshwater habitats, with effects across sectors. Toxic blooms of alien algae such as *Gymnodinium catenatum* and *Alexandium minutum* identified as invasive in some areas can have severe impacts on human health and commercial aquaculture production (Katsanevakis et al. 2018). Within freshwaters, the invasive freshwater HAB-forming cyanobacterium *Raphidiopsis raciborskii* is continuing to invade tropical, subtropical, and temperate regions (e.g., China; Zheng et al. 2023). Invasive taxa such as the rusty crayfish (*Orconectes rusticus*) can also affect physical habitats (e.g., increasing turbidity), and this may then mediate HAB formation, with affects across sectors including to human health (Ståhl-Delbanco and Hansson 2002,Welch 2014).

Invasive alien species create impacts on animal health, especially in terms of the productivity of aquaculture and productive environments. The impacts of invasive alien pathogens and parasites of aquaculture animals currently cause significant global economic effects (i.e., approximately US$6 billion annually on a global scale; Akazawa et al. 2014). The aquatic snails *Thiara granifera*, *Melania granifera*, and *Melanoides tuberculata* were introduced

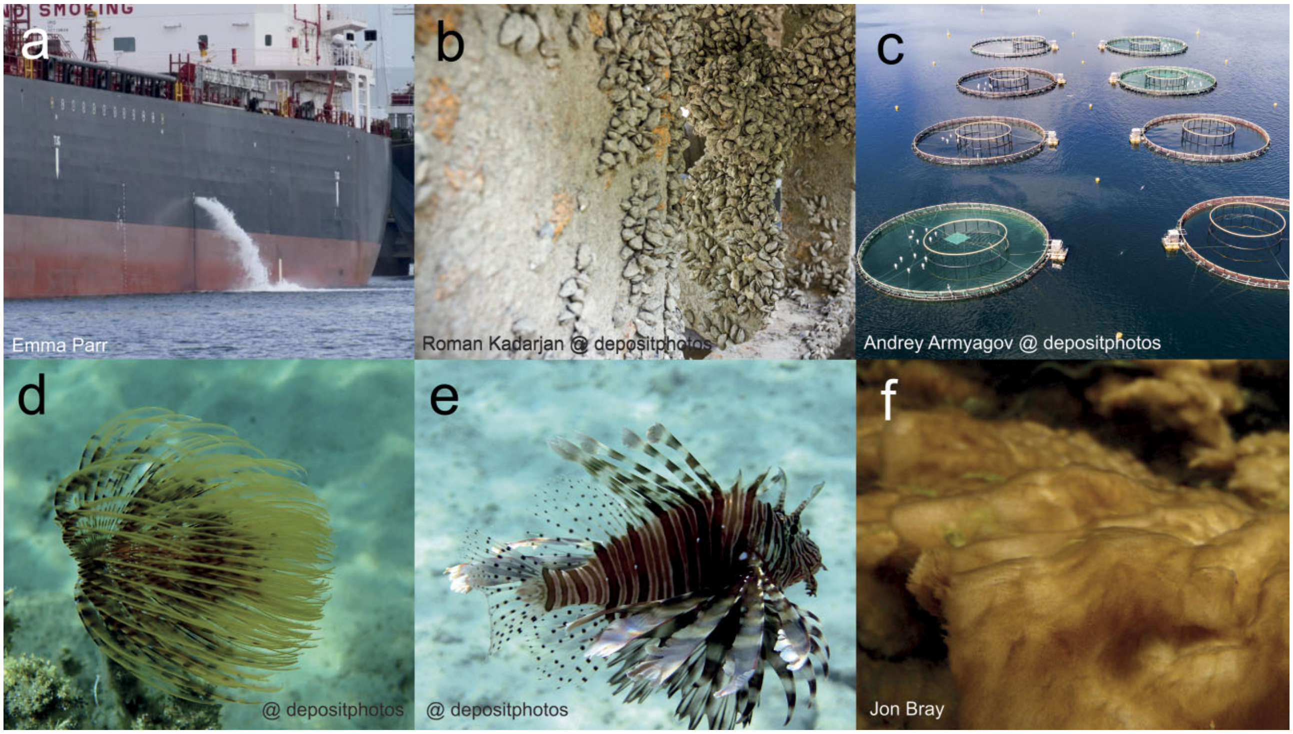

Figure 2. (a) Ballast, sea chests and (b) hull fouling associated with shipping pose significant biosecurity risks as pathways, as does the movement of organisms associated with aquaculture (c). Examples covered in text include (d) the Mediterranean fan worm (*Sabella spallanzanii*), spread primarily through hull fouling and aquaculture, (e) lionfish (*Pterois* spp.) likely spread through the aquarium trade, and (f) the freshwater bloom forming diatom *Didymosphenia geminata* primarily spread by recreational fishing.

Box 1. Distinctiveness of Terrestrial, Marine and Freshwater ecosystems

Terrestrial ecosystems support approximately 80% of all known macroscopic species, whereas marine ecosystems account for only ∼15%, while a further 5-10% have been described from freshwaters (Strayer and Dudgeon 2010; Grosberg et al. 2012). Thus, the potential number of invasive alien species as well as the number of plants and animals that might be impacted by invasive alien species are far greater on land than in aquatic ecosystems. Nevertheless, the breadth of animal life in marine environments is much greater than in terrestrial ecosystems and thus aquatic animal health includes certain classes of animals that are only found in aquatic environments, including sponges, cnidarians, bryozoans, bivalves, cephalopods, polychaetes, echinoderms, and of course fish (Grosberg et al. 2012; Briski et al. 2023). Freshwaters cover less than 1% of the Earth's surface, but hold as much as 10% of total species diversity (Strayer and Dudgeon 2010), and are also one of the most threatened of ecosystems types (Dudgeon et al. 2006). When examining animal health in productive systems, stark contrasts remain. Terrestrial animal production in farm systems is based at most on approximately 40 species, with greater historical understanding (Ahmad et al. 2020). In contrast, important animal species used in aquaculture indicate a total of 262 fish, crustacean and mollusc species (Garibaldi 1996), from a total of ∼654 animal taxa used in this industry (www.fao.org/fishery/en/statistics; download ∼4.7.22), many of which are not as well researched. As a result, current understanding of the threats posed by invasive alien species across sectors are much better understood in terrestrial ecosystems. What is understood as plant health, also differs quite markedly between the aquatic and terrestrial realms since only around 1% of vascular macrophytes are found in aquatic ecosystems and most aquatic plant life is non-vascular and dominated by algae (Grosberg et al. 2012). While approximately 150 plants species are used as food crops worldwide, far fewer macro and microalgae are used for this purpose (Piwowar and Harasym 2020). Furthermore, whereas the major threat to plant health systems from fungal pathogens (Avery et al. 2019), they may present a less significant risk in aquatic ecosystems (Grosberg et al. 2012). But aquatic diseases causing agents and their spread remain in relative terms, poorly understood. Throughout this article our definition of plant health includes the scientific and regulatory framework addressing the biosecurity risks arising from plant and algal imports as well as the protection of plants and algae from introduced pests and pathogens (Döring et al. 2012).

into the United States and Mexico through the pet trade and vector a trematode (*Centrocestus formosanus*) that infects fish gills, causing damages in aquaculture fish operations (Lee and Gordon 2006). The predatory gastropod *Rapana venosa* is responsible for the depletion of large stocks of commercial bivalves in the Black Sea since the 1950s (Katsanevakis et al. 2018). The invasive alien fan worm (*Sabella spallanzanii*; figure 2d) outcompetes other filter feeders for food and has contributed to the demise of the scallop-farming industry in eastern Australia (Lee and Gordon 2006).

The farming of seaweed is a rapidly growing industry, is now practiced in more than 50 countries (FAO 2021), and represents a growing proportion of global marine and coastal aquaculture production (Cottier-Cook et al. 2022). Unlike terrestrial agriculture, aquatic plant health cannot be easily supported using pesticides, biocontrol agents, or fertilizers, and therefore, diseases and pests are prevalent in cultivation (Campbell et al. 2019). In 2003, disease outbreaks led to seaweed losses of 39% in Zhejiang Province, China, and 64% in 1993 in Korea (Park et al. 2001). For many of these diseases, their pathogenic agents and treatments remain a developing area of study, and numerous disease-causing agents are undetermined and affect both micro- and macroalgae (for a review, see Ward et al. 2020). Disease effects in algal aquaculture may also increase under climate change, complicating management (Campbell et al. 2020, Cottier-Cook et al. 2022). Alien algae that escape from cultivation can also have negative ecosystem effects, such as in the case of the red alga *Kappaphycus alvarezii*, which is a commercially important aquaculture carrageenan species that has become invasive in farmed areas (i.e., India, Indonesia) and is causing coral die-off (Arasamuthu et al. 2023). Microalgal invasions often occur through accidental spread; for example, *Didymosphenia geminata*, a freshwater bloom-forming diatom, may be spread by anglers (Bothwell et al. 2009) or trout stocking (Bhatt et al. 2008) and can have ecosystem-wide impacts, affecting algal, invertebrate (Bray et al. 2020), and fish communities (figure 2f; Jellyman and Harding 2016). In a global assessment of invasive macroalgae introductions, 121 of 223 introductions into the wild were derived from aquaculture, either through escapes from cultivation or indirectly as contaminants of shellfish farming (Campbell et al. 2019).

But biosecurity risks from primary producers are not restricted to algae. Native Caribbean sea grass (*Thalassia testudinum*) meadows are presently threatened by the rapid spread of the invasive opportunistic sea grass (*Halophila stipulacea*), which also changes the sedimentation dynamics of coastal ecosystems (James et al. 2020). The edible freshwater macrophyte water cress (*Nasturtium officinale*), a native to Eurasia, has been introduced to many parts of the world, where it has established in the wild. This macrophyte is likely to have an impact on native aquatic plant diversity (Tasker et al. 2022) but also provides habitat for and facilitates the spread of alien snails such as *Planorbarius corneus* and *Pomacea canaliculata* (Xu et al. 2016). Both these snail taxa act as intermediaries for disease-causing agents that affect humans where uncooked water cress is consumed by people. Specifically, *P. canaliculate* can act as a novel intermediary host for *Angiostrongylus cantonensis* (rat lung worm), causing eosinophilic meningitis, which can have severe effects in humans (Yang et al. 2013). Similarly, *P. corneus* is a vector for *Echinonstomias echinatum* a trematode parasite that causes disease in humans (Svinin et al. 2023).

Alien animal and algal species represent an important component of most aquaculture production worldwide. For example, alien fish account for 17% of global aquaculture production, and, in some developing countries, between 65% and 90% of aquaculture production is based on alien species (Ju et al. 2020). Aquaculture introductions can negatively affect biodiversity through the deliberate and accidental releases of alien species into natural ecosystems and are a significant source of pathogens and parasites that move from aquaculture stock into wild populations (Bouwmeester et al. 2021). Farmed salmonids (e.g., *Ochorhyncus* spp., *Salmo* spp.) escape from pens, resulting in competition and interbreeding with wild salmonids, and can have negative biodiversity impacts through direct predation on vulnerable native taxa (Naylor et al. 2005, McIntosh et al. 2009). These salmonids can also facilitate the spread of parasites such as sea lice (Caligidae), as well as pathogens such as salmon anemia virus (Orthomyxoviridae), thereby placing increased pressure on dwindling wild populations (Naylor et al. 2005).

The transport of pathogens, parasites, emerging infectious pathogens, including zoonotic agents are increasingly recognized as a key threat in aquaculture, in productive environments, and to humans. For example, the accidentally discovered microsporidian *Enterocytozoon hepatopenaei*, which was found at low levels in a single pond in Thailand over 10 years ago, is now one of the most widespread and impactful pathogens in shrimp aquaculture (Stentiford et al. 2020). Diseases in aquatic biota are caused by a wide variety of infectious organisms, including viruses, bacteria, fungi, protozoa, and metazoan taxa, and their diversity and the risks they pose are still being understood (Krkošek 2017, Bossart and Duignan 2019, Kibenge 2019, Abdel-Latif et al. 2022). Pathogenic organisms such as *Enterocytozoon hepatopenaei*; viruses such as Haliotid herpesvirus-1 (HaHV-1), which causes abalone viral ganglioneuritis (Corbeil 2020); and zoonoses that have been identified to be multidrug resistant, including strains of *Vibrio* spp. (Zulkifli et al. 2009) which present clear biosecurity risks across multiple sectors. These diseases are among an increasing list of pathogens that require invasion biologists, human health professionals, virologists, and molecular biologists, among other disciplines to manage their impacts across sectors into the future (Bossart and Duignan 2019, van Dijk et al. 2021, Abdel-Latif et al. 2022, Hulme et al. 2023). The spread and impacts of known and emerging disease-causing agents, in aquaculture and aquatic ecosystems generally, are an issue of global importance to humans, aquatic productivity, and ecosystem health, especially as human populations increasingly rely on aquaculture (Sony et al. 2021, Carrique-Mas et al. 2023, UNEP 2023). These concerns are compounded where diseases are expected to have increased impacts under climate change (Montánchez and Kaberdin 2020), and human–animal transmissions appear to be occurring at unprecedented rates (Bossart and Duignan 2019), coupled with the realization that the environment plays a key role in the development and spread of antimicrobial resistance, a problem that, in isolation, is of global significance (UNEP 2023).

Current legislative and regulatory approaches are insufficient to manage invasions

Given the numerous links between sectors in aquatic environments, it is evident that an integrative approach, encompassing all four sectors, is essential to deliver appropriate biosecurity risk management. Currently, the risks posed to human, animal, plant, and ecosystem health by aquatic invasions are dealt with in a fragmented manner, and this is illustrated by different international and national legislative instruments that are specific to individual problems (Lee et al. 2008). For example, the most comprehensive and legally binding legislation addressing the global spread of aquatic invasive species is the International Convention for the Control and Management of Ships' Ballast Water and Sediments (United Nations Ballast Water Convention), which aims to reduce harm to marine environments by preventing the discharge of alien aquatic organisms and pathogens (Boviatsis et al. 2022). Organisms transported in ballast water and sediment have the potential to have impacts on human, animal, plant, and ecosystem health (Carlton 1985, Hallegraeff 1998, Bailey 2015, Gollasch et al. 2015), but ballast is only one of many pathways that lead to introductions (Outinen et al. 2021).

Aquaculture is widely regarded as one of the main means by which aquatic alien species have been moved worldwide (Naylor et al. 2001, Savini et al. 2010, Lins and Rocha 2023). The International Council for the Exploration of the Sea established a voluntary code of practice on the introductions and transfers of marine organisms, which sets forth recommended procedures and practices to reduce the risks and effects from the intentional introduction and transfer of marine (including brackish water) organisms (Gollasch 2007). Currently, international policies targeting aquaculture strongly emphasize the management of pathogens affecting the health of animals (Lee et al. 2008). For example, the Aquatic Animal Health Code of the World Organisation for Animal Health (WOAH, formerly the Office International des Epizooties) is part of a World Trade Organisation legal framework to develop measures for prevention, early detection, internal reporting, notification, and control of pathogenic agents in aquatic animals and to prevent their spread via international trade (Blattner 2021). However, despite the increasing use of algae in aquaculture worldwide (Cai et al. 2021), there is not yet an equivalent aquatic algal health code, even though this sector is similarly exposed to pests and pathogens that could be disseminated via trade (Ward et al. 2020, Cottier-Cook et al. 2022). Several alien parasites and pathogens, as well as algal biotoxins that harm aquaculture animals can also have impacts on human health, and although some of these risks are covered by the voluntary Code of Conduct for Fish and Fishery Products under Codex Alimentarius (FAO and WHO 2020), the risks of introducing or spreading such alien species are not addressed. International legislation addressing other pathways, such as through the movement of bait (Fowler et al. 2016) or through the aquarium trade (Patoka et al. 2018), also remains poorly developed. This lack of guidance or governance, including the development of best practices, has meant that pathogens have caused significant losses to aquaculture productivity in several developing nations, such as Tanzania (Rusekwa et al. 2020), the Philippines (Ward et al. 2020), and Indonesia (Mariño et al. 2019), even leading to some industries' collapse at local and regional scales. Although a variety of instruments operate to minimize harm to plant, human, animal, and ecosystem health, these are fragmented across sectors (for tabulated examples, see supplement S1). It is clear that the international regulatory environment has not kept pace with the growing biosecurity risks in aquatic environments and is no longer fit for purpose to deal with the cross-sectoral nature of biosecurity threats (Hulme 2021).

It has recently been suggested that a One Health approach may be an appropriate way forward, to build on these links, but its focus has generally been on the management of zoonotic diseases, occupational health risk, or antimicrobial resistance rather than on broader issues of biological invasions in aquatic environments (Stentiford et al. 2020, Jamwal and Phulia 2021). Importantly, One Health initiatives have, to date, failed to capture the commonalities among the risks faced by human, animal, plant, and ecosystem health and especially the important role that pathway management can play in reducing risks. For example, invasive alien threats to human, animal, plant, and ecosystem health are introduced to new regions as a result of hull fouling (Hewitt et al. 2004b, Drake and Lodge 2007), ballast water and sediments (Carlton 1985, Outinen et al. 2021), sea chests and anchor lockers (Hewitt et al. 2004a), canals (Katsanevakis et al. 2013), rafting on anthropogenic debris (Campbell et al. 2017, Rech et al. 2018), the movement of aquaculture gear and stock (Drake and Lodge 2007), the deliberate movement of species considered beneficial for fisheries (either commercial or recreational; Xiong et al. 2023), the movement of bait (Fowler et al. 2016), the ornamental trade (Ebner et al. 2020), and tourism (Bothwell et al. 2009). Many taxa are associated with multiple pathways (Hewitt et al. 2004a, Bailey et al. 2020), such that methods that focus on a single pathway are likely to have limited value.

Implementation and benefits of One Biosecurity to address aquatic invasions

The Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services recognized in its recent *Thematic Assessment Report on Invasive Alien Species and their Control*, that collaborative, multisectoral approaches such as One Biosecurity provide frameworks to prevent and control invasive alien species by strengthening the interconnections among the human, animal, plant and ecosystem health sectors (Roy et al. 2023). A One Biosecurity approach is essential to managing the risks across sectors from a rapidly growing and generally poorly regulated aquaculture and aquarium industries. Hulme (2021) outlined a global strategy for delivering One Biosecurity over the next decade, assuming there is general consensus on the value of the concept among scientists and policymakers. To achieve such consensus requires a more systematic approach to quantifying the costs of aquatic invasions on human quality of life and well-being worldwide and particularly the links among human, animal, plant, and ecosystem health.

As a first step, One Biosecurity would drive the development of a suite of more holistic, interdisciplinary risk assessment tools for the comparative assessment of biosecurity threats across sectors (Hulme et al. 2023). Invasion scientists need to work with veterinarians and epidemiologists to devise a standardized quantitative approach to rapidly assess actual and potential impacts of emerging invasive alien species across all sectors, rather than being sector specific (Hulme 2020). Adopting a One Biosecurity approach would facilitate the comparison of relative risks across the human, animal, plant, and ecosystem health sectors, identifying commonalities, synergisms, and redundancies. To date, such holistic risk assessments have yet to be developed, even in the terrestrial realm (Hulme 2021), but will be essential to understanding and mitigating the consequences of deliberate and accidental introductions.

To effectively implement these risk assessment tools will require that there are robust regulatory mechanisms at both national and international scales and that these are interdisciplinary in nature. Nations should develop national strategies to address these risks. One example of how this might be implemented is extending the progressive management pathway for improving aquaculture biosecurity to encompass other sectors (such as algal aquaculture and the aquarium trade; e.g., Cottier-Cook et al. 2022). This would require countries to develop a clear biosecurity strategy for these sectors to enhance biosecurity preparedness and to implement sustainable One Biosecurity management systems. However, the most pressing need is to implement regulations on a global scale that can enforce best practice in the aquaculture and aquarium trades, as well as biofouling associated with international shipping (Bailey et al. 2020), offshore oil, and gas and energy platforms (McLean et al. 2022), and recreation and tourism sectors (Xiong et al. 2023). The development of co-management approaches, with cross-sector, interdisciplinary provisions based on enforceable best practices, will assist in policy

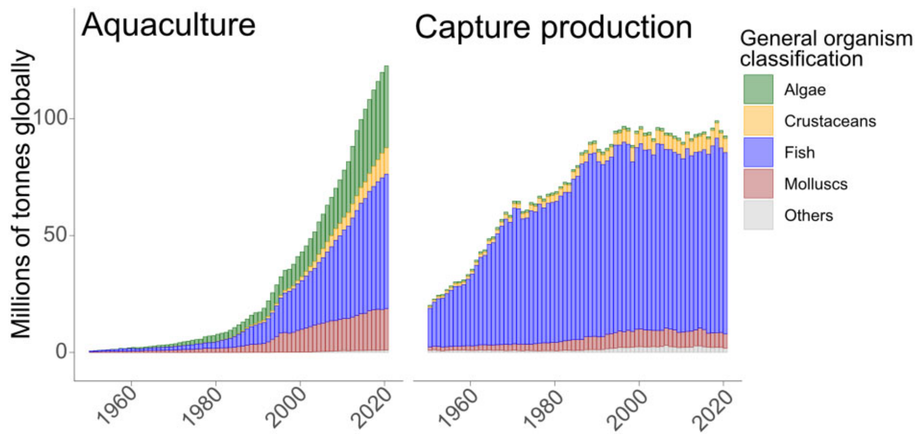

Figure 3. Food and Agriculture Organisation of the United Nations trends across aquaculture and capture production (fisheries and other natural harvesting methods) in millions of tonnes globally across broad organism classifications (www.fao.org/fishery/en/statistics).

development, management, and research focus. This will require industry and policymakers to acknowledge that the problem of aquatic invasions is multisectoral in nature. Ultimately, what may be required is an international biosecurity convention, but any decision on a new global instrument would need to be supported by a cost–benefit analysis of different options. Existing conventions and organizations whose mandates touch on biosecurity and invasive alien species (e.g., the World Health Organization [WHO], WOAH, the Intergovernmental Panel on Climate Change [IPCC], the Convention on Biological Diversity [CBD]) must recognize that the sectoral approach to managing these risks is ineffective and that a more holistic view is essential to address this problem (Hulme 2021). Whether this results in a dedicated new UN organization or tasking an existing UN organization (e.g., WOAH, IPCC, CBD, WHO) that would support the new instrument or creating a network of UN bodies that would cooperatively deliver the new instrument will need to be discussed in the future.

Future outlook

The global population is expected to reach 10 billion people by 2050, which means that global food production will need to increase by more than 50% to meet human nutritional demands (Alexandratos and Bruinsma 2012, van Dijk et al. 2021). Seafood is a significant part of global nutritional resources, where more than 3 billion people currently rely on wild caught and grown seafood as a significant source of animal protein. With declining rates of wild caught sources, aquaculture is increasingly employed and now accounts for over half (by volume) of aquatic productivity (figure 3). The farming of seaweed has seen rapid growth and is now practiced in more than 50 countries (FAO 2021). With global turnover reaching US$14.7 billion in 2019, seaweed production represents an ever-increasing proportion of total global marine aquaculture by volume (figure 3; FAO 2021). Other commercial sectors in the aquatic environment are also growing rapidly. For example, the ornamental fish market was valued at US$5.4 billion in 2021, and tropical freshwater fish accounted for 51.7% of sales, but this market is also anticipated to expand at a compound annual growth rate of 8.5% from 2022 to 2030 (Hoseinifar et al. 2023). The ornamental aquarium trade is a major pathway for the introduction of invasive alien freshwater fish and macrophytes (Chan et al. 2019), as well as other marine invertebrate species (Weigle et al. 2005), parasites, and pathogens (Collins et al. 2012, Smith et al. 2012).

As we have shown in the previous sections, aquaculture acts to facilitate organism and disease spread to a greater extent than other industries, because alien organisms are often selected for farming, and diseases and parasites prevalent in aquaculture are spread with alien stock movement. Diseases are prevalent in aquaculture because of higher organism densities than would occur naturally, and diseased organisms may persist without predation, thereby causing higher disease incidence and the persistence of vectors (Lafferty et al. 2015). This is exacerbated by warming seas, which can increase pathogen development, survival, transmission rates and can increase host susceptibility, affecting both aquaculture and natural ecosystems (Harvell et al. 2002, Sanderson and Alexander 2020). Antimicrobial use in farms also facilitates the evolution of resistance, creating novel strains with human, within-farm, and ecosystem health risks (Sony et al. 2021). The drive for greater aquaculture expansion over the coming decades will likely exacerbate the problems of aquatic invasions with significant implications for human, animal, plant, and ecosystem health. A fundamental change is required within the science, industry, and policymaker communities to address this issue before it gets completely out of hand. One Biosecurity provides the conceptual basis for such action through the delivery of a more holistic approach to managing cross-sectoral problems in aquatic environments.

Conclusions

A broad variety of impacts caused by aquatic invasives occur because of numerous introduction pathways, and have clear effects on human, animal, plant, and ecosystem health. These effects are rarely considered in an interconnected framework, and gaps in scientific effort and policy development are common, such that biological invasions that present problems to human, animal, plant, or ecosystem health should be considered together to properly address research, management, and policy development. Many of the issues discussed occur within and among sectors, are interrelated with trade-offs, and have direct and indirect effects that require interdisciplinary consideration. Examination of these problems, within a holistic framework such as One Biosecurity, offers clear benefits enabling an inter- or transdisciplinary approach that would streamline research and policy development, reducing redundancy across sectors. These issues are time critical and are are likely to become increasingly important with greater reliance on aquaculture, accelerating trade and under changing climates. A One Biosecurity approach should be integrated into aquatic biosecurity policy, management, and research in order to best manage biosecurity risks amid the greater volume and frequency of international shipping, rising demand for aquaculture products, and growth in the global aquarium trade that are accelerating the dissemination of invasive alien species worldwide.

Supplemental material

Supplemental data are available at *BIOSCI* online.

The data underlying this article were derived from sources in the public domain: https://www.fao.org/fishery/en/fishstat. data download ˜4.7.22).

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Author contributions

J. P. Bray (Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing), C.L. Hewitt (Writing – original draft, Writing – review & editing), and P.E. Hulme (Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing original draft, Writing – review & editing).

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