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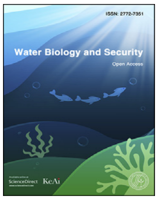

Review article

A one-health approach to non-native species, aquaculture, and food security

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ABSTRACT

One-Health is an umbrella term that integrates the health of the environment, humans and non-human animals. This approach is applied here to elucidate the impact of non-native invasive species on aquaculture and food security. Despite inherent biases against these species, a better understanding of their characteristics allows for the identification of those of greatest concern, minimizing the risk of food shortages and infectious diseases. This review summarises the positive and negative impacts of non-native species, delineating the specific areas they may impact. Additionally, this review gives an insight to the expertise and stakeholders that would need to be included if a "One-Health" approach were to be implemented by policymakers to better control non-native species.

Detailed examples illustrate the consequences of non-native species on trophic dynamics, ecosystem health, water chemistry, and human health, emphasizing the importance of managing them within a multidimensional framework. The "One-Health" approach is explained, and suggestions are made on how certain non-native species could be used to contribute to food security in low- and middle-income countries. Furthermore, recommendations are made to promote a more inclusive management strategy.

1. Introduction

Issues relating to the introduction of non-native species (NNS) into an ecosystem are often addressed at a single level of concern. For example, the impact of these introductions may focus on the dynamics of native populations (Goren and Galil, 2005; Manchester and Bullock, 2000), the health of particular species (Ercan et al., 2015; Gozlan et al., 2005; Peeler et al., 2011), food webs (Cucherousset et al., 2012; Eby et al., 2006), or economies (Diagne et al. 2020, 2021; Haubrock et al., 2022a,b). However, the introduction of NNS into an ecosystem has a ripple effect on society, culture, biodiversity and ecosystem services (Nentwig et al., 2017), which hinders implementation of effective legislation against future introductions (Hughes and Pertierra, 2016; Geller et al., 2020; Li et al., 2020). Many non-native aquatic and marine species are introduced from ballast water discharges, aquarium releases, and fish-culture escapes. Also many NNS are deliberately introduced for food production, recreation, or biological control (Schlaepfer et al., 2011). The negative impacts of these species often resulted from collateral effects because their potential benefits were assessed at only one level of concern.

One-Health (Cavalli, 2015; Stentiford et al., 2020) is particularly well suited to the issue of NNS introduction because it includes multiple stakeholders, such as health workers, aquatic animal health, and environmental health. These sectors have previously collaborated to varying degrees, but not to the level of the One-Health approach. The World Health Organisation (WHO) clearly defines health as "a state of complete physical, mental and social well-being and not merely the absence of disease in the human population" (Zinsstag et al., 2011). Likewise, One Health goes beyond the prevention of health crises by linking environmental quality (water, air), climate, food and agriculture, and biodiversity in a holistic manner. Therefore, it can help prepare us for future health emergencies (Lerner and Berg, 2015).

By taking a One-Health approach, we can identify the benefits and

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mitigate the risks associated with NNS, while protecting human and animal health and promoting sustainable food production systems that are resilient to environmental and economic crises. Promoting these production systems can include supporting small farmers and fishers, promoting simple food systems with resilient NNS, and decreasing food waste.

We apply the One-Health framework to NNS (Fig. 1). In doing so, we consider three level of impacts (negative and positive) that NNS have. (1) We consider the health, trophic, and genetic condition of animals themselves, (2) we examine ecosystems, their habitats and their functioning, and (3) we evaluate effects on humans, socially and culturally, as well as issues related to food security. We hope that this adaptation of the One- Health concept can serve as a basis for new legislation that addresses the health and environmental issues associated with the introduction of NNS.

2. Impact of non-native species introduction on animal health

2.1. Impact of non-native species on pathogen dynamics at the population level

The introduction of a NNS can have a direct impact on the health of native species by transmitting new pathogens to which native species may have little immunity or by altering the transmission rate of native pathogens already present (Peeler et al., 2011; Goedknegt et al., 2016; Gozlan, 2017). This can cause adverse effects at the individual level by altering metabolism and reducing growth, or at the population level through mass mortality. For example, the introduction of the Pacific oyster *Crassostea gigas* to the Wadden Sea led to the establishment of its parasite, the copepod *Myicola ostreae*, which successfully infected the European oyster *Ostrea edulis*, resulting in reduced growth rates and economic losses (Costello et al., 2021a). The generalist fish parasite *Sphaerothecum destruens* was accidently introduced to European waters from China in the 1950s and has infected several cyprinid and salmonid populations, causing either chronic mortalities or mass extinction events (Gozlan et al., 2005; Paley et al., 2012; Andreou et al., 2012; Ercan et al., 2015; Al-Shorbaji et al., 2016). When considering the introduction of a species for aquaculture, it is necessary to consider the underlying risk of translocating non-native pathogen species or different pathogen strains from the same species. The parasite *Gyrodactylus salaris*, for instance, was introduced into the Norwegian Atlantic salmon *Salmo salar* population by Baltic Atlantic salmon (Peeler et al., 2011). When a NNS acquires a native parasite from the introduced region, it can exacerbate infection-rates in native populations. The introduction of American shad *Alosa sapidissima* from the U.S. Atlantic coast to the Pacific coast, for instance, amplified the parasite *Ichthyophonus*, (Hershberger et al., 2010). Katharios et al. (2020) found that the parasite *Hanneguya* sp. reduced fecundity and increased mortality in *Pagrus major* individuals introduced into the Mediterranean Sea for aquaculture purposes.

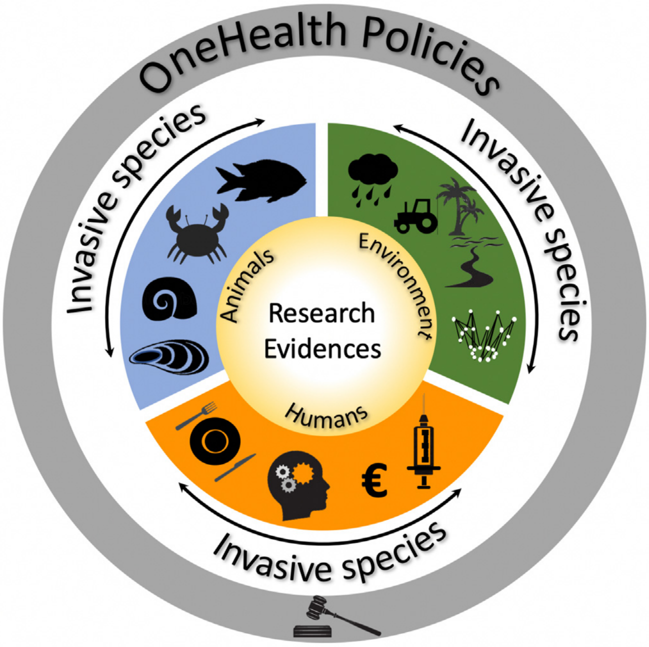

Fig. 1. One-Health approach to non-native species introduction. The core is research and evidence integrating animal, ecosystem, and human health (middle circle) in a common policy framework (outer circle), to facilitate legislation bridging environmental, animal, and human health policies. A One-Health approach to the issue of invasive species would offer better risk assessments regarding the impacts of non-native species on biodiversity, ecosystem services, aquaculture, and human well-being.

However, NNS introductions can play a beneficial role in native species health by diluting the infectious load and strengthening the management of infectious diseases (Keesing et al., 2006). Such cases take place when NNS interfere with the native host-parasite interaction through infection failure, predation, or mechanical intervention (Johnson and Thieltges, 2010). An excellent example of this is the laboratory and field experiments of Thieltges et al. (2009) who showed that two invaders, the Pacific oyster *C. gigas* and the American slipper limpet *Crepidula fornicata*, acted as decoys for trematode infection in mussels. In another field experiment, Goedknegt et al. (2020) demonstrated that, to a certain extent, *C. gigas* beds acted as a refuges for mussel populations from copepod parasites (*Myticola* sp.). The dilution effect can occur also with bacterial or viral pathogens, as demonstrated by Costello et al. (2021b) for the oyster herpesvirus OsHV-1.

Given the dilution effect, the introduction of a NNS in aquaculture facilities might favour animal health. Recent studies highlighted the beneficial effects of aquatic polycultures over monocultures, including protection against diseases (Thomas et al., 2021). Given the climate crisis, NNS from warmer waters will establish faster in warming systems, as happened with *Ruditapes philippinarum* or *Vaucheria* algae in the Wadden Sea (Reise et al., 2023). Conversely, heat-intolerant species will move northwards (Engelhard et al., 2014; Kleisner et al., 2017). In light of these shifts and considering that rates of infection in farmed aquatic animals are increasing with temperature (Reverter et al., 2020; Combe et al., 2023a,b), we must be cautious about the establishment of NNS for aquaculture. However, while accepting the presence of NNS, we also recommend a more extensive effort in controlling their introductions. We should adopt both short-term, i.e., higher investment in biosecurity measures and pathogen control (Stentiford et al., 2020; Rhodes et al., 2023) and long-term strategies, i.e., widening ecological research in host-diseases interaction and the physiology and immune system adaptability of NNS. This also would improve our knowledge of potentially suitable NNS for aquaculture use.

2.2. The role of the immune system in the health impact of non-native species

The successful invasion by some NNS can be explained by a range of factors, including their ability to overcome ecological barriers, reproduce rapidly, and adapt to new environments. However, the immune systems of some NNS may also play a role in their ability to overcome new environmental conditions (Fig. 2), including exploitation of available food resources (growth/activity patterns), stress tolerance, and evolutionary adaptability to new parasites and pathogens (Vincelli, 2016). NNS that establish a population may have stronger immune systems, allowing them to resist diseases and infections more effectively, which could give them a competitive advantage. Recently, Vela-Avitúa et al. (2023) have identified genetic markers (SNPs) in cultured individuals of Nile tilapia (*Oreochromis niloticus*) linked to quantitative trait loci (QTL) related to a significantly higher resistance to *Streptococcus iniae*, a

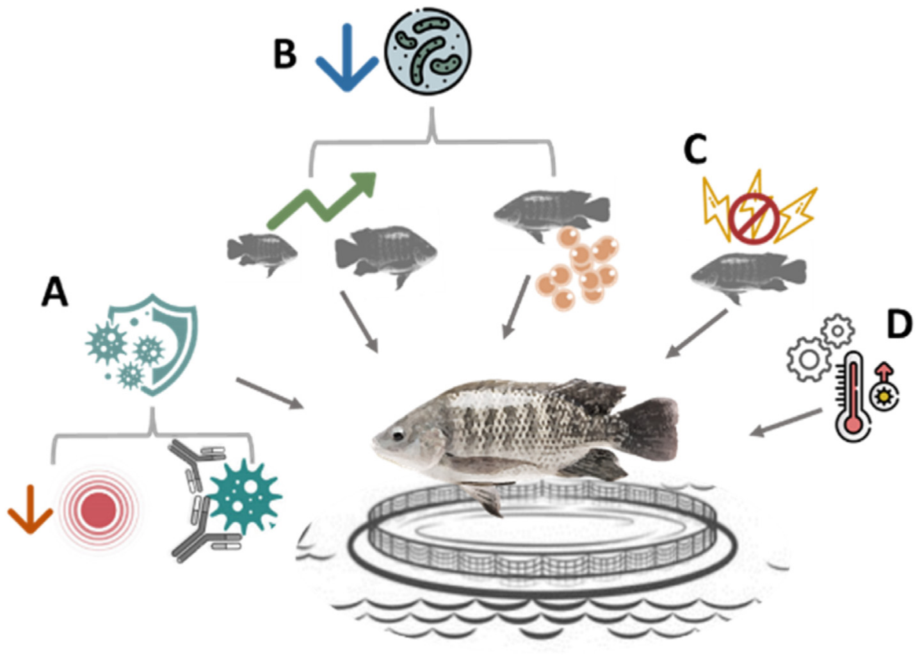

Fig. 2. Schematic representation of the potential mechanisms behind the success of non-native species to adapt to new environments from an immunological perspective: (A) a strong immune system that can cope with the infections in the new environment, with dampened inflammatory response and strong humoral defences; (B) large resources allocation to growth and reproduction due to low infection rates in the native range; (C) mechanisms to deal with stress; (D) immune response positively correlated with increased temperature.

pathogenic bacterium. Additionally, parasite-derived immunosuppressive molecules (e.g., proteases) may affect native and NNS differently, potentially due to differences in coevolutionary history of the parasite and hosts (Braden et al., 2017). When comparing immune performance between invaders and invaded, it is also worth considering whether NNS alter the immune functions of native species by elevating their stress hormones (Martin et al., 2010).

It is important to note that the relationship between immune systems and invasion success is complex and context dependent. The impact of immune systems on non-native success can be influenced by other factors such as environmental conditions, competition with native species, and interactions with other NNS. Also, the immune performance of NNS may decrease over time (Kołodziej-Sobocińska et al., 2018), as the number of encounters with potential pathogens increases. Fish inherited a common set of innate and adaptive immune pathways and receptors from their early ancestors, which were subsequently amplified, reduced or lost in the different lineages (Magadan et al., 2015). For example, several species, including the pipefish (*Syngnathus typhle*) and Atlantic cod (*Gadus morhua*), have undergone a complete loss of the major histocompatibility complex class II (MHC II) pathway, which is otherwise responsible for detecting bacterial pathogens in vertebrates (Haase et al., 2013; Malmstrøm et al., 2016). Therefore, interactions between infectious agents and native and non-native individuals are highly context dependent.

Aquaculture programs, including diversification of cultured species, require research regarding the immune system and the development of immunotherapies. This is important because the immune response of cultured organisms is influenced by various parameters, such as temperature, density, light, water quality, salinity, feed, immunostimulants, or stress management (Chaves-Pozo et al., 2018). In addition, the type of culture can contribute to both the decrease in immune responses and infectious processes (Fig. 2). Multi-species/multi-trophic approaches for example could enhance non-specific immunity of the species concerned (e.g., the alga *Gracilaria bailinae* benefits the hybrid grouper), thus decreasing the degree of virulence in the stocks (Zhang et al., 2022). From a different perspective, Teixeira Alves and Taylor (2020) suggested that pathogen risks to wild fish may be mitigated by acquired immunity in freshwater aquaculture systems, as an outbreak in the farm always induces an increase in parasites in the wild population due to spill over. These authors noted that if this exposure occurs at low levels, it may increase immunity rather than mortality in the wild fish population (Teixeira Alves and Taylor, 2020), although we have found no reported evidence of this.

However, the addition of NNS to a natural or artificial system could cause interspecific competition or predation, with effects similar to those associated with a chronic stress response, i.e., reduced growth and condition factors, reduced survival, and loss of immune function or immunosuppression (Fig. 2, Gilmour et al., 2005; He et al., 2018). Immune defense is a key activity of the host to detect potentially harmful bodies that may jeopardise its health and normal function of its systems, so the stress derived from the presence of NNS can lead to declines in abundance of native species, threatening them as well as being a significant barrier to the reintroduction of extirpated native species (He et al., 2018). On the other hand, NNS may have adaptable or flexible physiologies to mitigate the effect of stress. For example, an elevated baseline of glucocorticoid levels may also reflect adaptation to stressors in a novel environment at the peak of a population or range invasion, which appears to be essential for populations of *N. melanostomus* (Vincelli, 2016). Another example of adaptative mechanisms to cope with stress is the perciform yellow croaker *Larimichthys crocea*, one of the most economically important marine fish in China and East Asian countries. Transcriptome analyses of its brain after induction of hypoxia stress revealed new aspects of neuroendocrine-immunity/metabolism regulatory networks that may help the fish avoid brain inflammatory damage and maintain energy balance. Proteomics data demonstrate that its skin mucus, usually the main gateway for fish pathogens (Flores-Kossack et al., 2020), had a complex composition, suggesting its multiple protective mechanisms involved in immune defence, antioxidant functions, oxygen transport and osmotic and ionic regulation (Ao et al., 2015).

Thus, the success of a NNS depends on the non-native host species, the introduced pathogen species, the type and conditions of husbandry, and the immunity in the native host population (see Fig. 2, French, 2017). The likelihood of incursion, expansion, and persistence of microbial pathogens is limited in livestock and wildlife systems by the development of acquired immunity from natural infection, cross-immunity by a related pathogen, vaccines (French, 2017), and immune stimulants (Wang et al., 2017). In this sense, there are still many questions to be answered about the immune system and immune responses of farmed species, which is related to the fact that vaccines used in fish are not as effective as those used in mammals (Flores-Kossack et al., 2020). This is related to the immune organ structure, cellular characteristics and functions of teleost fish, especially the loss of MHC II and CD4, necessary for T-cell activation, and the invariant chain (Ii). Nevertheless, when a species with these characteristics (i.e., *G. morua*) is challenged, it can survive and establish immunity to bacteria. However, the underlying mechanism remains to be understood (Star et al., 2011). On the other hand, new approaches are being carried out, such as marker-assisted selection of the resistant, non-native individuals, which could protect non-native (and indirectly, native) stocks in the long term via the inheritance of these characteristics by offspring (see Vela-Avitúa et al., 2023).

Lee and Klasing (2004) associated optimal immune characteristics for adaptation to a new environment with two factors: non-natives may have attenuated systemic inflammatory responses, and/or display strong humoral defences. Humoral immunity is rarely associated with systemic inflammation and is therefore likely to be less metabolically or behaviorally costly. Thus it should present less risk of immune-mediated morbidity or mortality to an invading host than innate or cell-mediated responses. Global heating adds another stressor because heat stress is extremely detrimental to the ability of fish to resist infection and high water temperatures promote rapid growth of some pathogen populations (Caballero-Huertas et al., 2023; Frigola-Tepe et al., 2022). High temperatures also increase the metabolic rate and resulting oxygen demand of fish (Rottmann et al., 1992). Immune responses of sticklebacks *Gasterosteus aculeatus* infected in the laboratory to cope with the tapeworm (*Schistocephalus solidus*), including the amount of leukocytes in the head kidneys and their respiratory activity, were significantly higher at relatively low temperatures (9–15 °C) and associated with supressed parasite growth (Franke et al., 2019; Scharsack et al., 2022). Nevertheless, for some fish species, immune responses can be stimulated or at least positively correlated with increasing temperatures, including lysozyme activity and immunoglobulin M levels, as in tilapia (*Oreochromis mossambicus* and *O. niloticus*, respectively) (Martin et al., 2010; Ndong et al., 2007), two widely distributed commercial fish. Both species showed strong humoral defenses, which would improve production with heating. Defeating infectious agents through an effective and rapid immune response would lead to healthier stocks and therefore a positive contribution to food security. This is of particular interest to countries most vulnerable to climate change, because they will face the highest risks of antimicrobial resistance and the greatest need to minimize antibiotics, which will have an impact on human health beyond the aquaculture sector (Combe et al., 2023a,b; Reverter et al., 2020).

2.3. *The impact of non-native species on trophic changes in native populations*

The introduction and establishment of NNS can have profound impacts on native populations, particularly in terms of trophic interactions. Competition can result in reduced food availability for native species, affecting their growth, reproduction, and overall fitness. Native populations may experience declines or shifts in their abundance and distribution patterns as a result of increased competition from NNS. For example, in some water bodies in North America, native fish populations have experienced declines and shifts in their distribution patterns as a result of competition from non-native Asian carp species, such as Silver Carp *Hypophthalmichthys molitrix* and Bighead Carp *Hypophthalmichthys nobilis*. These invasive carp species are highly efficient filter feeders, outcompeting native fish for planktonic food resources. As a result, native fish populations such as the gizzard shad *Dorosoma cepedianum* and bigmouth buffalo *Ictiobus cyprinellus* have decreased in abundance, and their distribution has been limited to areas where they face less competition from the invasive carp (Sass et al., 2014). Also, NNS that are predators have substantial impacts on native populations, leading to population declines or local extinctions. A good example is the American Bullfrog (*Lithobates catesbeianus*), which has had detrimental effects on native amphibian populations (Laufer et al., 2021). Indeed, the introduction of non-native top predators can lead to trophic cascades and alter ecosystem dynamics. For example, Hughes and Herlihy (2012) found that non-native piscivorous fish were associated with reduced population sizes of native prey species and posed a potential threat to the persistence of prey species.

However, the impacts of NNS on trophic interactions are not always straightforward, such as modifying habitat structure, nutrient cycling, or interspecific interactions. For example, some non-native macrophytes can alter vegetation composition, which in turn affects the availability of resources for native herbivores and their associated predators. These indirect effects can have significant ramifications for trophic dynamics and community stability. A good example of indirect trophic impact, is the introduction of water hyacinth *Eichhornia crassipes* – a highly invasive floating aquatic plant native to South America (Villamagna and Murphy, 2010). It has been introduced around the world and is known for its rapid growth and ability to form dense mats on the water surface. These thick mats cover the water surface, reducing light availability for native submerged plants and phytoplankton. Furthermore, water hyacinth can extract large amounts of nutrients from the water, leading to nutrient depletion for other plants to survive and thrive. Such impacts are rapidly leading to trophic cascades and aquatic ecosystem collapse, particularly for planktonic feeding species (Crossetti et al., 2019). It also poses serious problems for fisheries and farming in a variety of ways (Tewabe et al., 2017).

Non-native species may exploit novel food resources or occupy unoccupied ecological niches in their new environments, leading to niche differentiation and resource partitioning among native and NNS. Non-native species may exploit resources that were previously unused or underused by native populations, potentially allowing for coexistence. However, if NNS outcompete native species for these resources, it can result in trophic displacement and changes in community structure. This has broader implications for ecosystem functioning (see section 3.4). Alterations in trophic interactions can have an impact on nutrient cycling, energy flow, and overall ecosystem stability. Changes in species composition and abundance can also impact primary productivity, nutrient dynamics, and the resilience of ecosystems to environmental disturbances. Understanding the implications of trophic changes is crucial for preserving ecosystem functions (see section 3) and effectively managing NNS (see section 5).

Conversely, native species can reduce the spread or chances of establishment of NNS. This is named biotic resistance (Beaury et al., 2019). For example, Tiralongo et al. (2021) found that rock goby *Gobius paganellus* from the Mediterranean Sea fed preferentially on a non-native crab *Percnon gibbesi*. They also noted that in protected marine areas where there were more predators than in unprotected areas, the abundance of non-native crabs was reduced. Other examples from temperate and tropical ecosystems show that the abundance, diversity and phylogenetic relatedness of aquatic plant communities have significant potential to act as a barrier to the establishment of non-native plant species (Petruzzella et al., 2020).

2.4. *The impact of non-native species on hybridisation with native populations*

The introduction of NNS increases the potential for hybridization with native populations. Hybridization between non-native and native species can lead to genetic introgression and reduced genetic diversity and fitness of native populations, compromising their ability to adapt to local environmental conditions (Huxel, 1999). A good example is the hybrid zone between the non-native common nase *Chondrostoma nasus* and the native species Soffie *Chondrostoma toxostoma* in Rhône River tributaries. The hybridisation between these two species is particularly interesting because morphological traits, allozymes and mtDNA sequences from both parental species are found in the hybrid group, clearly demonstrating bidirectional introgression, a situation not commonly found in hybridising species (Costedoat et al., 2005).

Hybridization between non-native and native species can also alter ecological interactions and ecosystem dynamics. Hybrids may possess a combination of traits from both parental species, potentially influencing their ecological roles and interactions with other species (Kovach et al., 2015). This can affect trophic relationships, resource partitioning, and community structure. In some cases, hybrids may outcompete native species, leading to their displacement or even extinction (Sales et al., 2018). Hybridization can lead to the production of hybrid offspring with enhanced fitness, known as hybrid vigor or heterosis. Increased adaptability and growth rates have also resulted from hybridization (Parepa et al., 2014), allowing them to outcompete native species and spread more rapidly in the new environment (Muhlfeld et al., 2009, 2014).

Hybridization between non-native and native species poses challenges for biodiversity conservation. It blurs taxonomic boundaries, making it difficult to define and protect distinct species and subspecies (Hirashiki et al., 2021). Conservation strategies need to consider the preservation of genetic diversity, preventing genetic introgression and maintaining the integrity of native populations. In some cases, active management interventions such as removal of hybrids or control of non-native populations are necessary to reduce hybridization risks and protect native genetic integrity (Buktenica et al., 2018). Conservation efforts should focus on preventing the introduction of NNS, monitoring hybridization events, and implementing strategies to mitigate genetic introgression and protect native populations (Jackiw et al., 2015). By understanding and addressing the impact of NNS on hybridization, we can promote biodiversity and ecosystem conservation.

3. Impact of non-native species introduction on ecosystem health

3.1. The impact of non-native species introduction on habitat diversity

The introduction of non-native plants can have profound impacts on habitat diversity, altering the composition, structure, and functioning of ecosystems. Invasive, non-native aquatic plants can outcompete native macrophytes, altering the composition and structure of plant assemblages, homogenize habitats, reduce aquatic-plant taxonomic and functional diversity, and diminish the availability of specific habitat types for native fauna (Aloo et al., 2013). Some NNS have the ability to form dense monocultures, dominating landscapes, and displacing native species (Gallardo et al., 2016; Gillard et al., 2017). This leads to habitat simplification, where a single NNS dominate the habitat, reducing the diversity of plant and animal species that rely on diverse habitats for their survival. In addition, NNS can disrupt natural disturbance regimes, flooding, or grazing patterns (e.g., Fleming and Dibble, 2015). These disturbances play a crucial role in shaping habitat diversity by creating a mosaic of different habitat types and successional stages. Non-native species are often more resistant to, or even benefit from disturbances, altering the natural patterns of disturbance, recovery, and regeneration of native habitats (Fleming and Dibble, 2015). The introduction of NNS can also contribute to habitat fragmentation, where once continuous habitats become fragmented into smaller, isolated patches. Fragmentation reduces habitat size, connectivity, and the ability of native species to move between habitats. This leads to reduced species diversity, increased vulnerability to environmental pressures, and limited access to resources and mates for native populations. It has a direct effect on meta-population dynamics, which rely on a constant process of colonization-extinction of suitable habitat patches.

Also, NNS can alter resource availability in habitats, reducing the availability of food, nesting sites, or shelter for native aquatic species (Schultz and Dibble, 2012). Non-native species can disrupt ecological interactions within habitats, affecting species that depend on specific interactions for their survival. For instance, non-native aquatic plants may disrupt the mutualistic relationships between native plants and their grazers. Disruption of these interactions can have cascading effects on the abundance and distribution of native species, ultimately reducing habitat diversity. Preserving and restoring habitat diversity is crucial for maintaining ecosystem health and biodiversity (Getsinger et al., 2014). Habitat restoration efforts should aim to enhance the diversity of native habitats, including the reintroduction of native plant species, habitat connectivity, and the re-establishment of natural disturbance regimes. Conservation initiatives should prioritize the protection of diverse habitats and the management of NNS to mitigate their impacts on habitat diversity including substrate quality and composition (Gallardo et al., 2016; Schlaepfer et al., 2011).

3.2. The impact of non-native species pathogens on ecosystem processes

The co-introduction of pathogens with NNS can influence the strength and magnitude of ecosystem processes through several pathways (Fischhoff et al., 2020). For example, parasites directly affect ecosystem connectivity (Lafferty et al., 2006) and provide a large percentage of biomass, therefore contributing to energy transfer (Lambden and Johnson, 2013). Studies have found the total parasite biomass in ecosystems is equal to that of the main invertebrates (Lagrue and Poulin, 2016), indicating that non-native parasites can directly contribute to ecosystem secondary production (Preston et al., 2016). Non-native parasites can also indirectly mediate the interactions of different components of the food web by altering their host behavior, and structuring the community (Wood et al., 2007). For instance, freshwater and marine snails infected with trematodes showed higher grazing rates on algae compared to their uninfected counterparts (Díaz-Morales et al., 2023). Through trait-mediated indirect effects, parasites can also influence biogeochemical fluxes in ecosystems. Pascal et al. (2020) reported the burrowing activity of the crustacean *Upogebia pusilla*, a keystone ecosystem engineer inhabiting European coasts, was substantially reduced when the shrimps were infected with the ectoparasites *Gyge branchialis*, with consequent decrease of bioturbation rates and biogeochemical fluxes. Besides their role in food web production and biogeochemical fluxes, previous studies underpinned the fundamental role of parasites in shaping biodiversity (Marcogliese, 2005; Hudson et al., 2006; Sures et al., 2017). Free-living metazoan species host one or more parasite species and themselves represent from a third to more than half of the diversity of the planet (Poulin, 2014). Thus, parasites can be considered a true mirror of ecosystem diversity.

Evidence suggests an essential link between the introduction of NNS and their non-native parasites, and ecosystem health (Bojko et al., 2021). Despite the general perception of a healthy ecosystem as one lacking diseases, a healthy ecosystem is one that persists, maintains productivity, organization (i.e., biodiversity), and resilience to a potential shift and is substantially rich in parasites (Costanza and Mageau, 2000; Hudson et al., 2006). However, Hudson et al. (2006) found that invaders reduced parasite diversity by replacing essential hosts and disrupting parasite life cycles. Nonetheless, introducing NNS into an ecosystem might lead to new links and complex interactions amongst competitors, introduced predators and native or non-native parasites, therefore bringing greater stability (Reise et al., 2023). The impact of co-introduced parasites on ecosystem health will undoubtedly depend on the dualism of generalist versus specialist species, where specialist parasites can be used as indicators of biodiversity (see Hatcher et al., 2012). Therefore, understanding the ecology of pathogen life cycles (including parasites, bacteria, and viruses) is a prerequisite for sustainable programs for pathogen control.

To our knowledge, few studies have analysed the effects of co-introduced parasites on ecosystem processes, except for Britton (2013), who showed that new parasites have an active role in reorganizing food webs. Under the One-Health concept – especially for aquaculture – integrated parasitological and ecological studies are needed on the role of NNS and their co-introduced parasites in aquatic ecosystems processes, not solely as vectors of diseases but also as contributors to ecosystem health.

3.3. The impact of non-native species on ecosystem chemical processes

Water quality is an important criterion for measuring the health of an aquatic environment. However, the introduction of NNS into an ecosystem can alter a number of physicochemical criteria such as dissolved oxygen (DO), transparency, turbidity, water color, carbon dioxide, pH, alkalinity, hardness, ammonia, nitrite, nitrate and others (Tumwesigye et al., 2022). These changes in water quality lead to profound and lasting changes, as has been observed in several contexts (see, for example, Boltovskoy and Correa, 2015; Mutethya and Yongo, 2021). Depending on the NNS introduced and the characteristics of the environment colonized, the impacts may be detrimental or beneficial, and will be explored later in this section. For example, some non-native aquatic plants directly alter nutrient cycling by changing rates of decomposition, nutrient uptake, storage, and release to the point that they dominate aquatic systems (Jo et al., 2017). The best-known non-native freshwater fish species for altering water quality is the common carp (*Cyprinus carpio*), which has been introduced around the world. Common carp feed by disturbing the top 200 mm of sediments, resuspending particles and releasing nutrients sequestered in sediments into the water column (Kaemingk et al., 2017) which increases turbidity and attenuates light. In addition, Chumchal et al. (2005) showed that turbidity increased with chlorophyll *a* and total phosphorus in systems with common carp. However, total nitrogen and total phosphorus levels in the water column decreased (Qiu et al., 2019). Prior to the introduction of common carp into Lake Naivasha (Kenya) in 1999, the Secchi depth of the lake was >1 m and the flora was dominated by floating and submerged aquatic plants (Beadle, 1932). The introduction of carp led to the disappearance of the floating water lilies and the submersed flora fluctuates between periods of recovery and absence with increased turbidity (Harper and Mavuti, 2004). However, Britton et al. (2007) found a regeneration of macrophytes in the near shore areas of Lake Naivasha since 2004 and a significant increase in fish species richness.

Non-native reef-engineer species can modify the benthic structure, which can in turn negatively affect submerged vegetation and alter oxygen dynamics in the water column. Invasive species such as zebra (*Dreissena polymorpha*) and quagga (*D. rostriformis bugensis*) mussels attach themselves to rocks, pipes, and boat hulls and form dense colonies (Karatayev et al., 2015). Mussels release particles after filter feeding in the form of pseudofeces, which excrete excess nutrients. The accumulation of such feces in the benthic environment can lead to a range of water quality problems and large amounts of carbon, nitrogen and phosphorus, as well as a decrease in dissolved oxygen concentration, which can lead to eutrophication (Burkholder and Shumway, 2011). These species can also increase ammonia, nitrate and phosphate concentrations in water (Vanderploeg et al., 2002). The high concentration of organic matter from zebra mussel feces and pseudofeces lead to oxygen depletion, negatively affecting benthic organisms (Caraco et al., 2000). Another illustration of NNS having a negative impact on water chemistry is *Gracilaria salicornia*, a red macro-alga introduced to Hawaii in the 1970s (Smith et al., 2002, 2004). In addition to monopolising the substrate to the detriment of a wide range of other algal species, this alga has strongly acidified the water, leading to the decline of coral reefs (Martinez et al., 2012).

However, in some cases, non-native filter-feeders remove suspended particles, allowing light penetration with recolonization of macrophytes, thus improving dissolved oxygen and nitrate uptake by plant roots. For example, zebra mussels can filter a wide range of suspended particles larger than 0.7 mm from the water, and their high filtration capacity helps to explain the extreme changes in water clarity and chlorophyll levels following their invasion (Sprung and Rose, 1988). Caraco et al. (1997) observed an 85% reduction in phytoplankton within two years of zebra mussel invasion, which in turn increased water clarity and macrophytes. The return of macrophytes in turn provided habitat and refuge for invertebrates and fish. Although zebra mussels are responsible of major ecosystem changes and as such are high-risk introductions, they also represent a potentially valuable tool to biologically filter eutrophic freshwaters as discussed by (Gozlan, 2008; Sagoff, 2005, 2007). Also, disease outbreaks can indirectly lead to changes in water chemistry, such as altered nutrient dynamics due to increased decomposition rates, or reduced oxygen levels following increased organic matter from dead or dying organisms. This is of particular concern in aquaculture, where systems are often closed with limited water recirculation (Yilmaz et al., 2023). Production could be rapidly affected, with dramatic consequences in a region of the world where food security is already an issue. Invasive non-native phytoplankton can also form harmful algal blooms, release toxins that impair water quality, and deplete oxygen levels leading to hypoxia (Costa et al., 2017).

3.4. The impact of non-native species on functional diversity

Functional diversity is that part of biodiversity which generally refers to the range of functions that organisms perform within communities and ecosystems. It is important to distinguish between ecosystem functioning and functional diversity, which refers to the biological characteristics of species (e.g., filter feeders, grazers, predators, etc.). However, there are many examples where the introduction of a species into an ecosystem has changed the structure of the community, reducing or in some cases eliminating a group of species, with a direct impact on the functional diversity present in the ecosystem. This loss of diversity can affect the redistribution of nutrients in the natural ecosystem, affect oxygen levels, and affect macrophyte communities resulting in ecosystems that function differently from their initial state. This leads to directional ecological succession (Flood et al., 2020). Therefore, trophic interactions are a key mechanism by which invaders influence communities (Noonburg and Byers, 2005; Salo et al., 2007). Thus, by significantly altering the structure of food webs, non-native introductions also alter the functioning of those food webs.

3.4.1. High trophic levels

Non-native predators are often the greatest direct risk of extinction to native species. For example, the Nile perch, *Lates niloticus,* has contributed to the extinction of over 200 endemic species in Lake Victoria (Witte et al., 1992; Lowe et al., 2000). However, it appears that this introduction has not directly disrupted ecosystem functioning as much as it has indirectly. As a new and profitable source of income, its introduction has led to an intensification of fishing activities with a decrease in the mesh size of the nets (Matsuishi et al., 2006). In combination with the removal of surrounding trees for smoking and cooking the fish, the level of fine sediment input to the lake has increased, and many other environmental disturbances resulting from social demands have intensified the eutrophication of the lake and thus modified its functioning. Therefore, a species introduction should not necessarily be seen in terms of function gained or lost, but rather in terms of function changed (i.e., from oligotrophic to eutrophic which includes nutrient cycles, oxygenation, macrophyte diversity etc.). A change in a food web is an indicator of a change in functional diversity, which may indeed have a direct or indirect impact on ecosystem function itself. Therefore, the ecosystem can rapidly move from one ecological succession to another quite rapidly, corresponding to a transition from a naturally functioning ecosystem to a modified one (Flood et al., 2020).

3.4.2. Intermediate to low trophic levels

Non-native species at intermediate to lower trophic levels may also affect the species functional diversity and thus ecosystem functioning. Species such as tilapia and common carp are omnivores, with intermediate trophic levels between primary producers and apex predators. They rate among the 100 worst invasive species (Lowe et al., 2000). These species generally co-occur with native species, but can compete for natural resources (e.g., predation on plankton, insects; Ramírez-Herrejón et al., 2014; Frei et al., 2007) and modify habitats (e.g., bioturbation and increased turbidity by carp; Matsuzaki et al., 2007). In Lake Erie, the introduction of primary consumers such as zebra mussels and other NNS led to a decrease in phytoplankton biomass and an increase in water clarity (Munawar et al., 2005). Although this lake suffered from eutrophication prior to the introduction of these NNS, their introduction posed a threat to the size, structure, and composition of the phytoplankton communities. This resulted in significant changes in the structural and functional characteristics of the food webs in the lake. The mussels have led to improved water quality, reduced phytoplankton, and led to better light penetration in the water column. This led to increased macrophyte diversity and growth. This in turn has impacted fish nurseries and other animal shelters. The mussel beds themselves also provide a new substrate, altering the water circulation and affecting the use of the lake for other activities such as boating and swimming (Munawar et al., 2005). This is an example of an ecosystem that has been altered from its pre-introduction state. It is thus important to keep in mind that such impact does not deal directly with the function of the ecosystem, but rather with the functional diversity that can be found within it. In some cases this can have an impact on ecosystem functioning, not through a net loss or gain of function, but as a modification of its natural function. For example, the non-native planktivorus fish *Limnothrissa miodon* has had little impact on the pre-existing fish assemblage of Lake Kivu or on the functioning of the ecosystem before its introduction. (Spliethoff et al., 1983; Ogutu-Ohwayo and Hecky, 1991; Marshall, 1995; Isumbisho et al., 2006). Although L. *miodon* is planktivorous, one might have expected its effect on the planktonic community to be significant. In this lake, however, the planktonic community was maintained stable by bottom-up web processes fueled by autochthonous organic matter (Llirós et al., 2012) rather than top-down predation pressure. The introduction of this apex predator has had little effect on the overall stability of the planktonic community (Isumbisho et al., 2006).

Predicting the impacts of NNS on ecosystem health is multifactorial and highly stochastic (e.g., Fig. 3). Recently, an ecosytem resilience approach was used to control the invasive Australian swamp stonecrop (*Crassula helmsii*) (Van der Loop et al., 2022). However, more diverse and complex food webs are not always sufficient barriers to the establishment of NNS (see for example the Laurentian Great Lakes, African Rift Lakes, or Midwest USA rivers). These species-rich ecosystems were already far from a pristine state when NNS were successfully introduced and established. In the context of aquaculture, difficulties arise from the simplicity of the production system. In such a system, with a reduced food web, it is easy to introduce, establish, and spread NNS within the wider ecosystem via biological escapes. Therefore, special attention, management, and policies need to be reinforced along this introduction pathway.

4. Impact of non-native species on human health

4.1. Impact of non-native species introduction on food security

Aquaculture plays a major role in global food security, which is one of the main concerns of the United Nations 2030 Agenda for Sustainable Development Goals (Belton et al., 2018; UN, 2018). Food security is recognized as one of the social, economic and cultural rights enshrined in the Universal Declaration of Human Rights (FAO, 2006, 2022; Security Council resolution 2417, 2018 [on conflict-induced food insecurity]). However, in a growing world, wild fisheries can no longer provide enough aquatic protein (Shelton and Rothbard, 2006), and it is estimated that aquaculture accounted for 49% of the total supply of food fish in 2020 (FAO, 2022). Aquaculture has been practiced for over 3000 years and its expansion has often been based on the farming of NNS (Arthur et al., 2010; Gozlan, 2017), including carp, tilapia, catfish, and salmonids (Allsopp, 1997). Carp and tilapia for example, have been introduced into tropical areas for aquaculture and account for 80% of tropical inland aquaculture production (Arthur et al., 2010). In 1994, carp accounted for 42% of the 18.5 million tonnes of aquaculture production (New, 1997). Tilapia, which are mainly farmed outside their native range (Shelton and Rothbard, 2006), have become known as the “aquatic chicken" because they are an affordable and high-yielding protein source that can be produced quickly and easily (Dey et al., 2000). Since the 1980s, almost all global introductions of tilapia have been for aquaculture. Tilapia is the third most farmed fish in the world after carp and salmonids, with global production of 1.49 million tonnes in 2002 (Fitzsimmons, 2003). Tilapia farming has exploded in Africa, Asia and Latin America. In 2002, about 70% of the world's tilapia production came from Asia, with 46% from China alone (Fitzsimmons, 2003). In Africa, most aquaculture production is based on carp and tilapia farming (FAO, 2000). It is therefore important to bear in mind that, given the large number of NNS cultivated worldwide, restricting aquaculture to the farming of native species in their historical range would pose a serious problem for food security in developing countries.

From the perspective of using NNS to ensure food security while conserving native species in aquaculture facilities, it is questionable whether polyculture (the farming of multiple species) could provide a sustainable solution to global food security. The use of NNS as components of polyculture systems (Stentiford et al., 2020) offers an option for supplying aquatic protein. India has moved towards polyculture systems where compatible and high yielding combinations of native (*Labeo rohita*, *Catla*, *Cirrhinus mrigala*) and non-native (*Hypophthalmichthys molitrix*, *Ctenopharyngodon idella*, *C. carpio*) are grown together in ponds (Dwivedi

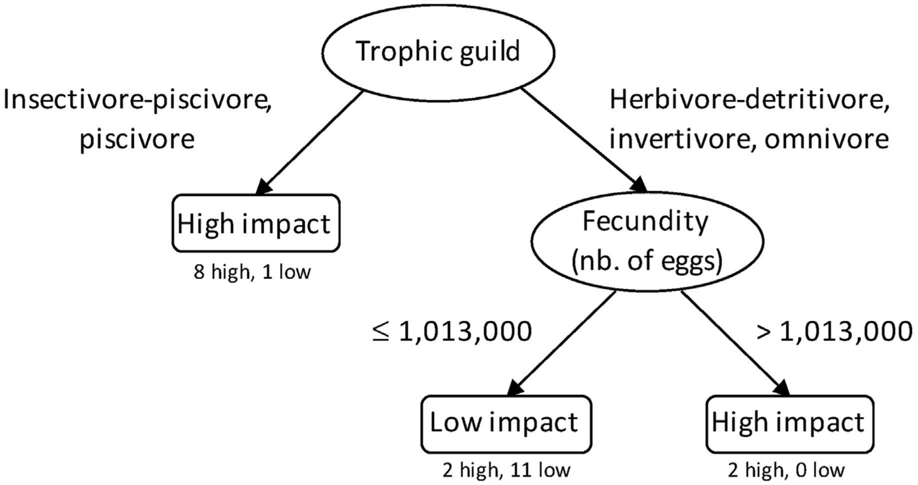

Fig. 3. Classification tree predicting ecological impact of non-native fish species in the Laurentian Great Lakes region. The number of species classified as having a high or low impact for a particular trait on an ecosystem is given for each node. (adapted from Howeth et al. (2016)).

et al., 2014). In Southeast Asia, non-native tilapia and carp are widely used in polyculture, both in ponds and cages (Amilhat et al., 2009) and in natural and modified freshwater wetlands (De Silva et al., 2006). Interestingly, the polyculture of non-native fish species (*O. niloticus*, *L. rohita*, *H. nobilis*) has been associated with a significant increase (between 49 and 180%) in total fish biomass, while having little impact on native fish communities (Arthur et al., 2010). It is essential that the management of such polyculture systems takes into account the ecology and niche preferences of native and non-native fish species reared together to avoid niche overlap and competition for resources. The use of NNS in polyculture systems remains of paramount importance for food security and should be carefully considered by governments and fisheries agencies.

4.2. *The impact of non-native species introduction on human diseases*

As aquaculture is one of the world's major entry points for non-native aquatic species, it is clear that the introduction of fish, molluscs and shrimps outside their native range can act as a Trojan horse for the introduction and spread of a wide range of zoonotic diseases or parasites that affect humans. The mechanisms of infection and transmission of aquaculture species to humans are only relevant in the context of NNS, because their introduction from remote geographical areas can potentially pose a new infectious risk to local human populations for which they have no acquired immunity. There have been several examples where non-native zoonotic bacteria for example have been associated with cases or outbreaks reported in humans due to exposure to various types of fish and/or seafood (see Weir et al., 2012). Humans can acquire such zoonotic bacteria by ingesting contaminated seafood or water, or through stings, bites, spine injuries, or open wounds. People who are frequently exposed to fish, their products or their environment (e.g., fishermen or fish processing workers) are at higher risk, and people with a weakened immune system may be at even greater risk (Palumbo et al., 1989; Weir et al., 2012). Under certain environmental conditions, some pathogens can be reactivated and transmitted to humans. This is the case for several waterborne zoonotic diarrhoeal agents such as *Cryptosporidium* and *Giardia*, and the zoonotic microsporidial agents Encephalitozoon and Enterocytozoon, which can exist as oocysts, cysts or spores dormant in water or sequestered in *Dreissena mussels* and clams *Corbicula* (Conn, 2014; Conn et al., 2014). Several *Aeromonas* spp. have caused disease in humans and farmed fish, although they are widely associated with freshwater aquatic organisms, including fish and crustaceans, and transmission is mainly by contact with contaminated mucus and tissues (Palumbo et al., 1989). Another example of potential human infection (through ingestion or contact) derived from the farming of non-native tilapia is the bacterium *Vibrio vulnificus*. There is evidence of non-native tilapia farms enhancing pathogen evolution and notably the acquisition of a plasmid that encodes the ability to proliferate in the fish blood (Carmona-Salido et al., 2021). Mycobacterial species such as *Mycobacterium marinum*, *Mycobacterium fortuitum* and *Mycobacterium chelonei* are widely isolated from non-native farmed species that act as reservoirs and transmit the pathogen to other susceptible fish and humans (Lowry and Smith, 2007). Therefore, the use of non-native-competent hosts for aquaculture purposes poses a high risk of disease amplification and thus emergence. One of the most invasive fish species in the world, *P. parva*, which is very often associated with aquacultures, carries in part of its native range *Clonorchis sinensis*, a trematode that is a major public health problem in Korea because of its prevalence as high as 40% of the population on average and up to 100% in some households combined with its usual severity in endemic areas where reinfestation is constant. Its association with *P. parva* has been singled out and its introduction into fish farms or the wild outside its native range increases the risk of trematode introduction into *C. simensis*-free regions (Choi, 1978; Rhee et al., 1983; Chung et al., 1991). Invasive snails have also invaded many new aquatic habitats (Morgan et al., 2001) including aquaculture ponds that provide favourable habitats for snail survival and reproduction. Biological control of invasive competent snails by farming non-native malacophagous fish could help in reducing infectious stage transmission and thus disease prevalence (FAO https://www.fao.org/3/ad002e/AD002E00.htm#TOC) of schistosomiasis. It is therefore important to consider that farming of NNS can have negative (enhancing) and/or positive (reducing) impact on human disease emergence and that impacts may depend on (i) the specific abiotic and biotic characteristics of the newly invaded ecosystems and (ii) its role as a competent or non-competent host or even as a predator of competent hosts.

Given the widespread use of NNS in aquaculture and their importance as a key resource for global food security, the question arises as to how to minimize the risk of human disease associated with farming of NNS (see Fig. 4). Pathogen surveillance is essential, particularly because many zoonotic agents do not cause disease in animals or because the clinical signs of disease in aquatic species differ from those seen in humans (Lowry and Smith, 2007). Therefore, it seems essential that local authorities implement a comprehensive communication plan with the population, communities and farmers about the origin and ecology of locally used NNS and the underlying health risks they pose. The key point is to understand the risk associated with the introduction of new species into an environment, species that may be carriers of novel non-native pathogens and thus introduce new risks to the health of local human populations. That is why we believe that a One-Health framework for assessing NNS should include these issues, which are too often neglected (Fig. 4).

4.3. *Impact of non-native species introduction on recreational activities*

Recreational fishing is a major source of non-native fish introductions. Carpio et al. (2019) estimated that nearly a quarter of freshwater fish introductions in Europe were deliberate, with the aim of establishing the fish for angling. Large voracious non-native predators

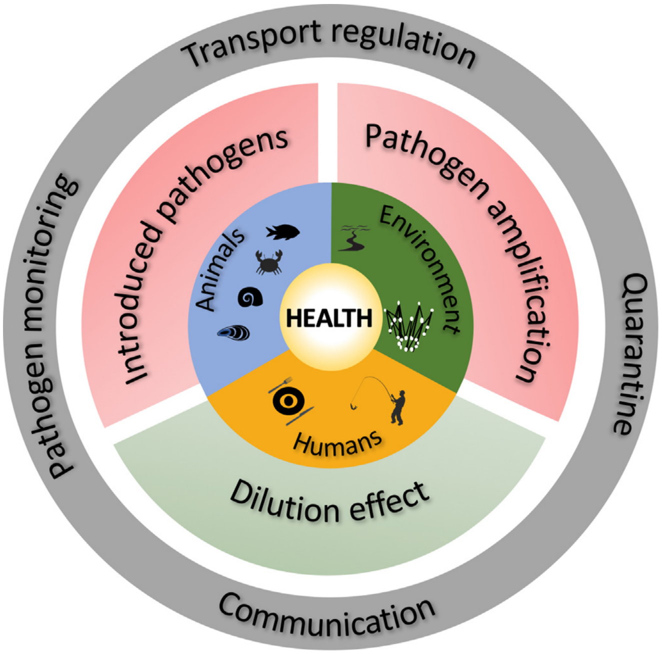

Fig. 4. Impact of non-native species used in aquaculture on disease risk. Non-native species used in aquaculture can co-introduce pathogens, notably via healthy carrier hosts, that will establish easily in a new habitat. Non-native species can also host native pathogens and thus amplify the infectious load. Alternatively, non-native species can enter in competition with native hosts and thus dilute the infectious signal. Negative impacts on disease risk are represented in pink; beneficial effects of non-native species are indicated in green. Possible policies to minimize disease risk while using non-native species for aquaculture purpose are in grey.

make them popular angling species (Sbragaglia et al., 2022). The proliferation of invasive species can then become the cornerstone of a recreational fishery, as is the case for trout in Patagonia, where fishing has become a significant source of foreign exchange currency, generating more than US$43 million per year (Pascual et al., 2009). In some areas, deliberate stocking by anglers and fishery agencies has been the main driver of NNS, as in western North America (Clancy and Bourret, 2020). Anglers often oppose conservation and management strategies, as in the case of invasive pike perch in England, where anglers prefer to illegally release rather than remove (Nolan et al., 2019). In addition, non-natives can be transported attached to fishing gear, boats and trailers, or in boat engines (Bussmann et al., 2022; Geist et al., 2022). It is therefore clear that for NNS control measures to be effective, stakeholders involved in aquatic recreation must be included and the risks must be properly communicated (Golebie et al., 2021).

Despite the perceived improvement in fisheries through the introduction of prized game fish, the negative impacts of NNS on recreational activities are numerous. Non-native plants can dominate waterways, such as the broad-leaved paperbark (*Melaleuca quinquenervia*) which was introduced into the eastern United States from Australia, restricts access to water bodies and affects the use of parks by residents and tourists (Serbesoff-King, 2003). Infestations of the invasive diatom *Didymosphenia geminata* in New Zealand reduce angler enjoyment and benefits, and block boating activities (Beville et al., 2012). Invasive crayfish species may have become the basis for recreational fishing in some places, but they also threaten native crayfish that are caught for traditional festivals (Lodge et al., 2012).

4.4. *Impact of non-native species on economic sustainability*

Non-native species make important contributions to aquaculture production. Shelton and Rothbard (2006) calculated that the global contribution of non-native fish to aquaculture was 17%, consisting mainly of carp, tilapia, catfish and salmonids farmed outside their natural range. The farming of non-native fish species is estimated to contribute US$2.59 billion to the economies of Asian countries, accounting for 12% in 2006 (De Silva et al., 2006). Chile is one of the world's leading producers of introduced salmonids and the value of its exports was at one time second only to the revenue generated by the copper industry (Pascual et al., 2009). Non-native species can account for a significant proportion or the majority of marine fish catches, as is the case in Cyprus (Kleitou et al., 2022). Commercial exploitation of the invasive red swamp crayfish *Procambarus clarkii* has been established for an international market, employing professional fishermen in Spain and Portugal (Banha et al., 2022).

Nevertheless, the negative impacts of invasive NNS and the costs associated with them cannot be ignored. A recent study estimating the global costs of non-native invasive species found cumulative economic losses of US$345 billion (Diagne et al., 2021). This estimate from the InvaCost database is likely to be very conservative because it includes some reports from African and Asian countries from where we have less comprehensive reporting (Diagne et al., 2020a,b). The Eurasian ruffe *Gymnocephalus cernua* imposes an impact of US$53 billion on commercial and recreational fisheries and *Dreissena* spp. cause US$19 billion in infrastructure damage (Cuthbert et al., 2021). Estimates of the impact of invasive fish species have revealed a potential economic loss of US$37.08 billion since the 1960s (Haubrock et al., 2022a,b). Tilapia is a damaging invader that feeds on and out-competes native species (Xiong et al., 2023). It is also an example where the income generated by farming tilapia may outweigh its costs in terms of loss of ecosystem services, but there are significant knowledge gaps on the economic impacts of aquatic invasive species (Cuthbert et al., 2021; Haubrock et al., 2022a,b; Xiong et al., 2023). In cases where a NNS has become established as a major aquatic resource, improved management and the search for alternatives are therefore more necessary than eradication (Xiong et al., 2023). Nonetheless, human food production has long depended on the translocation and introduction of plants and livestock. Restricting aquaculture to the cultivation of native species would seriously limit its contribution to food security (Shelton and Rothbard, 2006).

5. A one-health management approach to non-native species

5.1. *Explaining the need for a one-health approach*

At present, the risk assessments produced to deal with the introduction of NNS are species or ecosystem focused, which isolates the issue of NNS as ecological and economic problems (Copp et al., 2009; EC, 2018; EC Regulation 708/2007). It is time to move away from the linearity of policies dealing with environmental and economic issues to a network of policies that encompass issues relating to human, animal, and environmental health. For example, integrating the Convention on Biological Diversity (CBD), the International Plant Protection Convention (IPPC), the International Maritime Organization (IMO), and the Centers for Disease Control and Prevention (CDC) could be useful. It would be like changing our understanding of food chain ecology to trophic network ecology. The linearity of thinking, expertise, and task division has led to the non-native issue being treated as one aspect at a time. Here we showed that the issue of NNS introduction is particularly well suited for integration into a One-Health approach. This includes management options, a risk-based approach, and policies and measures relevant to One-Health. The expertise in the different fields already exists, so it means bringing together experts and stakeholders from different fields to create more diversity of expertise in government agencies that deal with environmental issues, and to bridge existing legislation from local, national and international levels. It means bringing together environmentalists with medical professionals (biologists, but also psychologists to deal with mental health issues, see Sax et al., 2022) and veterinarians for the risk-framing phase, then integrating it with the results of roundtables with local communities, and finally providing local and national policy makers with a workable set of sound One-Health options. This will provide the enforcement framework needed for sound risk-based management (see Fig. 5).

5.2. *Use and efficacy of management options for non-native aquatic species in food-based systems*

Managing non-native aquatic species in food-based systems requires the implementation of effective management options to mitigate their effects on production (Britton et al., 2010a,b). However, the production of NNS needs to integrate ecological sustainability in a holistic context of ecosystem services (i.e., regulating, supporting and cultural services). This is crucial in freshwater ecosystems because communities are linked longitudinally but often belong to different legislative juristictions in multiple countries (Gozlan and Britton, 2015). The management of NNS that are central to a food-based system versus those that are undesirable and have been accidently introduced must therefore be considered in an antagonistic way (Gozlan, 2016). This dilemma was dubbed the “Janus syndrome” by Gozlan (2015), referring to the two faces of the Roman god Janus. These two faces do not usually talk to each other because their motivations differ and no one is willing to look in the same direction, but poverty and economic growth should not be pitted against biodiversity conservation.

Preventing the introduction and establishment of unwanted aquatic species is the most efficient and cost-effective approach. The implementation of biosecurity measures (Pruder, 2004), such as strict quarantine protocols, risk assessments for imported species, and certification programs can minimize the likelihood of NNS being introduced into food systems. Collaborative efforts between governments, regulators, industry and research institutions are essential to establish robust biosecurity frameworks (Scarfe et al., 2006). Early detection is a vital component of management (Britton et al., 2010a,b; Poland and Rassati, 2019; Roy et al., 2014). Establishing monitoring programs to detect the presence of

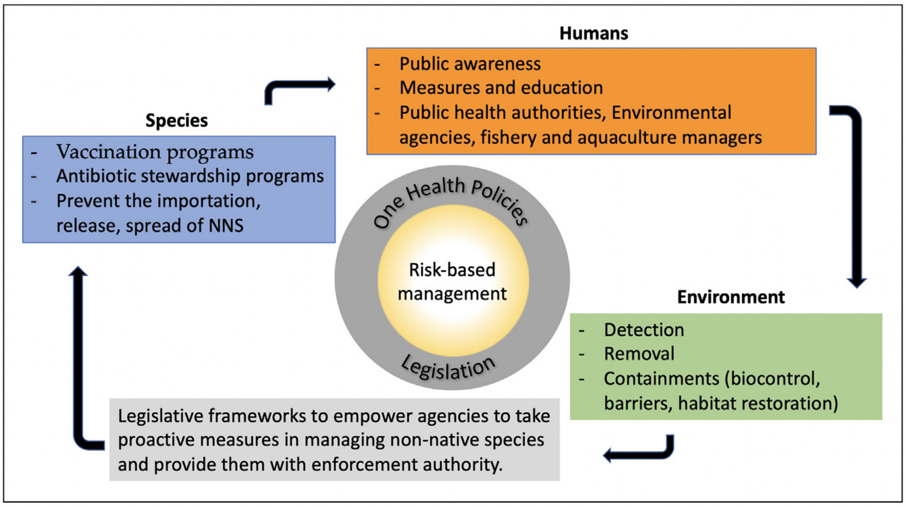

Fig. 5. Risk-based management framework showing the an integrated legislative framework that includes animals, environmant, and human health.

NNS in new areas can help initiate timely responses. Monitoring efforts can involve active surveillance, public reporting mechanisms, and partnerships with citizen scientists. Once detected, a rapid response plan should be implemented to prevent or minimize their spread. This may include targeted removal efforts, containment measures, and public awareness campaigns (Van Driesche et al., 2008; Liu et al., 2012). A good example is the total eradication of the topmouth gudgeon *P. parva* in the UK, a small non-native fish from Southeast Asia. Risk-based management was applied (Copp et al., 2005) as it was quickly recognized that a novel pathogen carried by this NNS was having a severe impact on native fish assemblages in aquaculture and in the wild (Gozlan et al., 2005, 2010). Government agencies calculated the impact on fisheries, aquaculture, and ecosystem condition (approximately US$5004 million, Haubrock et al., 2022a,b) and quickly established an action plan consisting of early detection, rotenone-based eradication (Britton et al., 2010a,b) and inclusion in national (Wildlife and Countryside Act, 1981) and European (Regulation (EU) 1143/2014) legislation. Another example is the successful eradication of the ectoparasite *Gyrodactylus salaris* by Norwegian environmental authorities which has been a major threat to wild Atlantic salmon (*Salmo salar*) since the 1970s. The establishment of a piscicide-based eradication program using rotenone to eliminate the parasite has been successful in reducing *G. salaris* from Norway and total eradication now seems possible (Sandodden et al., 2018).

When used appropriately, biological control agents can be effective in reducing the abundance and negative impacts of non-native aquatic species. However, risk assessment (see section below), host specificity testing, and long-term monitoring are needed to avoid unintended consequences and minimize ecological disturbance. In addition, physical barriers and exclusion techniques can be used to prevent the entry or movement of non-native aquatic species into food systems. These include the use of screens, nets, fencing, and fish exclusion devices. These measures can be particularly effective in aquaculture, as they prevent NNS from escaping and establishing themselves in natural environments. Regular maintenance and inspections are essential to ensure the effectiveness of physical barriers but can be costly with approximately US$18 billion being the cost of keeping Asian carp from the Great Lakes (https://glmris.anl.gov/glmris-report/). The general public can also influence the aquaculture sector by broadening their fish preference or chefs being more creative in the kitchen using NNS for ceviche, fried or as sushi. Changing our diet to include invasive species is also a way to reduce/control the spread of invasive species, provide cheap protein for a growing population, and therefore contribute to food security. Humans preferentially becoming the apex predators of non-native fish lessens the pressure on native species. Ulman et al. (2021) for example suggests that human action is needed to control abundances of the highly invasive Pacific red lionfish which has few natural predators. Therefore, lionfish culling by scuba diving should be allowed in all Mediterranean countries and diving clubs should be encouraged and provided with equipment to participate. This is an example of a creative One-Health approach to control and manage invasive lionfish thus, providing recreational acitivies and food at the same time.

Where the choice is made to deliberately breed NNS, the associated risks of escape must be taken into account. There must be a mechanism to assert the risks associated with the life history traits of the species and the health conditions of the original imported stock. The use and effectiveness of management options should be based on legislation similar to what has been done in Europe (EC Regulation 708/2007). This regulation establishes a "framework for aquaculture practices to assess and minimize the possible impact of NNS on aquatic habitats and thus contribute to the sustainable development of the sector". Alternatively, wealthy countries and large aquaculture companies should consider the introduction of a tax on the profits of farming NNS, which would be redistributed to support biodiversity conservation and restoration programs. Such a tax could help reconcile Janus with itself and allow fish farmers and conservationists to look in the same direction together (Gozlan, 2015).

5.3. Risk-based management of non-native aquatic species from a One-Health perspective

Risk-based management is a strategic and systematic methodology used in various fields to identify, assess, prioritize and manage the risks associated with different activities, projects, processes or systems. The central idea of risk-based management is to allocate resources and effort according to the level of risk presented by a given scenario. It includes components such as (1) risk identification, (2) risk assessment, (3) risk prioritization, (4) risk mitigation and management, (5) resource allocation, (6) monitoring and review, (7) adaptation, and (8) communication and transparency. This approach is commonly applied in fields such as business, project management, finance, health, security, etc. (COM (2013)76, European Union, 2014). When applied to the issue of NNS, it has often been limited in its power and relevance, as it has mainly dealt with the environmental/animal aspects of the problem. Risk-based management adapted to the One-Health approach would combine the eight components of the process to a broader base of risks such as human, animal, and environmental health. It would also be policy driven (Fig. 5). Basic risk assessments include likelihood, impact, and uncertainty (Copp et al., 2009). This qualitative assessment uses categories and if each category is clearly defined, it becomes a universal structure that can be shared across the different experts to get their input or scientific evidence that can then be used to estimate which potential events pose the greatest risk (OpenWHO, 2021). It can also identify that additional information or monitoring is needed. For NNS in aquaculture, it would be a joint consensus among stakeholders to first decide how to prioritize or categorize the risks. This would avoid focusing on specific species in a local area such as the problem of Asian carp invasion in the Colorado River. The Colorado crosses seven states (Wyoming, Colorado, Utah, New Mexico, Nevada, Arizona and California), and the federal government could add rotenone to the Glen Canyon dam to kill all the fish in the river. Instead, it could take a more general One-Health approach which would also consider the impact on the environment as well as the human aspect (i.e., fishing, well-being, religious etc.).

The first step in risk-based management is assessment of the potential risks associated with introduction of NNS. This involves evaluating the ecological impacts, the potential for disease transmission, and the socio-economic consequences. Ecological risk assessments (EC, 2018) can help identify the potential effects on native biodiversity, habitats, ecosystem functions, and disease transmission. Public engagement and education play a crucial role in risk-based management (Liu et al., 2012; Humair et al., 2014; Britton et al., 2011). Raising awareness about the risks associated with non-native fishes can promote responsible behavior among anglers, aquarists, and the general public at large (Gozlan et al., 2013). Knowing which native species help in the biological control of NNS should also be communicated to anglers. For example, in the Mediterranean Sea the invasive *P. gibbesi* was found to be eaten by the native rock goby, *Gobius paganellus* (Tiralongo et al., 2021). In addition, educational campaigns can highlight the importance of proper disposal of unwanted aquarium fish, responsible fishing practices, and reporting sightings of non-native fishes. Engaging local communities and stakeholders in management decisions fosters a sense of ownership and encourages active participation. Effective risk-based management requires supportive policies and legislation. Governments should develop regulations and guidelines to prevent the importation, release, and spread of NNS (Copp et al., 2005). Legislative frameworks can empower agencies to take proactive measures in managing NNS and provide them with enforcement authority. Collaboration between different government departments is essential to ensure a coordinated approach to risk-based management (EC, 2018). By adopting a One-Health approach, we can better conserve native ecosystems, safeguard public health, and promote sustainable fisheries management (Fig. 5).

5.4. *Policies and measures relevant to one-health*

Here we explore the policies, indicators and measures that are relevant to One-Health and outline how they can be used to promote the health and well-being of all living things. Cambodia for example established the Zoonoses Technical Working Group (Z-TWG, see OpenWHO, 2021), and Pakistan developed a priority list of zoonotic diseases in 2017. These countries applied the One-Health approach by involving a wide range of stakeholders. Cambodia and Pakistan were provided with access to mapping and analysis toolkits. The creation of such platforms has enabled ideas/information/reports to be shared for the benefit of all (OpenWHO, 2021). These strategies typically involve collaboration between human, environmental and animal health agencies to prevent and control the impact of these introduced species (Fig. 5). Finally, there is a whole set of environmental policies that could serve as a model to link the different level of risks associated with NNS which have significant impacts on human, animal, and environmental health. These address issues including climate change, pollution, and habitat destruction. One-Health policies that address environmental issues recognize the interconnectedness of these three domains and promote collaboration to mitigate negative impacts.

Several international agreements and conventions address the issue of invasive species. For example, the Convention on Biological Diversity (CBD), the International Plant Protection Convention (IPPC), and the International Maritime Organization (IMO) have developed guidelines and regulations to prevent the introduction and spread of NNS across borders. In addition, many countries have developed national policies to prevent the introduction and manage the impacts of NNS. In many countries, state or provincial governments have developed policies and regulations to address this issue at a regional level. In some cases, local governments have developed policies for parks or nature reserves. These policies may involve measures such as controlling or eradicating NNS (Donaldson and Cooke, 2016; Liebhold and Kean, 2019), restoring native habitats, and engaging with local communities to raise awareness and promote participation in NNS management (Liu et al., 2012). Some industries have also developed policies and best management practices to prevent the introduction and spread of NNS through their operations. For example, the shipping industry has developed guidelines to prevent the transport of NNS through ballast water discharge (Bradie et al., 2022). Ballast water treatment is effective but has its consequences, including the release of disinfectant by-products that are potentially toxic to aquatic organisms (Kurniawan et al., 2022), or changes in bacterial communities via recolonization of bacterial strains (Hess-Erga et al., 2019).

Policies for NNS are often too specific and miss the bigger picture by not making the link with human health. They mostly focus on preventing introduction, and concentrate on management impacts through a combination of measures that may vary depending on the specific context. In a growing human population with increasing pressure on food security, focusing only on the potential environmental impact of NNS without including the aspect of human health as well as the potential benefits limits the effectiveness of these policies (Fig. 5).

Therefore, it becomes urgent that we develop measurable parameters to provide information about the state or progress of a system or process. As such, One-Health indicators could help to measure progress towards achieving optimal health outcomes for humans, animals and ecosystems. One-Health indicators could include disease surveillance systems (Choi et al., 2016; Thurmond, 2003) about the occurrence and spread of diseases in human and animal populations from NNS. One-Health surveillance systems associated with the introduction of NNS could help to identify emerging zoonotic diseases and prevent outbreaks at an early stage. This could also have a further impact on our reliance on treatments such as antibiotics which can lead to resistance. This is a major global health threat that affects both human and animal health especially in aquaculture (Reverter et al., 2020).

Finally, specific One-Health measures, which are actions or interventions that are taken to achieve specific goals or objectives, could help address complex health challenges that require collaboration across disciplines. For example, One-Health measures could include vaccination programs for both humans and animals to prevent the spread of infectious diseases and protect public health. One-Health vaccination programs can help to prevent zoonotic diseases and promote the health of human and animal populations. One-Health antibiotic stewardship programs could promote the health of human and animal populations by reducing the development of antibiotic-resistant infections. Similarly, environmental conservation measures such as habitat preservation and pollution reduction could help to protect the health of ecosystems and the species that inhabit them. This would allow some NNS to be used to fill specific ecological gaps that are locally missing (Gozlan, 2008; Case, 2021). However, the latter has been a major driver for unnecessary and dangerous introductions.

6. Conclusions

Applying the One-Health framework to the issue of NNS management is an innovative way to link positive and negative animal, environmental, and human health impacts that arise from NNS introductions into an ecosystem or farming systems. Given the life history traits of NNS (i.e., broad habitat and climatic adaptation, rapid growth rates, high potential for resource competition, low susceptibility to pathogens, low systematic inflammatory responses or strong humoral defences), it predisposes some of these species to be cultivated in aquaculture, as they often allow good production at low cost in southern countries (e.g., wide diet, disease resistance, high fertility). Although their introduction and spread raises serious concerns for ecosystems, animals, and humans, NNS that are suitable for aquaculture and food production are useful for food security. As health is not limited to disease, the use of NNS can also contribute to human well-being in terms of social and cultural activities. Because of those interlinkages, we recommend that future farming programs analyze these issues under the holistic vision of a One-Health concept. Future aquaculture programs in developing countries should encourage polyculture, including the farming of non-native and native species. The ecological, biological, immunological and socio-cultural impacts of NNS should be considered to develop legislation that is context-sensitive and promotes the rehabilitation of wild ecosystems. Education campaigns on the ecological, economic, and social impacts of NNS and stakeholder involvement in management decisions will play a crucial role in risk assessment management. Collaboration between governments, regulators, industry, and research institutions needs to be strengthened to develop biosecurity measures and appropriate risk assessment programs and legislation. By adopting a One-Health approach to the farming sector, we could help conserve native ecosystems, protect public health, and promote global food security. Achieving such a goal is imperative in a growing world with increasing pressures on food security. The alternative solution, promoted by several international organizations and key figures in the pure tradition of Thomas Malthus (e.g., the Club of Rome with its Meadows Report; https://youtu.be/Dbo6uvJBtZg?si=ZG5GHomI4f4ecca9; Jane Goodall at the World Economic Forum or Commonwealth forum https://youtu.be/bxC1ke74RDk?si=pvTxUcI3rgXYxuLi; the Bill and Melinda Gates Foundation, https://youtu.be/y0PcT1hPVcE?si=honqSRwBLsplRt1q, 3.57 min), focus instead on accepted ways of reducing the human population and achieving a sustainable level of development (Gozlan et al., 2022).

Author contributions

Rodolphe Gozlan & Marine Combe: Conceptualization; All authors: Writing- Original draft preparation; All authors: Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Rodolphe Gozlan is an editorial board member for *Water Biology and Security* and was not involved in the editorial review or the decision to publish this article.

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