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Review Article

Are they always bad? Assessing benefits of non-indigenous species in aquatic environment and their implications

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ABSTRACT

Non-indigenous species (NIS), non-native, or alien species are any organisms living and spreading outside their natural habitat. Many of NIS spread to a new environment accidentally, while some other species are intentionally introduced by humans to a new habitat in many different pathways, as follows: 1) release; 2) escape; 3) contaminant; 4) stowaway; 5) corridor; and 6) unaided. Threaten native biodiversity may be the most problematic impact of NIS. They can also disrupt food-web organizations and affect the ecosystem structures. Additionally, the problem is exacerbated by disagreements regarding whether or not NIS should be permitted for aquaculture production. The likelihood of NIS escaping, being released from aquaculture, and establishing in its native habitat poses a significant threat to the ecosystem and biodiversity. NIS also have positive impacts as ecosystem engineers which may increase the biodiversity of native communities. Other benefits of NIS include providing an alternative food source and supporting fisheries and aquaculture sectors. Understanding the introduction process and the impacts of NIS should be supported by effective policy frameworks and management approaches, including risk assessment, prevention and control, pathway and vector management, early detection and rapid response, eradication, and mitigation and restoration. Furthermore, the crucial efforts would be raising public awareness, improving scientific research, and developing strategy regarding biosecurity issues as consequences of the emergence of interactions complexity among NIS and other global ecological change drivers.

1. Introduction

Non-indigenous species (NIS), non-native, or alien species are any organisms that are introduced by humans, accidentally or intentionally, into a new environment. Many of them succeed, living and spreading beyond their natural habitat range (Richardson *et al.*, 2011; Pysek *et al.*, 2020). Unfortunately, once they occupied a new area, sometimes problems might arise. NIS can cause a range of threats to biodiversity and native ecosystems and has become a major concern for the global communities (Ruiz *et al.*, 1997; Doherty *et al.*, 2016; Gallardo *et al.*, 2019). They can be described as 'invasive species' when they spread rapidly and become established in the new habitat or ecosystems and threaten native biological diversity (Richardson *et al.*, 2003; Pysek *et al.*, 2020). The International Union for Conservation of Nature (IUCN), the Convention on Biological Diversity (CBD), and the World Trade Organization (WTO) classified invasive species are only those non-native species that cause undesirable environmental and economic impacts (IUCN, 2000).

Despite their negative impacts, NIS may represent some benefits due to their essential ecological and economic roles include habitat alteration, or ecosystem engineering, trophic interactions, ecosystem services and alternative resources, and aquaculture purposes. This article will look at the introduction pathways and vectors of NIS into a new environment, negative and positive impacts, as well as their significances for aquaculture productions. Several examples of the policy framework and management approaches are also addressed. It will also discuss rebranding NIS and the ways we can benefit from them, especially from the aquatic environmental perspective.

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2. Introduction Pathway and Vector

Many NIS spread to new environments accidentally, while humans intentionally introduce some other species to a new habitat in many different pathways. Hulme *et al*., (2008) simplified a framework to classify the pathways of introduction into six categories based on the amount of human assistance, are as follows: (1) release, when an organism is introduced as a commodity for release; (2) escape, when an organism is introduced intentionally as a commodity but escapes unintentionally; 3) contaminant, when an organism is introduced unintentionally along with a specific commodity; 4) stowaway, when an organism is introduced unintentionally attached to or within a transport vector; 5) corridor, when an organism is introduced unintentionally through infrastructures that linked previously not connected areas; and 6) unaided, when an organism is introduced unintentionally without being interfered by humans or as natural dispersal of non-native species across regions.

Different taxa possess a variety of introduction pathways. For instance, vertebrates in aquatic and terrestrial habitats are introduced to the new environment mainly by releases or escapes. Similarly, aquatic flora is rarely released intentionally but more frequently stowaways or escapes, which are associated with canal or river transports. Escapes also appear to be an essential pathway of introduction for aquatic invertebrates in terms of aquaculture purposes. Microscopic organisms such as bacteria, parasites, and fungi are introduced mostly as contaminants in a specific commodity. Corridors and unaided pathways are less frequently assessed in both aquatic and terrestrial environments (Hulme *et al*., 2008; Hulme, 2009).

Moreover, NIS is introduced to a new habitat through several vectors such as transportation and shipping activities and aquaculture pathways (Richardson *et al*., 2003; Hulme, 2008; Williams *et al*., 2018). At least, there are 15 broad categories of vectors as media for organisms to spread outside their native habitat ranges (Table 1). It is widely recognized that transportation is one of the important dispersal vectors of NIS. It is usually associated with shipping activities of animals or plants trade. Historically, the first moment of biological invasions was started thousands of years ago. Animal and plant species have been transported and traded by humans since the end of the Middle Ages (1500 AD), a period that related to world exploration, colonialism, and the beginning of extreme changes in social structure, trade, industry, and agriculture (Preston *et al*., 2004; Hulme *et al*., 2008; Hulme, 2009). In the past decades, the maritime trade and shipping industry increase in frequency and magnitude, which lead to the accelerated rate of biological invasions in some regions (Hulme, 2009; Seebens *et al*., 2013).

Shipping-mediated vectors - ballast water and hull fouling - are the major pathways for unintentional introductions for many NIS worldwide (Ruiz *et al*. 2000; Lewis *et al*., 2003; Nunes *et al*., 2014; Bailey, 2015). In general, increasing invasion rate was associated with a high shipping intensity (Drake and Lodge, 2004). It was empirically investigated using the diversity and population level of the model fouling tunicate *Botryllus schlosseri*, a cosmopolitan invader of coastal marine communities (Lacoursie`re-Roussel *et al*., 2016).

Invasive zebra mussel *Dreissena polymorpha*, one of the most well-known aquatic invaders, was reported from the Laurentian Great Lake and caused negative impacts on the ecosystem both in Europe and North America (Karatayev *et al*., 2007; Bailey, 2015). Hallegraeff and Bolch, (1992) documented their finding of invasive dinoflagellates *Alexandrium catenella* and *A. tamarense* in ballast tanks of vessels in Australia from Japan and Korea. However, Seebens *et al*., (2013) revealed that immense shipping traffic in a port does not mean it has a high invasion menace. For example, North Sea ports in northern Europe are not categorized into the most threatened ports, although they have tremendous shipping activities. Different situations were found in a number of ports in Southeast Asia, the Middle East, even in the USA where were categorized as the invasion hot spots. Drake & Lodge, (2004) hypothesized that the different invasion risks in some places might depict different priorities of study about NIS, funding, as well as habitat or ecosystem, which have a differential vulnerability to NIS introduction.

Table 1. Pathways and vectors for NIS in aquatic environment (adapted from Carlton, 2001; Bax *et al*., 2003; Johnston *et al*., 2017)

Pathway	Vector	Target taxa
Shipping activities	Ballast water	Plankton, nekton, benthos
	Hull fouling	Encrusting, nesting, mobile species
	Solid ballast (sand, rocks, etc.)	Encrusting, benthos, meiofauna, and flora
Aquaculture and fisheries	Intentional release for stock enhancement	Single species
	Gear, stock or food movement	Various taxa
	Discarded nets, floats, trawls, etc.	Various taxa
	Discarded live packing materials	Various taxa
	Release of transgenic species	Single species
Aquarium industry	Intentional or accidental release	Aquarium fauna and flora
Drilling platforms	Ballast water	Plankton, nekton, benthos in sediment
	Hull fouling	Encrusting, nestling, mobile species
Canals	Species movement	Various taxa
Recreational boating	Hull fouling	Encrusting, nestling, mobile species
Floating debris	Discarded plastic debris	Encrusting, nestling, mobile species
Dive practices	Snorkeling and scuba gear	Bacteria, algal spores, small mobile species

Industry and aquaculture activities, including intentional pets aquarium and living animals trade, are other introduction pathways of NIS. Most of them are intentionally introduced to improve the value of aquaculture and cultivation enhancement.

Grosholz *et al*., (2015) obtained 126 NIS related to commercial aquaculture in California based on their literature study. Another study in China showed that ornamental species trades and aquaculture were two major introduction pathways that accounted for 74 species (34.7% of invasion) and 69 species (32.4% of invasion), respectively.

Some fast-growing NIS were found, such as marine alga *Saccharina longissima* and *Macrocystis pyrifera*, and pufferfish *Takifugu rubripes* which was introduced for an exclusive food market (Xiong *et al*., 2017). Another example is the non-native diatom *Nitzschia bizertensis*, which was found on mussel aquaculture in Tunisia. Based on the laboratory study, this species was able to survive and retain its toxicity through the filtration process of mussels (Bouchouicha-Smida *et al*., 2015; Chan and Briski, 2017).

Another introduction vector of NIS may be considered as miscellaneous pathways, mostly "unaided" such as natural dispersal and other unintentional routes. For example, floating marine debris can be a vector of NIS besides its problem, which mainly discussed the pollution perspective. Thus, it can provide a possible habitat for fouling species that might be transported to other regions by sea currents (Rech *et al*., 2016; Geburzi and McCarthy, 2018).

Some studies documented various species, including mollusks, bryozoans, and barnacles, settled on plastic litter, and some of them were considered as NIS (Barnes and Milner, 2005; Gil and Pfaller, 2016). Consequently, the number of NIS, especially in the aquatic environment, might increase along with the increase in amounts of marine debris.

3. Is There any Benefit of Non-Indigenous Species?

Most of the papers and studies about NIS generally discussed their negative impacts or harmful effects on the native community and environment. The most problematic impact is that NIS threatens native biodiversity. They can change population size, diversity, richness and abundance, and structure of native species community (Bax *et al*., 2003; Molnar *et al*., 2008; Kumschick *et al*., 2015; Doherty *et al*., 2016; Pysek *et al*., 2020). The European green crab *Carcinus maenas* is one example of NIS invaded the east coast of North America and interfered native community and population density (Griffen, 2011). The kelp *Undaria pinnatifida* is another NIS that caused ecological impacts on the native community. This species invaded firstly on the Mediterranean coast and now spread on the coastal area in more than 13 countries around the world (James *et al*., 2015; Epstein and Smale, 2017).

Both *Carcinus* and *Undaria* were included in the IUCN list of 100 of the world's worst invasive alien species (Lowe *et al*., 2000). NIS can also lead to the extinction of native species (Bellard *et al*., 2015). According to the IUCN Red List, NIS is the second most dangerous threat of species extinctions after habitat destruction. In detail, of the 680 extinct animal data, 34 cases (20%) addressed NIS as the only cause of extinction, while 82 and 77 species cited habitat destruction and harvesting, respectively (Clavero and Garcıa-Berthou, 2005).

Ecologically, NIS can also disrupt food-web structures since they can be found in all trophic levels and compete with native species for food resources (Gallardo *et al*., 2015; Giakoumi *et al*., 2019). Their impacts are also depended on their role in the trophic levels. NIS, which comes from a higher level of trophic, will have an influence on biomass and abundance of the affected native species in lower trophic levels (Gallardo *et al*., 2015). This situation is getting worse if there are more NIS that play a

IMPACTS ON	SPECIES	ECOSYSTEM ENGINEERING	ECOSYSTEM PROCESSES
⊕	• Food provisioning • Providing shelter from predator • Ecosystem engineering	• Structural complexity engineers (create or modify the habitat structural) • Bioturbation (burrowing infauna – roles in sediment transport and porewater flux) • Chemical engineers • Controlling the penetration of light	• Novel habitat creation • Modifying the sedimentation • Bioturbation • Filter-feeding • Controlling another NIS impacts
⊖	• Predation • Competition for resources • Hybridization • Disease transmission • Ecosystem engineering		• Modifying community structure • Creating of novel habitat • Change of water circulation • Modifying the sedimentation • Reducting light penetration • Bioturbation, Filter-feeding

Figure 1. Some examples of the positive and negative impacts of NIS on species and ecosystem (modified from Nunes *et al*., 2014; Sladonja *et al*., 2018).

role as a predator in the ecosystem because they can decrease the native community through predator-prey interactions. NIS is also reported to have negative impacts on water quality and affect their existing nutrients by turning the composition of photosynthetic species (Kettunen, 2008).

On the other hand, it should be noted that NIS - in some cases - may have positive impacts (Figure 1). Assessing this issue would be helpful to develop a better understanding of the ecological role of NIS, especially in the aquatic environment. Nunes *et al.*, (2014) found that the benefits of NIS may be ignored. Their study revealed that about 35% of the assessed NIS were reported beneficial for other species, but the whole picture was often undefined. Most of the examples herein are at the microhabitat level, which is usually outweighed by their more devastating negative impacts on a larger scale.

The introduction of NIS may increase the biodiversity of native communities by accomodating their local habitat. For example, the invasion of Pacific oysters *Crassostrea gigas* on resident mussel beds *Mytilus edulis* in the northern Wadden Sea. There was an ecological displacement from competitive to accommodative interaction between those species (Reise *et al.*, 2017). Furthermore, the increasing species richness will support the stability of communities and improve the resistance for further invasion (Stachowicz *et al.*, 2002; Marraffini and Geller, 2015).

The oysters also have essential ecological impacts on the coastal ecosystem. They re-engineer the ecosystem by spatially extending habitat modification, reintroducing the structural complexity and heterogeneity (van der Zee *et al.*, 2012), intensifying biofiltration and trophic subsidy (Epstein and Smale, 2017), and providing hard-substrate biogenic reefs as habitat for mobile, sessile, even infaunal invertebrates (Ruesink *et al.*, 2005), and other invertebrate species through secondary settlement on their shells (Herbert *et al.*, 2016). These biogenic reefs, therefore, may stabilize the sediments, protect intertidal habitat and prevent it from erosion (Nunes *et al.*, 2014).

While there is evidence of ecological benefits of *C. gigas* on species diversity and structural complexity of intertidal habitat, there is more evidence of their negative impacts on native communities. These oysters can extensively establish large areas across coastal habitats. It can lead to the biotic homogenisation of the native communities and decrease species diversity in intertidal habitats (Smaal *et al.*, 2009).

The colonization of *C. gigas* on soft-sediment in the Wadden Sea can also displace the native bivalves such as *Macoma balthica*, *Scrobicularia plana*, and *Cerastoderma edule* (Troost, 2010) even spatially suppress *M. edulis* to more unsuitable habitats and might be able to lower down the food resources (Eschweiler and Christensen, 2011). Moreover, Waser *et al.*, (2016) investigated the impacts of *C. gigas* on the distribution of birds on different intertidal mussel beds in the Wadden Sea. Their results revealed that the establishment of oysters leads to the decrease of the condition of mussels, which has negative impacts on three of four mussel-eating bird species. The effects of oyster settlements on the mussel and birds populations were also previously investigated by several studies (Scheiffarth *et al.*, 2007; Cadée, 2008a; Cadée, 2008b; Markert *et al.*, 2013).

Although reported to have negative impacts, zebra mussels *D. polymorpha* also play an essential ecological role in the aquatic ecosystem. As a sessile suspension feeder which attaches to substrate, their filtering activity increases habitat complexity as well as water clarity which supports aquatic macrophyte growth (Ward and Ricciardi, 2007; Gallardo *et al.*, 2015; Karatayev *et al.*, 2015; Sladonja *et al.*, 2018). The mussels may accommodate pelagic-benthic coupling, transferring materials, and direct connection of planktonic components on the water column to the benthos components of the ecosystem (Karatayev *et al.*, 2015). Their enormous growth and shell accumulations also result in the formation of new habitats as well as provide shelters to other invertebrates (Minchin and White, 2014).

Similarly, the non-ecosystem engineer group of NIS also has positive ecological impacts include providing ecosystem goods and services. For instance, the invasive Chinese mitten crab *Eriocheir sinensis* in the Baltic Sea. Their large carapaces are proper habitat for macrofauna and flora such as barnacles and algae. Other invertebrates such as bivalves, gastropods, crustaceans, and nematodes also inhabit the hairy patches on the crabs' claws (Normant *et al.*, 2007; Geburzi and Mc Carthy, 2018). The introduced Asian hornsnails *Batillaria attramentaria* (formerly referred to as *B. zonalis* and *B. cumingi*) were also identified to have positive effects on both native and introduced mudflat species. Besides the use of their shells as a habitat for other invertebrates, other facilitations include indirect grazing effects and bioturbation (Wonham *et al.*, 2005).

Another study found that invasive red macroalga *Gracilaria vermiculophylla* positively affects native invertebrates such as gastropods and bivalves, which inhabit *Zostera marina* seagrass beds. *Gracilaria* provides an intermediate embedded biogenic habitat, whereas the seagrass facilitates a basal biogenic habitat for the seaweeds and invertebrates (Thomsen, 2010). The seaweeds also provide food resources for grazers, e.g., gastropod *Littorina littorea*, attachment space on algal branches for invertebrates, e.g. bivalves *M. edulis*, and shelter for refuges to avoid the predators, e.g. large crabs *C. maenas* (Norkko *et al.*, 2000; Thomsen *et al.*, 2007; Nyberg *et al.*, 2009). Biomass of the invasive green alga *Caulerpa taxifolia* in southeastern Australia was also associated positively with the composition of the epifauna community, both species and individuals (e.g., gastropod, *Batillaria australis*) (Gribben *et al.*, 2013).

Other benefits of NIS include providing alternative food sources, improving aesthetic values, and supporting fisheries and aquaculture sectors (Bax *et al.*, 2003). For example, introduced oysters in the estuarine habitat may contribute as food for fish and other invertebrates, even for human consumption.

Furthermore, oysters may also support the production of finfish or crabs, which are economically important species (Ruesink *et al.*, 2005). In Indonesia, non-native freshwater Nile tilapia *Oreochromis* spp. is an important food source and has been introduced for aquaculture purposes (CABI 2019). However, several studies revealed that the introduction of tilapias negatively affects native communities.

Nile tilapia is categorized as a "potential pest" (Simoes-Vitule, 2009). This species can reduce the habitat diversity, alter the trophic structures in the aquatic ecosystem, decrease the relative density and the body size of the indigenous fishes, and may influence water quality as a result of sediment bioturbation and nutrient excretion (Starling *et al.*, 2002; Arthur *et al.*, 2010; Zengeya *et al.*, 2013; Gu *et al.*, 2015; Shuai *et al.*, 2018). In fact, there are no NIS that absolutely have positive impacts. As mentioned before, even though there are ecological or economic benefits of NIS, their subtle or long-term negative impacts should be a cause of concern for all stakeholders.

4. NIS for Aquaculture Purposes: Can It be Approved?

Aquaculture is the fast-growing sector of the fisheries and has become a notable contributor to food production over the past decades. Currently, it accounted for 46 percent of the total production and contributed 52% of fish consumption worldwide. It is also predicted to develop further along with the increasing demand for aquatic food (Food and Agriculture Organization of the United Nations in FAO, 2020a). Despite its crucial role in the global food industry, aquaculture may have negative impacts. One of the problems is the use and introduction of NIS for aquaculture purposes. As a result, aquaculture is often criticized for having an important role as the introduction pathway by which NIS can become established outside of their natural habitat and may influence the native biodiversity (Shelton and Rothbard, 2006; De Silva *et al.*, 2009; Lin *et al.*, 2015).

Approximately 5,612 records of NIS introduction were associated with aquaculture (FAO, 2020b). Some developing countries, e.g., Brazil, India, and the Philippines, also highly depend on NIS in their aquaculture sector. Similarly, the majority of the aquatic food industry in Israel is from exotic fishes (Shelton and Rothbard, 2006). Furthermore, China, the largest fish producer with a total of 35 percent of contribution to the world's fish production (FAO, 2020a), also yield at least 252 NIS in their cultivation, including fish, mollusks, crustacean, and algal species (Lin, *et al.* 2015; Ju *et al.*, 2020). Generally, these species are introduced for aquaculture and support the fisheries industry due to their high reproductive rate, wide environmental tolerance, diseases resistance, and trophic adaptability (Canonico, 2005; Xu and Ming, 2018).

Moreover, the issue is further complicated by the differences of view about whether NIS can be approved or not for aquaculture production. The possibility of NIS to escape, be released from aquaculture, and establish in the native habitat may cause a serious problem to the ecosystem and biodiversity (Vitule *et al.*, 2009; De Silva, 2012; Ju *et al.*, 2020). Other impacts of NIS include lineal competition and predation, habitat modification, trophic disruption, growth inhibition, genetic shift, and pest or diseases introduction (Hill, 2008; Lima-Junior *et al.*, 2018). The escape and invasion of NIS are considered as the primary concern of the world's aquaculture industry (FAO, 2020a). In China, for instance, approximately 68 farmed NIS are reported to have escaped and established wild populations. About 52 of those species are considered to have negative impacts on the native habitat, and this number is predicted to increase in the future (Ju *et al.*, 2020).

The intentional introduction of NIS for aquaculture purposes may include the transfer of "hitchhiking" species; any uninvited biota that is associated with or maybe translocated with the culture target species; which have been potentially harmful to fisheries production and native ecosystem (McKindsey *et al.*, 2007; FAO, 2020a). Different from the target species, the introduction of hitchhikers was mainly unintentional. For example, protozoan *Vorticella* sp., scutariellid temnocephalidan (*Caridinicola* sp.), and bdelloid rotifer; were found associated with ornamental shrimps imported from Indonesia into the Czech Republic via international trade in 2015 (Patoka *et al.*, 2015). McKindsey *et al.*, (2007) reported three main groups of hitchhiking species related to shellfish aquaculture: 1) alien macrospecies, such as macroalgae, tunicates, crabs, and other bivalves; 2) alien phytoplankton, such as toxic dinoflagellates and diatom; and 3) alien parasites and disease-causing organisms, such as viruses, bacteria, protozoans, and invertebrates.

On the other hand, the situation results in a paradox in terms of global food security. The introduction of NIS for aquaculture purposes has been implementing worldwide over the last five decades (FAO, 2020a). Even though negatively causing ecological and economic problems, some exotic species remarkably contribute to the acceleration of aquaculture and aquatic food production. Non-native tilapias *Oreochromis* spp., for instance, play an important role in the aquaculture practices in some Asian countries, such as China, Indonesia, the Philippines, India, and Sri Lanka (De Silva *et al.*, 2009; Arthur *et al.*, 2010; Lin *et al.*, 2015). Likewise, shellfish, e.g., oysters, scallops, mussels, and snails, contribute 56.3 percent of the global marine and coastal aquaculture in 2018 (FAO, 2020a).

As the fast-growing and expanding of the aquaculture industry to fulfill human needs, options and efforts will have to be implemented carefully about which species to cultivate, how to feed, what system to use, and in which habitat (Klinger and Naylor, 2012). Many approaches have been conducted on developing aquaculture systems and models which take into consideration of biosecurity and ecological sustainability. For example, some advanced cultivation systems, such as recirculating aquaculture systems, aquaponic systems, integrated multitrophic aquaculture, and offshore aquaculture, have been developed, but each system has strengths and weaknesses that should be considered (Klinger and Naylor, 2012). The application of molecular genetic tools also enhances our understanding of biological invasion in the aquaculture industry as well as its ecosystems and support their integrated management approaches accordingly (De Silva, 2012; Darling *et al.*, 2017; Dulić *et al.*, 2019). Modeling is another method that has the potential to assess the sustainability of aquaculture production and its impacts (Cranford *et al.*, 2012). For instance, the Farm Aquaculture Resource Management (FARM) model was created by researchers in Europe. This model provides information about the shellfish farming industry and ecological impacts, which are essential to support farmers, managers, or regulators (Gallardi, 2014). Also, strengthening policy frameworks, management actions, and regional collaborations are crucial for the development of a sustainable aquaculture industry (Ju *et al.*, 2020; FAO, 2020a).

5. Policy Framework and Management Approaches

Management actions to control the introduction of NIS have been conducted over the last three decades in response to their fast-growing number and establishment (Bailey, 2015). These measures include prevention, control, and restoration or *post-hoc* eradication (Hulme, 2006; Bart and Simon, 2013). In terms of the framework for biological invasion, in 1989, Canada recommended the first procedures for ballast water treatments by regulating all vessels to exchange their ballast water in the open deep-water before releasing it to the system. These guidelines were aimed to prevent the introduction of Eurasian Ruffe, which was transported unintentionally by transoceanic shipping arriving in the Laurentian Great Lakes. Together with Australia, they lifted up the ballast water issue at the International Maritime Organization (IMO) (Bailey, 2015). As a result, in 1991, IMO published Guidelines for Preventing the Introduction of Unwanted Organisms and Pathogens from Ship's Ballast Waters and Sediment Discharges. IMO also published the 'Guidelines for Control and Management of Ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens in 1997 (Bailey, 2015; Rastegary, 2017).

In Indonesia, the government has released the legal frameworks relating to invasive species problems include Act No. 5/1990 on Conservation of Biological Diversity and its Ecosystems; Law No. 16/1992 on Animal, Fish and Plant Quarantine; Government Regulation No. 27/1999 on Environmental Impact Assessment; No. 14/2002 on Plant Quarantine; and No. 15/2002 on Fish Quarantine, respectively. Then, Law No. 32/2009 on Environmental Protection and Management; Law No. 45/2009 amending Law No. 31/2004 concerning fisheries. There are also technical regulations at the ministry level, such as the regulation of the Minister of Marine Affairs and Fisheries No. 41/2014 on Import Prohibition of Hazardous Fish Species from Overseas into Indonesia Territory; and No. 9/2020 concerning Fisheries Management Area. Although there are many regulations, the government needs to reinforce the management implementation of NIS and their research priorities which hitherto are very limited.

In the context of management of NIS, there are five areas of management approaches that are essential and should be considered: risk assessment, pathway and vector management, early detection and rapid response, eradication, and mitigation and restoration (Pysek and Richardson, 2010). Risk assessment is the initial stage of the risk management process of NIS. It includes prevention which means any rational approaches conducted before the introduction of NIS. This action is often recommended and a more cost-effective strategy than managing NIS after the invasion (Simberloff, 2006; Pysek and Richardson, 2010; Faulkner *et al.*, 2017). Prevention can be focussed on two aspects, i.e., species-centered and pathways-centered approaches (Hulme, 2006).

In the species-centered approach, identification of NIS taxa is conducted, usually by assessing their risk and then their prevention strategies. This effort, however, has some problems such as requiring data support, facing difficulties to identify traits prediction, and the developed approaches have not been assessed for all taxa (Hulme, 2006; Kumschick and Richardson, 2013). On the other hand, the pathway-centered approach is likely more useful. It focuses on how NIS is introduced and then develops early detection strategies based on the specific introduction pathways and vectors (Hulme, 2006). Once introduction pathways and vectors of NIS are recognized, some suitable approaches can be implemented based on the targeted management (Pysek and Richardson, 2010). Furthermore, any attempt at risk assessment needs to consider: the different stages of invasion (whether it looks at the risk of early introduction of NIS); taxa difference (e.g., vertebrates and invertebrates) (Kolar and Lodge, 2002); ecosystem specificity (e.g., freshwater and marine); or impact types (Kumschick and Richardson, 2013).

Early detection and rapid response strategies are, therefore, another essential step dealing with NIS management. The problem is that - in many cases - NIS are challenging to detect, identify, and map because they may spread from all over the world. The need for taxonomy in invasion biology is also crucial to prevent misidentification of NIS that can lead to further serious problems (Pysek and Richardson, 2010). Meanwhile, control and eradication can be achieved when early detection and rapid response of NIS are well implemented. These efforts can be conducted in some standard practices include mechanical, chemical, and biological approaches. The two first methods often pose a limitation related to how large the area of invasion. Mechanical or physical removal of NIS is more effective at smaller scales of invasion, whereas chemical treatments such as biocides and chlorine are usually be implemented only in limited patches (sites or individual organisms). Therefore, biological treatments include biocontrol and ecological approaches, maybe a more appropriate effort to eradicate NIS, although there is also potential harm to non-target species (Hulme, 2006; Guo *et al.*, 2018).

Mitigation and restoration initiatives are other efforts associated with ecological approaches in managing NIS. According to Guo *et al.*, (2018), this approach has two main aspects: (1) restoring native species and (2) manipulating biomass of the restored community to achieve and sustain population size. Mostert *et al.*, (2018) developed a multi-criterion approach to improve a framework of restoration. The criteria include the major NIS threat to the area, density and time frame of invasion, area size, and disturbance level. This approach would be useful if it is well-planned and implemented. Also, Hulme, (2006) suggested that the management approach of NIS should comprehensively consider six key aspects: i) the expected effects to the environment and economy; ii) the technical alternatives available to management; iii) the ease to define which the species can be targeted; iv) the risks related to the management options; v) likelihood of success in eradication, containment or control; and (vi) the degree of public concern and stakeholder interest. More importantly, those approaches should be conducted along with surveillance and monitoring in every stage of management (Cook *et al.*, 2016), including by engaging the public as the crucial role of citizen science and increasing their understanding and awareness of biosecurity issues (Pysek *et al.*, 2020). Therefore, management strategy is a holistic approach (Figure 2) that includes the knowledge of invasion stages, prevention, as well as long-term management of NIS and their surveillance (Geburzi and McCarthy, 2018).

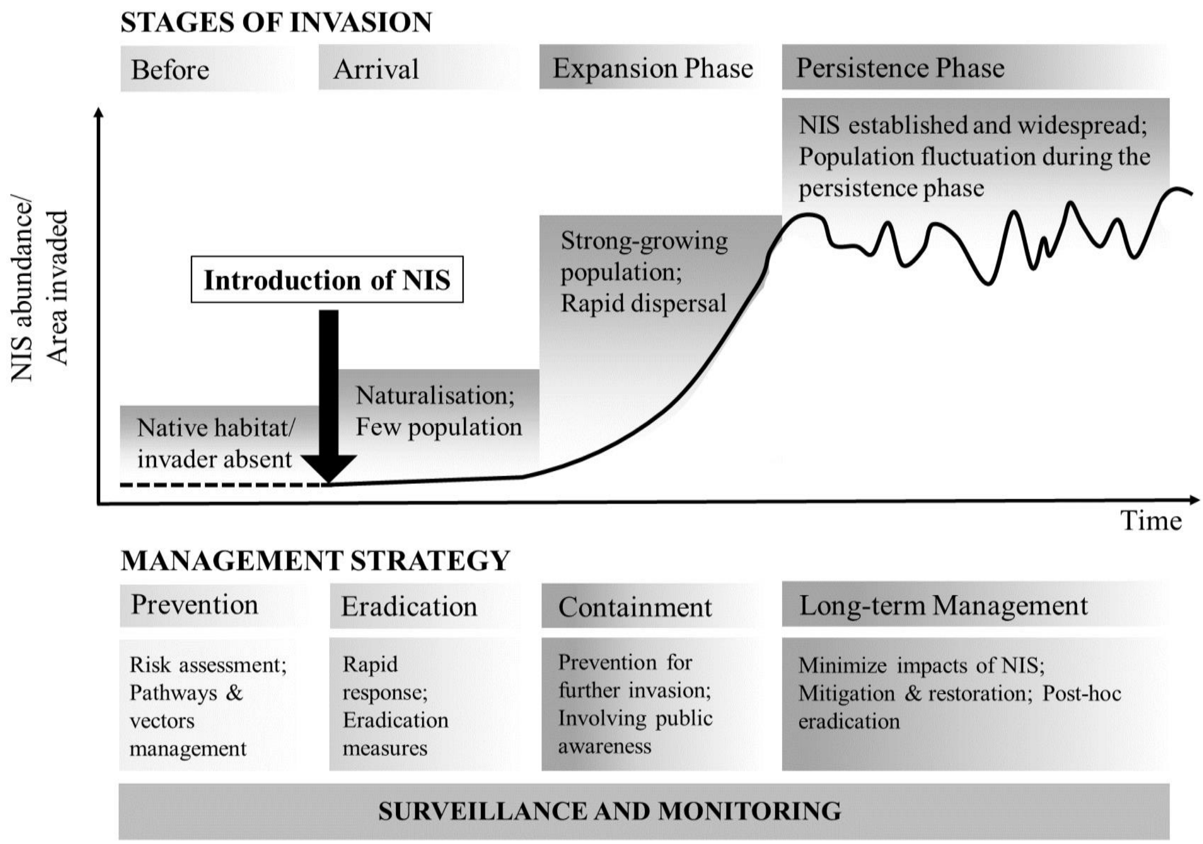

Figure 2. Stages of invasion of NIS and their management strategy includes surveillance and monitoring of the efforts (modified from Boudouresque *et al.*, 2005; Geburzi and McCarthy, 2018)

6. Rebranding Non-indigenous Species: Is It Possible?

Generally, there is *"a kind of militaristic attitude toward invading species"* (Briggs, 2007) among the environmental management community. This situation may prevent the objectivity of examination of species invasion impacts (Craig, 2010). Furthermore, it has been suggested that the attitude to accept NIS in 'novel ecosystem' and rationalize defeat or conciliation should be involved by the environmental management as a course of action in the future (Caroll, 2010). People's perspective is a key factor to reframe thinking by which NIS is also associated with the ecological significances, including the negative, neutral, or positive impacts (Shackleton *et al.*, 2019). Even though in low percentage (less than 50% coverage of the NIS assessed), media publications also influenced the perception of the "worst" of NIS, and it was related to the number of scientific research for NIS (Geraldi *et al.*, 2019).

Despite implemented many ecological approaches, managing NIS should also consider the local knowledge as a crucial aspect in developing integrative strategies that could benefit their implementation. (Bart and Simon, 2013). Engaging local communities and stakeholders play a crucial role in ensuring the outcomes of NIS management (Caceres-Escobar *et al.*, 2018). Perception of invasion biology should not only focus on the impacts but also on their social perspective, value and beliefs, and benefits provided by NIS (Hanley and Roberts, 2019; Kapitza *et al.*, 2019; Potgieter *et al.*, 2019). For instance, public denial of mitigation or eradication of NIS may be because the target species (e.g., fish, livestock) is beneficial for them (Glen *et al.*, 2013). Although it can be challenging, involving local values can prevent the rejection of the public to the management actions as well as can educate them about the knowledge of ecological and economic impacts of the targeted NIS (Vane and Runhaar, 2016).

As mentioned previously, some NIS are also farmed for aquaculture purposes. This situation will be a dilemma as it will lead to severe risks and may deteriorate native ecosystems, economies, and human well-being (Ju *et al.*, 2020). Thus, stakeholders, including governments, managers, even the public, should consider short and long-term impacts and benefits that arise from NIS, and their management strategies (Caroll, 2010), because it is not possible to totally recover their negative impacts. Moreover, there are other pressures than NIS would for anthropogenic activities, pollution, overfishing, mindless development, and global climate change. All of those are evidently to destruct habitat and reduce species population (Craig, 2010; Caroll, 2010; Thomas, 2013; Russell and Blackburn, 2017). Therefore, the crucial efforts would be raising public awareness, improving scientific research priorities, and developing strategies on both local and global scales regarding biosecurity issues as consequences of the emergence of interactions complexity among NIS and other global ecological change drivers.

7. Conclusion

Many NIS spread accidentally to new environments, while others are deliberately introduced to new habitats by humans via various mechanisms. Native biodiversity loss may be the most serious consequence of NIS. Additionally, they can destabilize food webs and alter the structure of ecosystems. Additionally, NIS has beneficial effects as ecosystem engineers, which may increase native community biodiversity. Among the additional benefits of NIS are providing a substitute food source and supporting fisheries and aquaculture. Understanding the process of NIS introduction and its consequences requires effective policy frameworks and management approaches, which include risk assessment, prevention and control, pathway and vector management, early detection and rapid response, eradication, and mitigation and restoration. Additionally, critical efforts would be made to increase public awareness, advance scientific research, and develop a strategy for biosecurity issues that arise due to the complexity of interactions between NIS and other global ecological change drivers.

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