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Overview Article

Hurdles and opportunities in implementing marine biosecurity systems in data-poor regions

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Abstract

Managing marine nonindigenous species (mNIS) is challenging, because marine environments are highly connected, allowing the dispersal of species across large spatial scales, including geopolitical borders. Cross-border inconsistencies in biosecurity management can promote the spread of mNIS across geopolitical borders, and incursions often go unnoticed or unreported. Collaborative surveillance programs can enhance the early detection of mNIS, when response may still be possible, and can foster capacity building around a common threat. Regional or international databases curated for mNIS can inform local monitoring programs and can foster real-time information exchange on mNIS of concern. When combined, local species reference libraries, publicly available mNIS databases, and predictive modeling can facilitate the development of biosecurity programs in regions lacking baseline data. Biosecurity programs should be practical, feasible, cost-effective, mainly focused on prevention and early detection, and be built on the collaboration and coordination of government, nongovernment organizations, stakeholders, and local citizens for a rapid response.

Keywords: nonindigenous species, biosecurity frameworks, bioinvasions, marine, biosecurity guidelines

Marine nonindigenous species (mNIS) are recognized as an issue of a global nature with potential consequences for biodiversity and ecosystem function. The impacts of mNIS on ecosystems have consequences for the delivery of goods and services with both socioeconomical and ecological repercussions (Katsanevakis et al. 2014, IPBES 2019, Diagne et al. 2020). Socioeconomic damages can result from a loss of commercial value, such as decreased tourism and other recreational activities (e.g., sport fishing, swimming); from the destruction of commercially valued natural resources (e.g., fish and shellfish stocks); from interference with industries (e.g., the loss of aquaculture production, infrastructure damage); and from consequences for human health (e.g., poisoning, intoxication, injuries; Molnar et al. 2008, Nunes et al. 2008, Katsanevakis et al. 2014, Tsirintanis et al. 2022). Indirect costs are known but often harder to quantify and result from a wide range of impacts on marine ecosystem health. These impacts include acute disturbance during the outbreak, or the boom phase of the invasion (Simberloff and Gibbons 2004, Zaiko et al. 2014), and unpredictable long-term chronic effects on the marine environment, which inevitably affect biodiversity and ecosystem functioning (Nunes et al. 2008). The impacts of marine biological invasions are often exacerbated by climate change and other cumulative anthropogenic stressors (Rilov et al. 2018, Azzurro et al. 2019) and are expected to intensify in many regions worldwide (Essl et al. 2020). Therefore, the development of effective biosecurity programs involving the detection, monitoring, and management of nuisance species (Bowers et al. 2021) is crucial to protect and maintain the value of natural environments and their associated commercial, cultural, and recreational importance for future generations. The level of regional and national biosecurity actions can limit the likelihood of biological invasions and their impacts (Roura-Pascual et al. 2021).

The wide range of impacts associated with mNIS has fostered the worldwide development and implementation of biosecurity programs and strategies at different geographical and temporal scales, from local to national levels (Oidtmann et al. 2011, Piola and McDonald 2012; https://pacman.obis.org). However, these programs vary greatly because of factors ranging from a lack of awareness and technical expertise to the uneven distribution of knowledge and limited resource availability. Often, biosecurity measures are initiated as a reactive approach following notorious invasions and focus on controlling the spread of a limited number of mNIS (Watkins et al. 2021). Some countries also implement preventive measures (e.g., quarantine services and border surveil-

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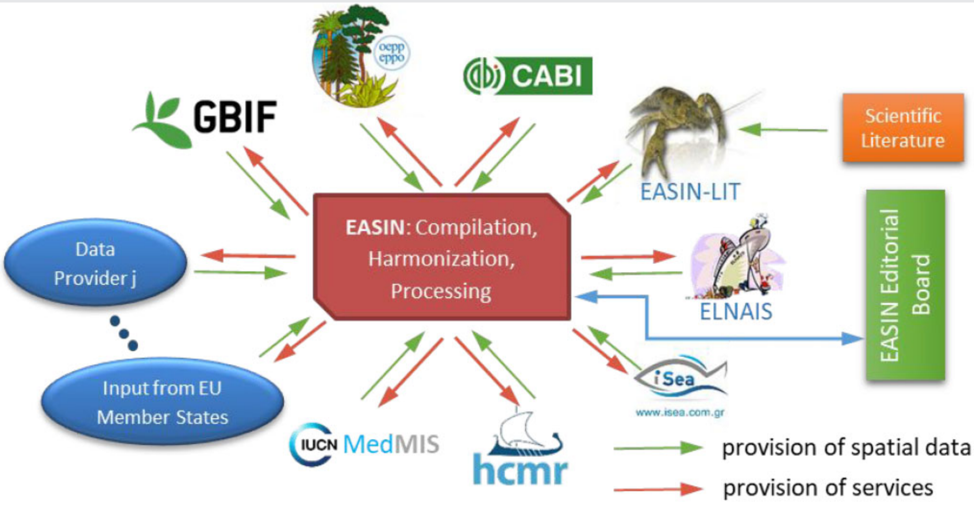
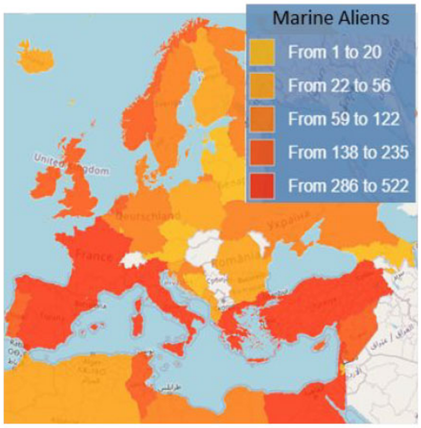
Box 1. EASIN (European Alien Species Information Network): an example of an online platform integrating multi-source data and supporting science and policies.



EASIN was launched in 2012 by the European Commission (Katsanevakis et al. 2015). It enables easy access to data and information from a variety of global, regional, or national information sources through online tools and interoperable web services. In the core of the EASIN platform is the EASIN Catalogue, which is the most comprehensive inventory of alien species in Europe. The updating and quality assurance of the EASIN Catalogue is secured by an international Editorial Board of taxonomic experts (Tsiamis et al. 2016). The EASIN Catalogue currently (August 2022) includes ~14000 alien and cryptogenic species, of which 1602 are marine.



EASIN is appointed as the information system facilitating the implementation of the EU Regulation on Invasive Alien Species (EU 2014). Specifically, EASIN includes a Notification System to facilitate a timely comprehensive notification by member states of new detections of invasive alien species of EU concern and related eradication measures.

lance). However, only a few countries have established long-term monitoring programs that systematically survey potential mNIS through time (e.g., Germany, since 2009; Canada, since 2005; New Zealand's Marine Surveillance and Marine High-Risk Site Surveillance programs, since 2002; and the US National Invasive Council Management Plan, first introduced in 2001; Baker 2001, CCFAM 2004, Buschbaum et al. 2012, Ministry for Primary Industries 2015).

The global nature of marine biological invasions (Carlton 1989, Carlton and Geller 1993, Ricciardi 2007) and the fact that several countries have exclusive economic zones within the same body of water make collaboration and coordinated actions imperative for successful biosecurity management and response (Faulkner et al. 2020). Inaction or inappropriate action from one country may compromise the success of management programs in neighboring countries. For example, the EU regulation on the prevention and management of the introduction and spread of invasive alien species (1143/2014) indicates that member states may establish mechanisms for cooperation, including the "exchange of information and data, action plans on pathways and exchange of best practice on management, control and eradication of invasive alien species, early warning systems and programs related to public awareness or education." Over the last two decades, the implementation of the European Union's Marine Strategy Framework Directive (MSFD) has been criticized for the poor (or absent) collaboration and coordination among member states in the elaboration of measures to assess the good environmental status in marine coastal waters, probably because of the limited economic resources, experts with a multidisciplinary background, and timescale of the MSFD (Cavallo et al. 2019). Specifically, regarding mNIS, a lack of monitoring programs and a lack of taxonomic expertise were reported across several countries. In fact, most countries only partially addressed the topic of mNIS through monitoring (European Commission 2020a, 2020b). Despite the initial shortcomings, the MSFD has offered a common framework for assessing and monitoring mNIS in the European Union. Among the most noteworthy achievements at the European Union level in mNIS monitoring and reporting within the last decade are the creation of baseline mNIS inventories for all European Union member states up to 2012 (Tsiamis et al. 2019), and the development of the European Alien Species Information System (see box 1).

Despite ongoing policy-based efforts to prevent the spread of nonindigenous species (NIS) in general (terrestrial, freshwater, and marine), the number of NIS is increasing globally (Seebens et al. 2017) and is expected to increase by 35% by 2050 (Seebens et al. 2020). Currently, approximately 2700 mNIS are recorded worldwide (Costello et al. 2021), highlighting the need for setting priorities in management actions (McGeoch et al. 2016). Unfortunately, most current efforts addressing mNIS are focused on developed countries and temperate regions (Costello et al. 2021, Stranga and Katsanevakis 2021). mNIS research efforts have been linked to the national spending for research and development (Tsirintanis et al. 2022), the gross domestic product, the number of universities in a country, and English proficiency, as well as scientific output, in general (Man et al. 2004, Meo et al. 2013). Concerted actions are incipient in developing countries and particularly those in tropical regions, where limited resources justified the prioritization of fundamental needs related to health, food, social security, and political stability. In addition to those limitations, the lack of local expertise, baseline knowledge of native biodiversity, and access to information (often in English) hinder the detection and monitoring of mNIS. Notable exceptions are the IMO's (International Maritime Organization) GloBallast (http://archive.iwlearn.net/globallast.imo.org/index.html) and GloFouling (www.glofouling.imo.org) projects, dedicated to developing countries. With a strong focus on developing countries, these initiatives were aimed at promoting mNIS baseline survey capabilities (GloBallast) and best practices to limit the transport of mNIS via ship biofouling (GloFouling). The disparity in the management of marine bioinvasions among countries is reflected in the uneven distribution of mNIS records worldwide (and associated reported costs), with higher numbers found in developed countries of temperate regions than in their tropical counterparts (Hudgins et al. 2023). The limited information from the southern hemisphere is striking (Costello et al. 2005), and records are often found in reports but not on online databases (Floerl et al. 2006). Also, it is worth noting the discrepancy between the records in online database (Seebens and Kaplan 2022). The complexity of monitoring and controlling invasions originates from the lack of information on species distribution in understudied locations, which is exacerbated by difficulties in classifying the native range of some species (Marchini et al. 2015, Costello et al. 2021). Both make managing mNIS particularly challenging in countries with limited resources or where there is a paucity of historical records. Altogether, this highlights the lack of awareness of mNIS impacts and inefficient surveillance or monitoring efforts (Stranga and Katsanevakis 2021, Nuñez et al. 2022).

By committing resources to efforts where they are proven to be most cost-effective, regions aiming at developing biosecurity strategies from scratch can start by preventing the introduction of new mNIS while simultaneously building the basic biosecurity capabilities within their jurisdictions (i.e., developing biosecurity-relevant policies, establishing baseline surveys, gathering data from surrounding regions, performing risk assessments to support initial decision-making). Effective management of mNIS may occur at different stages and can be categorized into three levels: preborder, border, and postborder (figure 1). It should cover all possible management options (i.e., prevention, control, protection, detection, surveillance, and response; figure 1). The UN Decade of Ocean Science for Sustainable Development represents a period in which a series of methodologies and new technologies have sufficiently matured and in which other emerging next-generation tools are being developed, greatly assisting mNIS management (see the supplemental material). The implementation of molecular approaches for monitoring marine biodiversity (Stat et al. 2017, Djurhuus et al. 2020), artificial intelligence applications for species recognition (box 2; Wäldchen and Mäder 2018), and improved modeling techniques for predicting current and future mNIS distribution and ecological impacts (e.g., Ovaskainen et al. 2017, Lyons et al. 2020, Tikhonov et al. 2020) can greatly foster mNIS management in data-poor regions. The informational support may be sought through large data sets accumulated globally and becoming more easily accessible through the proliferation of open-access online international databases (e.g., Olenin et al. 2014, Katsanevakis et al. 2015, Costello et al. 2021). International journals dedicated to biological invasions (Lucy et al. 2016), as well as the increasing effort toward citizen scientists' involvement in biosecurity initiatives (Larson et al. 2020), aid further in empowering marine biosecurity management (Giovos et al. 2019). Because international, national, and regional mandates increasingly require the implementation of effective biosecurity programs, the next-generation biosecurity toolkit is expected to be further enhanced by robust, affordable, and fit-for-purpose technologies (e.g., Grimm et al. 2017, Hunter et al. 2018, Maslin et al. 2021).

We, therefore, present our suggestions to fill the aforementioned gaps in biosecurity programs within data-poor regions as follows. First, we describe an ideal biosecurity management program, illustrating the methodologies and actions needed at each step of the process. Following this, we examine the overarching management process in detail at three levels (preborder, border of the national waters jurisdiction, and postborder), highlighting the most critical actions for the effective management of mNIS in data-poor regions. Finally, we propose an action plan with priority measures based on resource availability at a local level to help stakeholders design and implement feasible, meaningful, and accurate biosecurity programs. Such a plan reflects current best practices in some parts of the world supported by the scientific community encompassing a range of actions that incorporate ecological, economic, and social perspectives (Ricciardi et al. 2017), as well as emerging and innovative tools that can foster the early detection of mNIS and facilitate timely action. On the basis of the application of best-known practices and state-of-the-art technologies, benefiting from lessons learned by countries that have established cutting-edge biosecurity programs sustained by decades of research, the proposed tier-based action plan has a twofold goal: to guide the design and implementation of biosecurity programs and to help improving or fine-tune existing biosecurity programs.

Building a robust biosecurity management model

Ideally, biosecurity systems should target all steps of the multistage invasion process (preborder, border, and postborder) during which timely and appropriate intervention can contribute to the disruption of the invasion process (i.e., game over—the invasion fails). The first attempt to establish a global biosecurity framework could adopt concepts of the Agreement on Sanitary and Phytosanitary Measures published by the World Trade Organization (WTO 1995). This allows for an adaptive approach to emerging biosecurity challenges and enables environmental practitioners to effectively protect marine resources in a changing world. The Swiss cheese model (Reason 1990), often used to visualize a multifaceted approach to pandemic response, can also be applied for conceptualizing an efficient mNIS biosecurity program

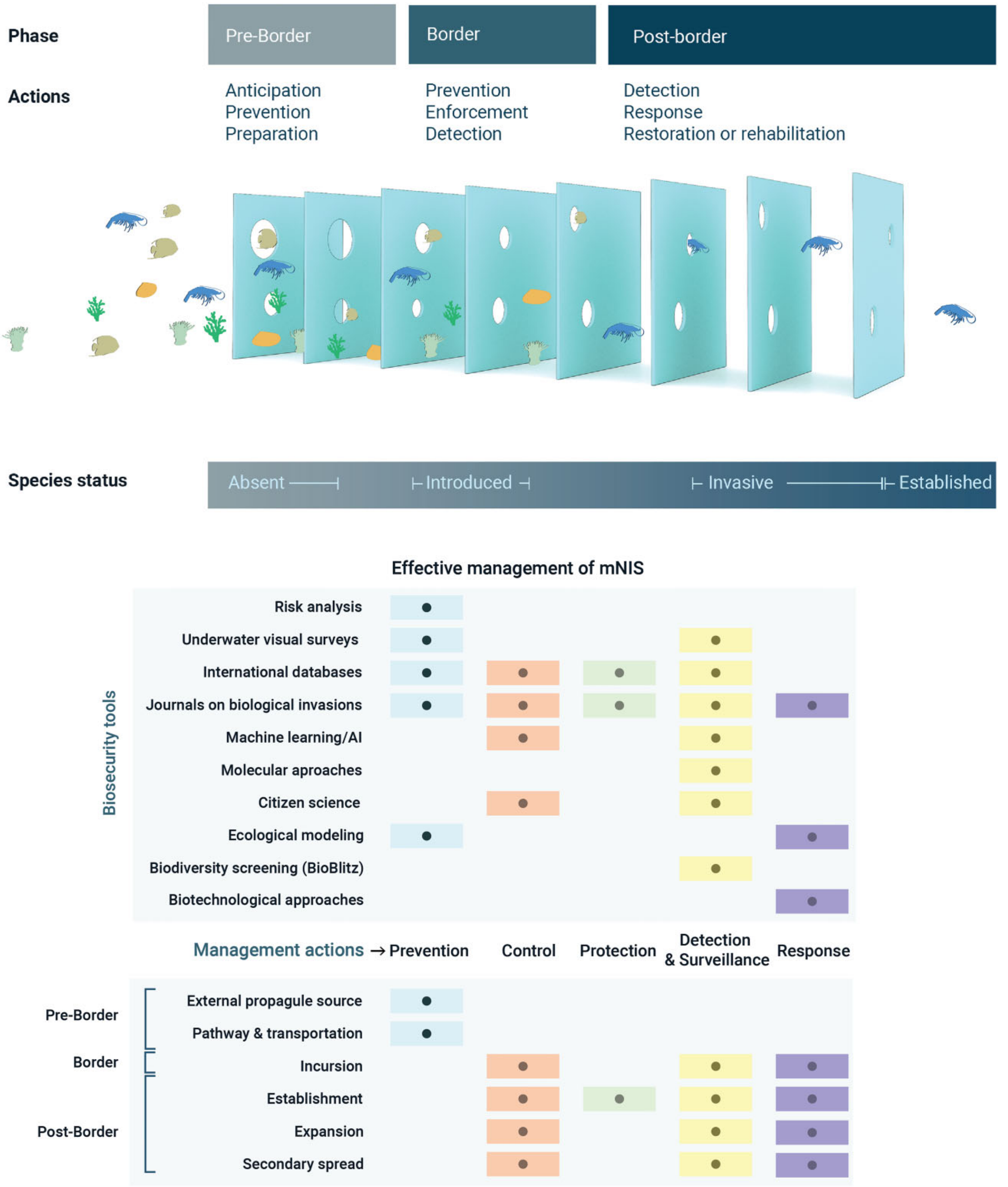


Figure 1. Schematic representation of the invasion process throughout the pre- to postborder biosecurity continuum. The figure is based on the Swiss cheese model, with an indication of key actions to stop or minimize the spread of marine nonindigenous species (mNIS) and the status of the species across the different phases of the invasion process. Border refers to the exclusive economic zone of a country or any territory with autonomous jurisdiction. Bottom: Conceptual biosecurity model for an effective management of mNIS (modified from Olenin et al. 2011). Different management actions are presented in the context of preborder, border, and postborder throughout the different stages of the invasion process in combination with the biosecurity tools available for effective management of mNIS.

Box 2. Automated identification of species from photographs and videos.

Artificial intelligence (AI, using machine learning and neural networks) has made amazing strides, notably in recognizing human faces. It is also being used to identify patterns on photographs of individual patterns on whale fins and flukes, and whale shark markings. It is revolutionary in helping citizens learn how to identify species (such as in iNaturalist) and is poised to enable automation of biodiversity monitoring through analysis of videos and photographs. The use of images has the added benefit of having minimal disturbance to biodiversity (nothing being killed) and images can be archived for future research. A leading global example is the citizen science platform iNaturalist, which uses AI to put a taxonomic name (species or higher level) against one species per image. Volunteer experts help confirm identifications and images with more than 100 confirmed identifications are used to train the AI. Data are automatically published into the GBIF. It contains over 2000 projects that record invasive species, and over 1800 focused on marine species. Other national citizen science platforms have developed similar systems, usually with a terrestrial focus. However, several organizations have established AI identification systems: FathomNet is the Montery Bay Aquarium Research Institute system for training AI using expert knowledge to detect marine species. Squidle+ is an online platform for marine image storage, mapping and annotation developed in Australia with the potential for community image storage, expert annotation and AI training. VIAME is NOAA's (the National Oceanic and Atmospheric Administration's) AI for video analysis, detecting fish in images and videos, which are then expertly annotated. Automated identification of plankton is the focus of Ecotaxa and www PIC. CoralNet AI uses deep neural networks to annotate benthic images. It is in use for semiautomated annotation of benthic images of coral and rocky reefs. Linne Lens identifies multiple animals (especially fish) in real-time on videos from a smartphone app. It can count and name fish and other species in videos and photographs. Therefore, automated species identification from photographs and videos is operational and now widespread. Given verified images of mNIS it could be used to provide immediate identification anywhere in the world with a smartphone and internet connection.

(figure 1). As in a pandemic response, no single biosecurity intervention is perfect at preventing the introduction or spread of mNIS. Each intervention and management action (layer) has holes, but multiple layers of protection significantly reduce the overall risk of marine bioinvasion and associated impacts. Preventive measures taken at the preborder and border stages are more efficient in mitigating the introduction and establishment of nonindigenous populations than measures taken downstream. Postborder measures (in response to the introduction and, sometimes, establishment of mNIS) are less efficient and more costly. Postborder management options can be separated into several components: detection, response, and recovery or adaptation. All components require significant effort and may be resource and skill demanding, but it is essential to have each of them in place to ensure that the "cheese barriers"" are effective. Finally, cooperation is essential, particularly in shared waters, because the marine environment lacks physical borders, and mNIS introduced in one location can rapidly spread to adjacent ones, rendering efforts ineffective.

Implementing biosecurity programs can be particularly challenging in countries (or regions) lacking historical biodiversity and mNIS records. Nevertheless, it is possible to learn from the experience of countries with successful biosecurity strategies, following standardized international management frameworks implemented at the preborder, border, and postborder stages.

In the following sections, we detail the components of a comprehensive biosecurity program and exemplify tools and approaches proven to be useful or that are promising and effective in tackling marine biosecurity issues, with more details in supplemental table S1.

The tools and approaches suggested in the present article are based on best biosecurity practices in some parts of the world, for their successful implementation in data-poor regions, it is crucial to carefully consider local contexts (including economic, political and other constrains), and engagement with scientists and practitioners on the ground.

Management actions throughout the invasion process

The following will describe the management process at the three stages of the invasion process.

Preborder. The development of effective strategic measures relies on identifying and, whenever possible, quantifying the types of biosecurity risks in a given region. The primary purpose of preborder biosecurity efforts is to eliminate or minimize the risks of mNIS introductions, because eradication or control-based management measures are costly and often unsuccessful (Ojaveer et al. 2015). At the preborder stage, it is essential to understand the vectors and pathways of potential introductions of mNIS in each area. The primary pathways and vectors for the introduction of marine species include ballast water, biofouling of commercial and recreational vessels (e.g., hulls, anchors), aquaculture, ornamental species trade, live seafood, marine litter, and the opening of artificial canals (Katsanevakis et al. 2013, Williams et al. 2013, Ibabe et al. 2020). Pathways may be interlinked and uniquely specific to each region (e.g., in the Mediterranean Sea, the Suez Canal is the main pathway of species introductions from the Red Sea; Zenetos et al. 2012, Galil et al. 2021). Currently, a multiple- rather than single-vector analysis is proposed to gain a better understanding of risks and inform mitigation actions (Williams et al. 2013). The analysis might involve ad hoc exploration of the vector intensity based on the empirical data from commercial shipping, recreational boat movements or aquaculture activities and associated propagule pressure in the region (Floerl and Inglis 2005, Kaluza et al. 2010, Wang et al. 2018, Ashton et al. 2022). Alternatively, modeling approaches can be employed to evaluate the importance and interconnection of the vectors (Seebens et al. 2013, Xu et al. 2014.

Once the main vectors and pathways are characterized, a list of high-risk species (i.e., species that may be invasive and cause significant economic or ecological damage) can be developed (figure 2). Updated national and regional inventories of mNIS can be particularly challenging but highly relevant in the more biodiverse tropics as, substantial conservation benefits can result

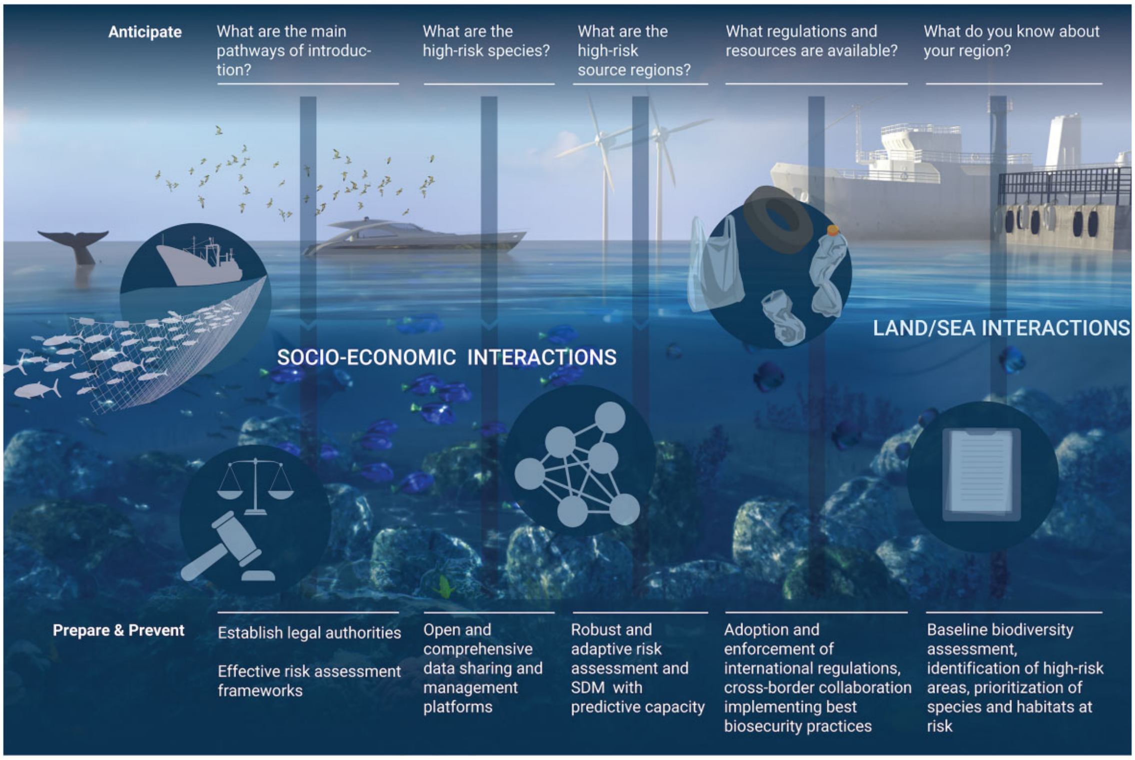


Figure 2. Considerations, critical aspects, and key actions at the preborder level intended to prevent the introduction of nonindigenous species. SDM, species distribution models.

from early interventions (Tricarico et al. 2016). Further analyses should address the likelihood of those species establishing viable populations on the basis of an environmental comparison between the source and the reception areas (e.g., Tzeng 2022), including species' biological traits (Cardeccia et al. 2018). For example, in 2014, a new Regulation on the management of invasive species entered into force in the European Union (European Commission 2014), establishing a Black List of invasive species of Union concern for which specific rules for the prevention, early detection, rapid eradication, and management have been adopted. This regulation is an European Union–wide biosecurity program requiring thorough risk assessments of invasive species, enforcing robust measures for preventing their intentional or unintentional introduction and setting the mechanisms for their management. Terrestrial and freshwater species dominate the current Black List, and the first marine species was included in 2019 (*Plotosus lineatus* Thunberg 1787; European Commission 2019), with the addition of another species in 2022—namely, *Rugulopteryx okamurae* (E.Y. Dawson) I.K. Hwang, W.J. Lee, and H.S. Kim (European Commission 2022). More marine species are expected to be included in the future.

Species distribution models (SDMs), informed by occurrence or abundance data, environmental conditions, and local vectors or pathways, can also be useful to predict spatial patterns of biological invasions and identify key locations for incursion response. However, limitations exist in ecological modeling for biological invasions, because mNIS may not follow model assumptions, and the balance between niche and dispersal limitations for each species may not be accounted for (i.e., stochastic events, geographical barriers, and dispersal constraints; Václavík and Meentemeyer 2009, Barbet-Massin et al. 2018, Lake et al. 2020). SDMs provide a useful indication of where a species may find suitable environmental conditions, but not how fast it may colonize new locations. This can be estimated from monitoring data on the natural spread of mNIS populations, as well as human-mediated (e.g., boat traffic) spread. In addition, a central assumption of SDMs for biological invasions is that a species native or realized niche may not be its potential niche because of limitations by predators, competitors or pathogens. Therefore, a species may appear to expand its niche when released from these ecological constraints (Parravicini et al. 2015). The information generated in data-rich regions from extensive monitoring of invasion events can be used to inform global models and test whether later stages of the invasion can be predicted by models calibrated with records from both the native range and earlier invasion stages. Robust models can help identify locations in which mNIS are most likely to colonize and support the development of prioritized management strategies within biosecurity programs before mNIS cross the preborder stage of invasion.

In the last decade, substantial progress has been made in advancing preborder biosecurity measures globally. One of the best examples of international regulation for preborder mNIS control and probably the most widely implemented is ballast water management. The International Maritime Organization (IMO) adopted the 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments, which entered into force globally in 2017. Ratified by 84 contracting States, representing more than 80% of the world's tonnage, it declares that, by 7 September 2024, all ships must install an approved ballast water treatment system (BWTS) to replace the current practice of midocean exchange. Conversely, biofouling remains largely unregulated, although the importance of hull fouling for marine bioinvasions is unquestionable (Murray et al. 2011, Darling et al. 2012, Brine et al. 2013, Katsanevakis et al. 2013, Ulman et al. 2019, Ashton et al. 2022). Nevertheless, regulations and enforcement at the global scale are minimal (but see Resolution MEPC.207(62), IMO 2011).

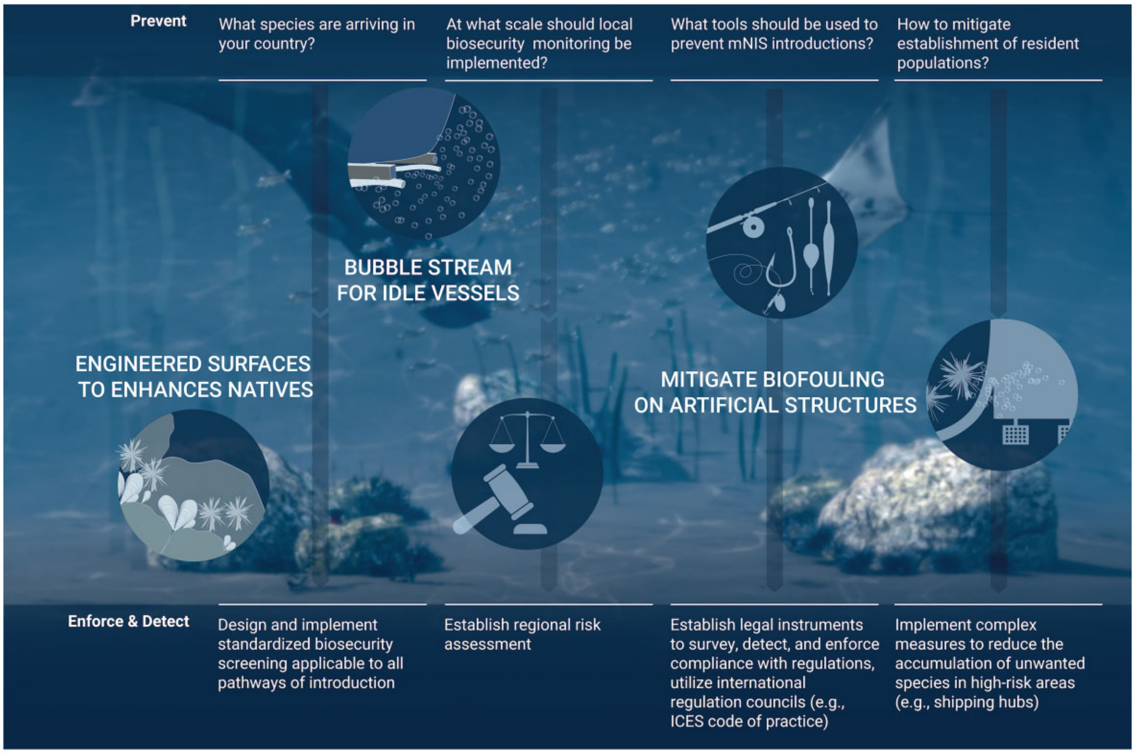


Figure 3. Considerations, critical aspects, and key actions at the border level intended to prevent the establishment of nonindigenous species.

Following the success of the Ballast Water Convention (BWC), the IMO promoted the GloFouling Partnership project to protect marine ecosystems from the negative impacts of biofouling mNIS (www.glofouling.imo.org). However, currently, the best practices outlined by this project are applied only voluntarily, i.e., effective hull maintenance, antifouling coating renewal, proper in-water hull cleaning, and regular hull inspections (Floerl et al. 2010). Several regulations exist for aquaculture biosecurity within the European Union and countries such as New Zealand, Australia, the United States, and Canada (Minchin 2007, Copp et al. 2016). However, globally enforced frameworks are lacking. Similarly, the emerging vector of marine litter, which has been gaining relevance over the last decade, requires attention because of the global distribution, buoyancy, and high levels of colonization that plastic litter can support, which facilitates the transport of species to nonnative regions (Barnes 2002, Campbell et al. 2017, Carlton et al. 2017, Rech et al. 2018, Audrézet et al. 2021). International conventions and legislation must be evaluated for efficiency with scientifically validated data while clearly outlining expected actions and an appropriate timeline for implementation by participating nations (figure 2).

Border. The border (i.e., national waters within the exclusive economic zone of a country) is the critical point at which actions can be taken to control the introduction of potential mNIS by targeting them (e.g., screening for prohibited species related to aquaculture or aquarium imports) or, more likely, their vectors (e.g., commercial shipping; figure 3). However, to accomplish this, the receiving country must have legal authorities, regulations, and policies in place for either pathways (e.g., ballast water) or species (e.g., prohibited lists). For example, many countries are implementing the IMO BWC by creating or modifying existing legislation to be able to legally enforce it, including outlining the penalties for noncompliance. However, enforcement remains a global challenge as resources are limited and compliance and monitoring programs insufficient. Recognizing that it is not feasible to perform compliance checks on every arriving vessel, a risk-based approach based on the best available science can be used to identify those vessels posing a greater risk on the basis of a combination of factors, e.g., vessel type, travel, and maintenance history. Such an approach has proven effective in New Zealand, where higher-risk vessels were identified for compliance checks before a vessel can inadvertently introduce mNIS to nearshore environments (MPI 2022). However, it is relatively data-intensive, requiring information on both the vessel and its operations. Furthermore, effective border control requires up-to-date and real-time data for decision-making to ensure that potential mNIS are identified early and a response to vectors or species can be implemented, which may require the regulations and policies to be updated to ensure the greatest protection against mNIS threats.

Regardless of the regulation implemented, effective management at the border requires timely screening and prompt detection of potential mNIS. Interventions around shipping generally target ballast water or hull fouling. For ballast water, this is usually a compliance check to ensure the vessel has either undertaken midocean exchange or is using an accepted ballast water treatment system. Vessels deemed not in compliance may be forced to retain untreated ballast water or treat this ballast using a shore-based system. Mitigating biofouling may include disinfection, eradication, or quarantine (Olenin et al. 2011, Abdo et al. 2018). Notably, there is a positive relationship between hull fouling loads and an increased likelihood of mNIS being present (Inglis et al. 2010, 2012), as well as between the presence of fouling in niche areas (e.g., thruster tunnels or propellers) and the likelihood of mNIS presence (Moser et al. 2017, Ulman et al. 2019). Among the most cost-efficient border-based

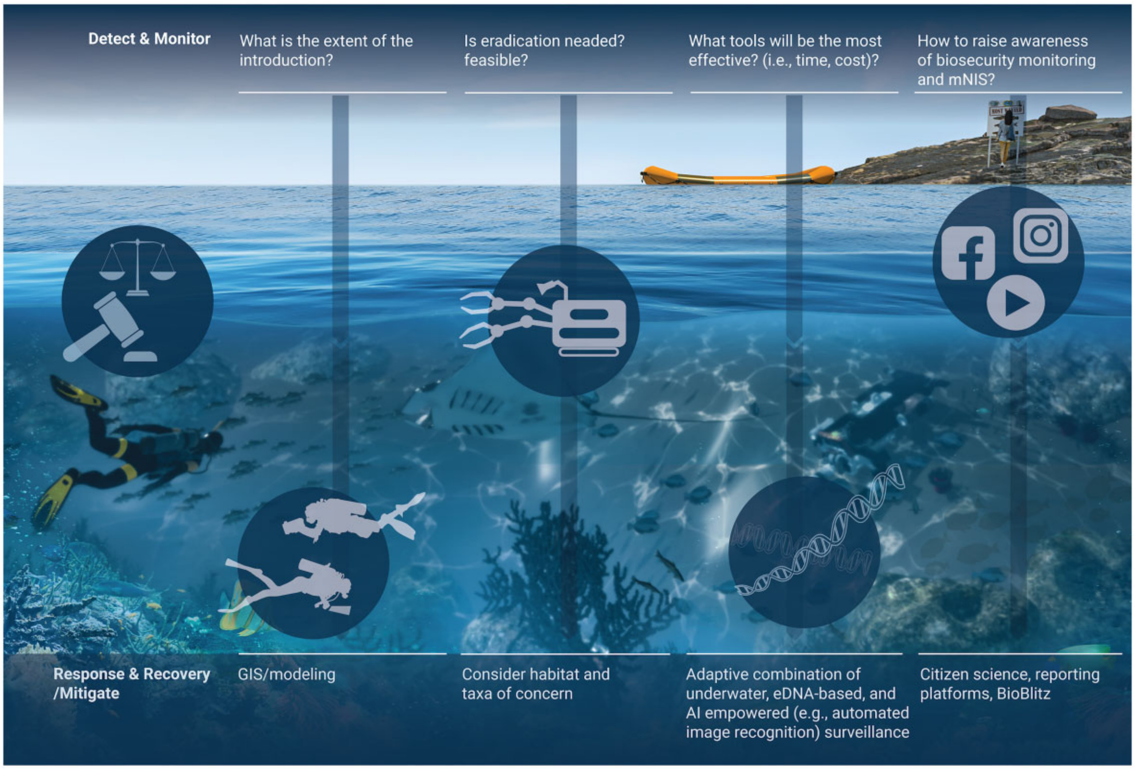


Figure 4. Considerations, critical aspects, and key actions at the postborder level intended to prevent the spread of nonindigenous species.

observation techniques to address biofouling is the fouling rank scale (Floerl et al. 2005), initially applied in New Zealand (MPI 2017 in Floerl et al. 2005) and later in Australia (DAWR 2015 in Floerl et al. 2005). Although the assessment of the level of fouling (and similarly, the antifouling paint age) could be an easy and rapid tool to indicate the risk of a boat spreading mNIS, it must be noted that it did not always correlate with the presence and abundance of mNIS (Peters et al. 2019, Ulman et al. 2019, Ashton et al. 2022).

Regarding the introduction of mNIS through aquaculture and ornamental species trade, the ICES Code of Practice on the Introductions and Transfers of Marine Organisms has been applied in its member countries (most European countries, North America, and Russia). When a member country is planning to introduce a new species for aquaculture or trade, it needs to submit a thorough plan to a committee for review and approval (outlining reasons for the introduction, information on the biology and ecology of the species and receiving environment, risk and impact analysis of the introduction, and management plan for the species). The application of this code, which restricts higher risk mNIS imports, has greatly reduced the number of these species that accidentally escape into the natural environment. Similarly, the Food and Agriculture Organization of the United Nations' Code of Conduct for Responsible Fisheries (FAO 1995) discourages the use of mNIS in aquaculture, calls for risk assessments, and requests consultation with neighboring states before introducing a new species (figure 3). In the European Union, compulsory measures have been implemented through the regulation "concerning the use of alien and locally absent species in aquaculture" (European Commission 2007), which led to a marked decrease in new introductions via aquaculture (Katsanevakis et al. 2013). However, it does not necessarily prevent the movement of species already introduced or established in a country, and such movements may still spread pathogens. To maximize biosecurity, authorities need to consider fishery, aquaculture, and nature conservation regulations. For example, although an introduction may have potential industry benefits, is there a risk to native biota should it escape into the environment?

Postborder. mNIS that cross the border pose a risk of becoming established in the recipient region, often occurring in shallow-water coastal environments. Multiple actions are needed to manage species that may establish outside their native range: protection, detection and surveillance, pathway management, and response (figures 3 and 4).

Protection. Over the past two decades, several studies have demonstrated the critical role played by artificial marine structures associated with transport hubs such as ports and marinas, coastal urban centers, and aquaculture farms (Firth et al. 2016). The seawalls, breakwaters, pontoons, piles, wharves, and other artificial structures associated with these environments provide attractive habitats for a wide range of marine organisms, but are often disproportionately colonized by mNIS, and may act as stepping stones for further spread (Glasby et al. 2007). A single aquaculture farm can include more than 50,000 square meters of man-made substrata (Floerl et al. 2016a). The presence of extensive areas of coastal infrastructure in proximity to maritime transport hubs can facilitate the establishment of founder populations of mNIS and, subsequently, act as extensive sources of propagules for domestic spread (Floerl et al. 2009). Detached gear and other floating litter from aquaculture infrastructures can further promote mNIS spread to adjacent regions. Preventing the colonization and establishment of mNIS on high-risk infrastructure is the first line of defense for postborder biosecurity management.

Several approaches for disrupting the first phase of the postborder invasion process either already exist or are at various stages of development or evaluation. Biocidal antifouling coatings provide limited and short-term biofouling protection for aquaculture infrastructure (Bannister et al. 2019) but are generally unsuitable for static coastal infrastructure (Hopkins et al. 2021a). Presently, initiatives are underway to develop environmentally benign technologies for maintaining infrastructure perpetually biofouling free. These include, for example, the use of continuous bubble stream (microscopic air bubbles generated by fine bubble diffusers; figure 3; Hopkins et al. 2021b) to prevent larval settlement or native biocontrol agents, such as gastropods (Atalah et al. 2014). However, considering the potential side effects of biological measures in the management of marine biofouling to the wider ecosystem (Atalah et al. 2013), a risk analysis should be taken before their implementation (see Hopkins et al. 2021a for a review on biofouling management options). Another promising line of research is the development of ecoengineering approaches for promoting native assemblages or particular native taxa on infrastructure to improve invasion resistance to mNIS (Perkol-Finkel et al. 2012, Dafforn 2017, Airoldi et al. 2021). Although these technologies are largely in development, increased recognition of the scale of coastal urbanization and its associated impacts (biosecurity risks being one) have opened up opportunities and markets for ecoinnovative biofouling prevention and enhancement of native communities (Dafforn et al. 2015).

Detection and surveillance

Established hub-monitoring and marine-surveillance programs are a prerequisite for efficient rapid response (including disinfection, eradication, quarantine) and control of further expansion (Olenin et al. 2011). In this regard, early warning systems are highly recommended (Magaletti et al. 2018). On the basis of policy relevance, one example is the EU Invasive Alien Species Regulation (1143/2014). The regulation gives a clear definition of *early detection notification* according to which the member states shall use the surveillance system and, without delay, notify the commission, in writing, of the early detection of an invasive alien species. A proposal for a regionally harmonized early warning system on findings of harmful aquatic organisms and pathogens in the Baltic Sea was developed within the framework of the INTERREG Baltic Sea Region Program project COMPLETE (www.balticcomplete.com). The proposed early warning system is embedded in AquaNIS (Olenin et al. 2014) as a dedicated functional module and has three main blocks or stages: detection and reporting, decision procedure, and warning signal and actions. Detection of potential harmful aquatic organisms and pathogens is the prerogative of institutions that monitor mNIS on behalf of member states, conduct targeted research, or collect citizen science data. The alert is sent to all registered recipients designated by the participating parties, such as national focal points (e.g., state port-control authorities, ministries of transport or environment). Decisions are made locally depending on the specific situation and national legislation.

Countries with well-established biosecurity systems (e.g., New Zealand; MPI 2022) consider a rather complex but efficient tiered surveillance approach, cascading from general national or regional surveillance to targeted hub (high-risk sites) surveillance to targeted programs (i.e., investigative on-demand diagnostics focusing on a particular area of concern or emerging and suspected incursion case). However, it is extremely difficult to ensure comprehensive surveillance across relevant temporospatial scales in countries with vast coastlines, multiple marine ports, or financial stringency. Therefore, it is crucial to prioritize surveillance areas (considering different incursion risk criteria) and carefully select the methods (ensuring their cost-effectiveness, as well as relevance for the considered habitats and taxa of concern) and design (trade-off between the reasonable effort and adequate temporospatial coverage, considering environmental peculiarities of the region). To make these decisions, it is essential to have baseline information on the region's biodiversity (both native and nonindigenous), habitat diversity and distribution, operating introduction vectors and their dynamics, and the history of mNIS introductions in adjacent waters (Olenin et al. 2011, Lehtiniemi et al. 2015, Zaiko et al. 2018). All this information might be scarce or unavailable in data-poor regions. This and other limitations (including, insufficient monitoring resources or expertise) often hinder the ability to detect mNIS incursions promptly, compromising successful response and disruption of further invasion process (Rodionova and Panov 2006, Coutts and Forrest 2007, Read et al. 2011, Lehtiniemi et al. 2015).

Fortunately, several tools have emerged recently that can facilitate the detection and surveillance of mNIS. Recent advances in molecular sciences have the potential to revolutionize the effectiveness of marine surveillance and monitoring, providing an unprecedented ability to detect and monitor species of interest in complex environments and to identify potential biosecurity threats, assuming they have genetic markers (figure 4; Aylagas et al. 2020, Bowers et al. 2021). The environmental DNA and RNA (eDNA, eRNA) based methods (e.g., metabarcoding or taxa-specific assays, such as ddPCR or qPCR) can be—and are—readily applied to deliver different types of biodiversity information required for science-based biosecurity programs—for example, presence and distribution of target species (e.g., targeted detection of unwanted pests, assessment of management success) and more (Ricciardi et al. 2017, Zaiko et al. 2018, Westfall et al. 2020, Hupało et al. 2021). Although current eDNA and eRNA sampling and analytical approaches lack standardization (Zaiko et al. 2022) and are not yet optimized to harness the full potential of these methods (Bowers et al. 2021) in routine biosecurity programs, they may become a cost-effective solution for rapid identification of invasive species with limited access to taxonomic expertise. Automated image identification of species (see below) is another alternative for an accurate and low cost mNIS detection, widely available in the near future with only occasional need for laboratory examination of specimens, particularly when native and nonnative species are not easily distinguished morphologically.

When available, well-structured programs for citizen science surveillance of mNIS can also play an essential role in the early detection of potential invasions (figure 4; Giovos et al. 2019). If well managed, they can not only raise awareness among the public but also help suppress severe limitations in terms of resources faced by most government agencies in detecting and responding to mNIS (Ricciardi et al. 2017). For example, BioBlitz (biodiversity screenings with the help of taxonomists) allows cataloging biodiversity in an area within a limited timeframe and in the context of resource scarcity (Meeus et al. 2021). Apart from its educational scope, this (or other similar) citizen science-based initiative can aid the detection of mNIS in coastal areas. Through the development of defined frameworks and associated infrastructure (e.g., reporting platforms) and the implementation of awareness campaigns, the public can assist in acquiring accurate data and reporting. In addition to this engagement and interaction between scientists, naturalists, policymakers, and local communities to gather data, further efforts (that can be more scientifically driven) are possible. For example, it can be envisaged that in the very near future operationalized molecular surveillance will become available to feed into citizen-science programs and school curricula, building up an extended (nationwide) biosecurity workforce (see e.g., New Zealand's Biosecurity 2025's campaign to make all New Zealanders aware of the importance of biosecurity and to get them involved in pest and disease management; www.mpi.govt.nz/biosecurity/about-biosecurity-in-new-zealand/biosecurity-2025/biosecurity-2025/a-biosecurity-team-of-4-7-million).

The emergence of machine-learning technologies and automation using autonomous underwater vehicles (AUVs) with live video recording systems will foster our capability to promptly identify and therefore prevent the spread of mNIS. Even relatively inexpensive systems can help the rapid and reliable assessment of biofouling, which can then be used to check for compliance with biofouling standards when available (First et al. 2021). AUVs coupled with cameras can cover larger areas. In association with algorithms that incorporate information about mNIS of concern, they can contribute as an early warning tool to prevent the dissemination of nonnative organisms.

As more data are gathered through the different sectors (universities, private sector, government, public), employing available resources and technologies and developing new technology, a higher degree in the level of detection and surveillance can be implemented. It is worth noting that effective communication channels to report and verify new detection and a timely and adequate response pipeline are critical to any efficient biosecurity program (regardless of its complexity). This step should be well thought through and implemented early on.

Domestic pathway management

A multitude of vessel types (e.g., cargo ships, fishing vessels, passenger and vehicle ferries, water taxis, tourism vessels, recreational yachts and launches) occupy the coastal waters of most seasides (Tzeng et al 2021). In addition, industrial activities such as aquaculture or natural resource extraction involve movements of specialized vessels or infrastructure within or between coastal regions. Together, these movements form complex maritime transport networks that can facilitate the transfer of nonindigenous pathogens and macroorganisms via hull fouling, ballast water, or other entrainment mechanisms among a nation's coastal urban centers, ports, marinas, natural anchorages, aquaculture farms and other locations (Floerl et al. 2016b). For example, between 2016 and 2019, there were more than 200,000 commercial vessel voyages around New Zealand (a maritime nation with a relatively small population) that connected approximately 75 domestic ports and industrial facilities. In addition, an even higher number of recreational vessel movements connected the nation's urban coastal centers (where most mNIS are established) to several hundred natural destinations, including remote bays, coastal islands, marine reserves, and iconic (national parks) or other high-value natural environments (Parretti et al. 2020). For example, around Auckland, in New Zealand, there are at least 8700 recreational boats, and even if only 5%–20% have high biofouling levels, hundreds of boats may already be transporting invasive species within the region (Brine et al. 2013). Recreational boating has been recognized as a major vector responsible for both primary introductions and secondary spread and should be the target of management regulation (Murray et al. 2011).

Several useful avenues exist for understanding and managing the biosecurity risk associated with transport pathways. These include quantifying key domestic pathway relative strengths and dynamics. Understanding the dynamics of a domestic network is key to minimizing the spread of mNIS that have made it through the preborder and border stages and have managed to establish a founder populations. Tools such as network modeling and graph theory can enable scientists and biosecurity managers to identify transport hotspots (e.g., locations that have strong incoming and outgoing links to a large number of other locations) and other influential network nodes or connections (figure 4; Kolaczyk and Csárdi 2014, Samsing et al. 2019, Iacarella et al. 2020). Where resources (finances, personnel, infrastructure) are limited (as is generally the case), their prioritization toward high-risk locations can be particularly cost-effective in disrupting domestic spreading pathways (Hatami et al. 2021).

Incentives or requirements that encourage best-practice vessel maintenance is a useful management tool. For example, in New Zealand, some regional jurisdictions do not allow domestic recreational vessels from other jurisdictions to enter their ports or marinas if they cannot document compliance with hull maintenance requirements, such as recent hull cleaning or antifouling treatments. Also, commercial vessels entering the United States, Canada, and the Panama Canal must have a ballast water management plan onboard and conduct ballast water management reporting to the US Coast Guard.

They also include biosecurity management plans for maritime industries. This can include, for example, voluntary treatment of aquaculture stock (for associated biofouling or pathogens), equipment (e.g., net cleaning rigs and farm pens), and infrastructure (e.g., lease pontoons that may be moved between regional or domestic ports and marinas) to prevent the accidental transfer of mNIS. An example of guidance prepared for commercial and private maritime sectors is provided by the Australian government (Department of the Environment and New Zealand Ministry for Primary Industries 2015, Marine Pest Sectoral Committee 2018; www.marinepests.gov.au/commercial/vessels).

Finally, they include regional partnerships and communication platforms. For example, the Top of the South Marine Biosecurity Partnership in New Zealand is a dynamic collaboration among three regional councils, the central government, the marina and aquaculture industries, and regional Indigenous tribes. Sharing of critical information (e.g., arrival or departure of potential high-risk vessels, detection of new mNIS) and resources (e.g., availability and operational protocols for treatment and response) and codevelopment of standardized regional rules and policies (e.g., biosecurity requirements for visiting vessels, global permits for the rapid application of treatment agents or methods) have resulted in a dramatic reduction in the response time to regional pest detections and, likely, the establishment of new populations of mNIS present in other parts of the country (www.marinebiosecurity.co.nz).

Rapid response

The main objective of a rapid response is to eliminate any risk associated with the presence of the mNIS detected (Locke et al. 2003). The first action follows immediately the report of a mNIS. If the species is not already known from the area, then managers need to decide whether the species should be contained to prevent future spread or eradicated on the basis of whether the mNIS has a known negative ecological or socioeconomic impact (Ojaveer et al. 2015, Giakoumi et al. 2019). The decision needs to be made promptly (when populations are small and spatially constrained or limited) to increase the chances that eradication or control efforts are successful. Regardless of the approach taken, policies need to be established to regulate the associated actions, such as eradication attempts (Myers et al. 2000, Wotton et al. 2004).

To tackle mNIS efficiently, management protocols with clearly set goals are beneficial to foster timely and efficient responses and must be optimized for biosecurity benefits and resource availability. An efficient response protocol must integrate not only expertise and knowledge on the biology of the mNIS of interest but also information about the uses, ownership, and characteristics of the infested site (Anderson 2003). Proactive guidelines should include quantifying the multiple vectors of the mNIS introduction, the risk category of the mNIS (Ojaveer et al. 2015), and the use of models to inform the predicted spread of the invasive organisms (Sarà et al. 2013) in realistic incursion and response scenarios. When confronted with a lack of knowledge regarding the potential impacts of an mNIS, managers should assume they will cause impacts until it is proved otherwise (Davidson and Hewitt 2014), because the reevaluation of risk status is rare, unless ecological and economic impacts become apparent (Ojaveer et al. 2015). And in this case, it can already be too late.

Recently, Giakoumi and colleagues (2019) analyzed 11 management actions aiming to control the populations of mNIS, ranging from physical (mechanical) removal of the target species and rehabilitating the environment to doing nothing. Actions that scored high in their assessment were education and public awareness and encouraging the targeted removal and commercial or recreational use of dead specimens. Public awareness and education were considered critical components of the response management plan. Citizens can play a relevant role in the early detection of new NIS (Maistrello et al. 2016), fostering fast responses while helping the monitoring of secondary spread (Miralles et al. 2016) in a relatively inexpensive way. In contrast, eradication by physical removal requires enormous effort and resources; it might be effective in controlling the spread only temporarily and requires cooperation between many stakeholders (both governmental and nongovernmental organizations), such as in British Columbia, where the European green crab is the focus of a large-scale collaborative control project among the federal government, local Indigenous groups, and an environmental stewardship group. There are a few cases of successful removals of mNIS worldwide, all relying on prompt actions once a species is detected (Ojaveer et al. 2015, Usseglio et al. 2017, Giakoumi et al. 2019). High environmental connectivity in the marine environment renders efforts to eradicate well-established populations unrealistic. Nevertheless, controlling invasive populations at sufficiently low densities can be effective in mitigating their impacts (Green et al. 2014, Usseglio et al. 2017). The lionfish populations in the western Atlantic Ocean and the Caribbean Sea have been controlled through targeted removals (Usseglio et al. 2017, Giakoumi et al. 2019) and, in some cases, combined with a market-based approach supporting a sustained supply and demand of this species (Chapman et al. 2016). It was also the case of the blue swimming crab (*Portunus segnis*), which invaded the Gulf of Gabes (southeastern Tunisia) within only 1–2 years, with serious consequences on coastal fisheries, and because its eradication was not possible, a related fishery was established in the region to control its high densities (Crocetta et al. 2015, Rabaoui et al. 2015). However, unsuccessful removal actions are comparatively more frequent (Ojaveer et al. 2015). Given the uncertainty associated with the response stage of any biosecurity plan (e.g., the mNIS of interest and its associated risks, the extent of the area infected, the health status of natural populations and ecosystems in that area, hydrodynamics, the similarity of environmental characteristics between donor and receptor areas, the time until detection, the resources available), a precautionary approach should be prioritized (Ojaveer et al. 2015, Miralles et al. 2016), directing the efforts at the initial stages of the process and hindering the establishment of new mNIS.

Building feasible biosecurity programs based on local needs and limited available resources

Data-poor regions should capitalize on the likely limited knowledge gathered regionally and incorporate data and expertise gained from decades of biosecurity research worldwide. This combination will provide a framework for implementing customized biosecurity programs based on the best practices that are currently conducted in some regions. Furthermore, it will enable resources to be allocated to meet current needs and maximize the outcomes and benefits to society. In the present article, we present specific actions proven to be efficient globally and organize them into a flexible plan of action. This plan of action can be customized on the basis of the needs required for implementation, according to the resources and data needs (from low to high), to accommodate multiple situations across the world table 1.

Clear prioritization schemes should be question driven and score based to enable transparent decision-making and the generation of consistent, comparable outcomes between regions while incorporating adaptive changes as available information and regulations improve (McGeoch et al. 2016). Although available resources and the size and nature of invasion risks vary widely across regions, a concerted effort is required, in both time and space, to implement formal prioritization schemes and generate globally comparable data that will inform internationally coordinated mNIS interventions (McGeoch et al. 2016). Especially in data-poor regions, one cannot ignore the knowledge of Indigenous people, who often have superior knowledge of their local environments. Working closely with them can play a major role acquiring and documenting knowledge that will be critical for the management of mNIS. Also, to improve efficiency, the management of mNIS should be built on cross-border cooperation to ensure that these actions are not undermined by the absence of action in a neighboring state or country. Cross-border collaboration among scientists from data-poor regions is essential for creating a robust data set and promoting coordinated regional biosecurity programs. For example, although the Mediterranean is a data-rich region (Stranga and Katsanevakis 2021), a recent collaboration among 126 marine scientists from 16 countries led to the collection of more than 5000 records of 239 alien or cryptogenic taxa, including many first records at the Mediterranean or country level, which cumulated in a valuable large-scale open-access data set of georeferenced records (Katsanevakis et al. 2020). Similar efforts in data-poor regions could prove valuable in creating a baseline of mNIS species distributions. This collaboration may include sharing resources and scientific knowledge, which, whenever possible, is to be supported by governmental and nongovernmental associations (e.g., academic research networks).

Regions or countries with inadequate biological invasion records should first build reference libraries on the distribution of native species, using a comprehensive review of available data sources on the local marine biodiversity. The curation of a reference data set can include scientific literature, biological inventories and reports, unpublished data (e.g., private and museum collections), data from neighboring regions with similar habitats,

Table 1. Key proposed actions for countries with different resource levels for each stage of the invasion process.

Resources	Low	Medium	High
Preborder	Assessment of pathways and vectors of mNIS introduction	Establish and implement baseline biodiversity assessments and monitoring in high-risk sites	Establish and implement comprehensive biodiversity surveys in artificial and natural habitats
	Identification of high-risk sites for mNIS introduction	Implement risk assessments for prioritizing pathways or vectors, source regions, and species of concern	Establish and implement regular preborder pathway screening for unwanted organisms (e.g., screening of biofouling on vessel hulls using cameras and AI platforms, ballast water testing with eDNA or eRNA approaches).
	Ratification of International Conventions (e.g., Ballast Water Management Convention) and enforcement of best practices related to biofouling management		
	Compilation of information about local biodiversity		Generate comprehensive reference repositories of data on native biodiversity, including genetic information
	Establish regional partnerships		Generate online systems linked with international databases with information relevant for the country/region
			Develop and establish a resourced Biosecurity Act providing details about all actions required throughout the stages of the invasion process, including the regulatory bodies and report channels to mitigate the establishment and the potential effects of mNIS
Border	Enforcement of conventions and codes of practice (e.g., ballast water convention and ICES Code of Practice on the Introductions and Transfers of Marine Organisms). Vessels posing a greater risk on the basis of some combination of vessel type, location of travel, maintenance history, etc., should be targeted	Apply modeling approaches to identify high risk species	Implement active biofouling mitigation in the shipping hubs or fixed artificial structures (e.g., the use of continuous micro air bubble streams to prevent larval settlement, use of native biocontrol agents, or application of ecologically friendly antifouling treatment on aquaculture facilities)
		Develop, implement, and enforce early warning systems built on curated databases, AI platforms, modeling, and molecular approaches (e.g., qPCR for targeted species)	
		Quantification of biofouling on vessel hulls using underwater cameras and AI platforms	Screening for mNIS using a combination of visual (ideally supported by AI) and molecular methods
Postborder	Create a platform as a communication channel to report and verify potential mNIS detections	High-risk site surveillance and mNIS-specific surveys for high-priority species	Large-scale systematic monitoring surveys, incorporating eDNA-based approaches, video recording systems coupled with AUVs, and machine-learning technologies
	Establish adequate response pipelines in case of mNIS detections	Regular screening of coastal areas for new incursions and distribution of established mNIS using eDNA metabarcoding and species-specific assays (e.g., qPCR targeting high-risk species)	Develop species distribution models to help in the early detection of likely invaders
	Join global research programs related to the biodiversity discovery and archive	Encourage best-practice vessel maintenance by limiting the movement of domestic recreational vessels when they do not undergo hull maintenance (e.g., hull cleaning or antifouling treatments)	Develop AI tools to be able to identify mNIS from photos uploaded by scientists and citizens
		Biosecurity management plans for maritime industries	Promote the proliferation of native assemblages through the development of ecoengineering approaches in harbors and other artificial structures—improve invasive resistance
		Establish guidelines for the response toward establishment of mNIS (quantification of the multiple vectors of mNIS introduction, risk category of mNIS, models to inform the predicted spread of the invasive organisms)	Targeted eradication or control programs
		Biodiversity screenings (Bioblitz)	Environmental rehabilitation
		Citizen science programs	

Note: The steps are cumulative; that is, high-resource countries should take the actions indicated in both low and medium levels, except where an action is a direct improvement on the action in the lower resource level.

species known as *cosmopolitan*, and species with life-history traits suggesting the potential for long-distance dispersal (Castlilla et al. 2005). By generating country-level lists of local species, identifying areas of high biodiversity value, and contributing to existing international databases and information systems, data-poor regions can begin systematic prioritization of the species, pathways, and sites that pose the greatest risks to degradation by mNIS. A good example is the recent development of such a reference for the tropical South Pacific region (Lane et al. 2021). A desktop review identified 169 mNIS across 21 Pacific Island countries and formed the basis for the continued development of marine biosecurity awareness and capability for the region. Also, recent reports resulting from baseline assessments of benthic marine species in Brazil highlighting areas nearby harbors as hotspots of mNIS and linking these results with major vectors of introduction (Soares et al. 2022). Once a reference library is created, it can be used to investigate mNIS characterized worldwide as capable of causing a high degree of damage. Some species have specific environmental requirements (e.g., salinity, temperature) that may hinder their ability to colonize contrasting environments. On the basis of predicted distribution ranges of high-risk mNIS, a risk assessment analysis can be conducted to fine-tune the list of mNIS of potential concern for a given region. In addition, biodiversity inventories might be needed in some data-poor regions, and if that is the case, building gene libraries for reference specimen collection will support the future implementation of molecular-based detection strategies.

While generating new biodiversity inventories, fundamental practical steps can be simultaneously undertaken. For example, ratifying and enforcing international conventions (such as the International Convention for the Control and Management of Ships' Ballast Water and Sediments) is pertinent in regions lacking local biosecurity programs. Efforts can be focused on the essential resources and infrastructure present in the region to support preventive actions and enforcement. These actions are the most cost-efficient strategy and do not rely on resource availability or baseline data. Nevertheless, baseline data may be critical to identify invasive events (Gardner et al. 2016). A thorough understanding of the multiple vectors and pathways for the introduction of mNIS will help direct efforts. It is important to understand and estimate the relative contribution of the existing biosecurity risks. Risk analysis should be combined with the assessment of multiple vectors of invasion, as well as the identification of high-risk areas for mNIS introduction (e.g., ports, aquaculture facilities), to prioritize investigative actions in a few selected areas (i.e., pilot studies and preliminary monitoring programs). To inform the delineation of high-risk areas, it is crucial that researchers and environmental monitoring agencies can readily access up-to-date, accurate, and comprehensive data regarding ship traffic, aquaculture production, and existing biosecurity efforts. A unified and organized platform or database for collecting and curating basic data on vectors of mNIS introduction (e.g., ship origin and abundance, aquaculture imports, and cumulative production) may allow researchers to gain a broader understanding of mNIS risk within a region and inform the direction and location of initial preliminary monitoring efforts. In addition, they can support GIS tools and modeling for risk assessments.

Depending on the countries' capabilities, and once the risk analysis is conducted, a monitoring program, including early warning systems, should be established in high-risk areas and focus on high-risk species. Ideally, such a program should cover multiple trophic levels and employ adequate and efficient sampling designs and approaches (including novel technological advancements in the field). Engaging citizens in this process has improved the collection and consolidation of mNIS sightings and provides real-time monitoring of mNIS distribution and occurrence. For example, using the iNaturalist network, it is possible to engage scientists and citizens in the early detection of predefined nonnative species by mapping the records of the locations of those species through free online tools (see a recent project launched for terrestrial pests in the Pacific; www.sprep.org/news/early-warning-system-for-new-invasive-species-launched-using-inaturalist). Indeed, several studies demonstrated the potential for citizen science to contribute valuable information at local scales where traditional scientific information is lacking to inform timely management (Larson et al. 2020, Epanchin-Niell et al. 2021, Kousteni et al. 2022). In contrast to many scientific studies, most citizen science systems employ independent expert verification of specimens. For example, iNaturalist publishes over 50 million research-grade data points into the Global Biodiversity Information Facility (GBIF). The top-16 species occurrence data sets in GBIF (www.gbif.org/dataset/search?type=OCCURRENCE) are all from high-quality citizen science publishers, many publishing monthly updates in contrast to data from the scientific community. Nevertheless, because of the economic and ecological risk posed by introduced species, governments should employ experts to screen citizen science, social media, and other sources for potential findings of invasive species.

Countries developing or improving biosecurity programs should prioritize actions that are already implemented in other countries and, whenever possible, follow consistent approaches and protocols. To tackle a global issue such as the management of mNIS, concerted and standardized actions are needed across regions. Therefore, building international networks supported by open-access databases (with analytical tools) and establishing collaborations with neighboring countries to leverage efforts and maximize outcomes is essential. The system should connect and interlink stakeholders and responsible authorities with information on invasive species, including the early communication of potential mNIS to neighboring countries and joint research programs. We recognize that implementing state-of-the-art biosecurity programs, such as those in place in the countries at the forefront of this topic, is highly demanding in human resources and costly. Therefore, joining global initiatives such as the eBioAtlas (https://ebioatlas.org) and BIOSCAN (https://ibol.org/programs/bioscan) programs may provide great opportunities to start building baseline information in data-poor regions. These research programs aim to advance the global knowledge of biodiversity through molecular techniques and offer unique platforms to expand the limited knowledge on species distributions, a critical step toward managing mNIS worldwide.

One inefficiency in mNIS management is that hundreds of websites with information on mNIS—often outdated and often with false records—get perpetuated through online data systems (Costello et al. 2021). This duplication of effort is wasteful, and the resulting confusion needs to be repeatedly corrected. The literature is not the best place for such reassessment because it takes a minimum of months for papers to be published, because they vary in their accessibility, and because they may become outdated within months. A globally coordinated, expert-supervised system that integrates data from different sources and provides web services to national data systems would be more cost-efficient, current, and accurate than existing systems (Costello et al. 2021). Although candidate systems for such a service exist, such as AquaNIS, the European Alien Species Information Network, the World Register of Introduced Marine Species, and the

Table 2. Glossary.

Word or acronym	Definition
Antifouling	Prevention or reduction of marine underwater growth (biofouling) on surfaces such as vessel hulls and aquaculture structures.
Biofouling	The accumulation of microorganisms, algae, or animals on surfaces such as vessel hulls and aquaculture structures.
Biosecurity programs	Policies and measures (usually national or regional) implemented to manage, control, and protect people, natural resources, plants and animals against potentially harmful species and diseases.
Ecoinnovative	Ecoinnovation is the development of products and processes that contribute to sustainable development, applying the commercial application of knowledge to elicit direct or indirect ecological improvements.
Ecological or ecoengineering	The inclusion of ecological principles in the design of infrastructure to enhance its ecological value.
eDNA/eRNA	Molecules of DNA/RNA shed from organisms that are detectable in the environment. These nucleic acids can be analyzed to detect the presence of a defined species in an environmental sample, such as a water sample or sediment sample, without requiring the direct observation of the organism itself.
Invasive species	Any NIS or even native species that undergo active spread and that have an adverse effect on biological diversity, ecosystem functioning, socioeconomic values or human health.
NIS	Nonindigenous species—a species that has been moved from its native dispersal range to a new area. Marine NIS (mNIS) are usually transported by shipping, boating and aquaculture activities. For the purposes of this manuscript, we define NIS as including algal, animal and microorganism species (e.g., pathogens).
Pathway management	The management of vectors (e.g., vessels or aquaculture equipment) that can facilitate the spread of NIS into or through a particular place.
PCR	Polymerase chain reaction: Method of amplifying specific DNA sequences for easier detection and analyses.
Surveillance	Activities undertaken to detect harmful organisms new to a region or place.
Stepping stone	Marine NIS often spread along shorelines via successive establishment in port, marina, or aquaculture environments (e.g., transport hubs). These places act as stepping stones for domestic spread. Expansion into natural habitat occurs from there on.
Transport hub	In the context of maritime transport networks, hubs are ports and marinas—the nodes in the network.
Vector	Means by which nonnative species can be introduced to or spread within a certain region (e.g., ballast water in ships)

Global Invasive Species Database, none are sufficiently resourced to provide an early warning system or are optimized for mNIS management.

In addition, the enforcement of international conventions and best codes of practice is critical. Developing efficient solutions requires the involvement of nonscientists (i.e., the public, decision-makers, and policymakers), but often scientific information to inform decision-making is lacking or inefficiently conveyed. One option, understandable by a wide and varied audience, is to describe these impacts in terms of economic costs. Informing people on the potential expenditures and losses due to impacts of biological invasions is a fundamental step to raise public awareness and compel policymakers to focus more appropriate attention on invasions and to estimate the costs of invasions for specific taxa, geographic regions or activity sectors, as well as their drivers (Diagne et al. 2020). Priority should be given to management decisions that prevent invasions, because successful cases of eradication are rare (and highly costly). When preventive measures fail, cost–benefit analyses should be performed before deciding on eradication or other control measures. In this case, the task of scientists is to make such analysis operational, understandable, reliable, and fast, so that managers can proceed with sound scientific decisions. With the advent of machine learning, exponential progress is expected to happen in the near future, supporting the management of mNIS at multiple levels of the invasion process. Specialized terminology used in the paper is presented in table 2.

Supplemental material

Supplemental data are available at *BIOSCI* online.

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Disclosure statement

The authors declare no conflicts of interest.

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