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REVIEW

# Marine biosecurity: protecting indigenous marine species



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**Abstract:** Nonindigenous species (NIS) are those that have been intentionally or unintentionally introduced outside of their native range as a consequence of human activity. If these species then threaten indigenous species and biodiversity, and/or cause economic damage, they are referred to as "invasive." Biological invasions are not only one of the greatest threats to indigenous marine biodiversity, but they can also cause massive economic and ecological damage. Their presence could also lead to a water body failing to achieve good environmental status under the forthcoming EU Marine Strategy Framework Directive. As the rate of invasion to Great Britain and European waters continues to increase, particularly in light of climate change, the emphasis by member states is on prevention rather than on control or eradication an NIS once an invasive NIS has become established. This paper reviews NIS biosecurity planning for the marine environment, including the most current legislative background, pathway identification and highlights the main issues with the current risk assessment processes. The potential impacts of marine NIS, practical biosecurity measures from Great Britain and internationally are also reviewed. The aim of this paper is to draw attention to the challenges associated with preventing the introduction of marine NIS and to highlight the urgent need for concerted action across the EU member states and marine industries to produce robust biosecurity plans to protect indigenous species.

**Keywords:** biosecurity, marine, non-indigenous invasive species, planning, indigenous, protection

## Introduction

Nonindigenous species (NIS) are those that have been intentionally or unintentionally introduced outside their native range, as a consequence either directly or indirectly of human activity.[1] Once established, if these species then threaten biodiversity and/or cause economic damage, they are referred to as "invasive".[1,2] Biological invasions are not only one of the greatest threats to marine indigenous biodiversity,[3] second only to habitat destruction,[2] but they can also cause massive economic and ecological damage.[4,5] Increased international trade has caused an exponential increase in the spread of NIS around the world over the last few decades,[6,7] and this trend has been observed in Great Britain (GB).[8,9]

The estimated cost of NIS to the economy in GB is £1.7 billion a year.[10] The annual cost of "marine-based" industries (eg, shipping and aquaculture in GB) is estimated to be £39.9 million, although this is probably an underestimate, as there is little distinction made between native and NIS during pest control operations.[10]

More than 90 NIS have been identified from British and Irish (including Republic of Ireland and Northern Ireland) marine and brackish environments.[8,11] Their arrival has been principally due to shipping, including ballast waters and sediments, fouling

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of hulls and other associated hard structures, and imported consignments of cultured species.[8] The majority of marine NIS in GB originate from the North Pacific, followed by the Northwest Atlantic.[8] Many are initially reported from the sites of anthropogenic activity, such as ports, marinas, and aquaculture facilities, particularly in the English Channel, with a number subsequently spreading north to the North or Celtic Seas.[8] In addition, many marine species have naturally extended their native range with increasing sea water temperature,[11] however, this review is primarily aimed at NIS introduced through human activity.

Biosecurity plans are critical in providing a framework to reduce the risk of the introduction of marine NIS. The International Maritime Organization (IMO) recognized this importance and produced in 2011, a biofouling management plan and record book for the shipping industry.[12] At a national level, for example, the GB Non-Native Species Framework Strategy,[13] the new Invasive Alien Species Strategy for Northern Ireland[14] and the Scottish Government Code of Practice on Non-Native Species,[15] typically follow a three-stage approach including i) prevention, ii) rapid response, iii) control and containment. At a regional level, this approach has been adopted in Scotland, for example, in the production of biosecurity plans by the Firth of Clyde Forum[16] and the Solway Firth Partnership.[17] Biosecurity plans for NIS are also under development in Orkney for ballast water management[18] and the Shetland Isles.[19] However, a few examples of how biosecurity planning can be practically implemented by maritime industries at the site or operation level in Europe. The biosecurity planning guidance for preventing the introduction of disease for finfish farmers/traders and shellfish producers is being a notable example.[20,21] By contrast, in New Zealand and Australia, their biosecurity measures for marine NIS are better developed and have been far more integrated with plant and animal health, placing a strong emphasis on border control (ie, prevention) and rapid response. These and other international examples of practical guidelines of how to minimize the introduction and spread of NIS, however, need to be understood for a wider variety of maritime activities before the biosecurity of indigenous species can be achieved.

This review provides an overview of biosecurity planning for the marine environment, including the most current legislative background, pathway identification, and risk assessment processes. The potential impacts of marine NIS are reviewed, together with the examples of practical biosecurity measures that have been used to control or eradicate these species. UK and international experience, including the successes and failures of biosecurity planning has also been explored in some detail, including plans developed for freshwater and terrestrial environments.

## Why do we need biosecurity plans to protect our marine indigenous species?

The unintentional introduction of species to a region outside their normal range is widely recognized as a major threat to indigenous species diversity,[22] arising from habitat modification, changes in ecosystem functioning, additional disease and parasitic introductions, and genetic impacts, such as hybridization with native species.[23]

### Habitat modification

The accidental or intentional introduction of NIS can cause significant changes to ecosystems.[24] For example, the Pacific oyster, *Crassostrea gigas*, was intentionally introduced for aquaculture purposes in the US and Europe in 1928 and 1950s, respectively. This oyster naturally recruits to uncultivated regions in certain areas and can form dense intertidal hummocks of shell and live oysters.[25] This species has been found to substantially reengineer a habitat to provide additional structures for other species, however, it can also cause significant changes to sediment porosity, bioturbation activity, and biogeochemical cycling.[24] The Mediterranean mussel, *Mytilus galloprovincialis*, was also accidentally introduced to South Africa in the late 1970s. This species is now the dominant intertidal mussel on the west coast, where it has considerably modified the natural community composition.[26] The carpet sea squirt, *Didemnum vexillum*, has been shown to have a negative impact on species diversity and abundance on the Georges Bank, northeast US[27] and in the Netherlands.[28] Lengyel et al[27] found that the number of benthic macrofauna significantly declined with an increase in the abundance of *D. vexillum* and that benthic species composition was significantly altered after the appearance of this species on the Georges Bank. In the Netherlands, species diversity also decreased significantly, following the rapid increase in *D. vexillum* colonies, which can locally cover >95% of the hard bottom in the regions of Oosterschelde and Grevelingen.[28]

### Ecosystem functioning

Ecosystem services are a set of ecosystem functions, many of which are critical to human survival (eg, climate regulation, air purification, and nutrient recycling).[29] Ecosystem functioning is intrinsically linked to biodiversity and thus, changes in

biodiversity can cause significant changes to the functioning of a particular environment or system. For example, Levin et al[30] showed that an invasion by the NIS *Spartina* hybrid in the US, caused a shift in the system from an algae based to a predominantly detritus-based system. Furthermore, it changed the hydrodynamic regime in the estuary, which led to reduced survivorship of key species that supported higher trophic levels, such as migratory shorebirds.[30] In addition, the lionfish, *Pterois volitans*, and *Pterois miles* were most likely introduced to Florida coastal waters in the mid 1980s by either releases or escapes from marine aquaria.[31] *Pterois volitans* has dramatically expanded its range in the last 30 years, throughout the Caribbean, Gulf of Mexico, and as far south as Brazil.[32] These species are highly efficient predators and their rapid increase in abundance in the Bahamas coincided with a 65% decline in the biomass of native prey species over 2 years, raising concern that this will have a serious deleterious impact on the structure and function of reef communities.[33] Consequently, *P. volitans* has been recognized as one of the main species for conservation concern.[34]

## Disease and parasite introduction

There are many cases of intentional movements of stock introducing NIS, including parasites and disease. For example, the trematode, *Gyrodactylus salaris*, was transported with Atlantic salmon, *Salmo salar*, from Swedish hatcheries to Norway and resulted in serious salmon mortalities in the recipient region.[35] The importation of the Japanese eel, *Anguilla japonica*, for cultivation trials in Europe also released a nematode, which has gone on to spread and to cause significant damage to other eel species, such as the native eel *Anguilla anguilla.*[36] In addition, the copepods *Mytilicola orientalis*, a gut parasite of bivalves; and *Myicola ostreae,* a parasite that lives on the gills of the Pacific oyster, *C. gigas*, have both been found in Ireland,[37] France,[38] and the Netherlands.[39]

## Genetic impacts

Genetic impacts can occur either through the selection or modification of specific genetic traits linked to performance between native and NIS species or through the inter-breeding of NIS escapees from aquaculture facilities with natural populations. In the case of the former, the Japanese Yesso scallop *Patinopecten* (*Mizuhopecten*) *yessoensis* was intentionally hybridized with the smaller native species *Chlamys farreri* in People's Republic of China to improve growth performance.[40,41] This can result in a significant fraction of genetic variation residing at a higher organizational level (among populations) in aquaculture species compared with natural populations, where all variation resides below the family level.[42] Genetic complexes will develop with a population often relating to the environment in which the population resides. Aquaculture practices of both inbreeding and selection of individuals for specific traits, however, can magnify the development of these genetic complexes in a population.

Aquaculture (and potentially marine aquaria) escapees can also breed with natural populations. This hybridization and subsequent introgression can then lead to a breakdown of the genetic complexes, and forcing a reduced fitness in the hybrid individuals.[43] For example, evidence has been found in the introgression of the Mediterranean mussel, *M. galloprovincialis*, genes into native Australian population.[44]

# Legal drivers and legislative context

This section is not intended to be a comprehensive review of the complex set of acts, directives, and regulations covering NIS in the marine environment. Instead, it provides an example of the main UK legal and regulatory drivers, which although there is no explicit legal or regulatory requirement for maritime operators and developers to produce biosecurity plans for NIS, do consist of several existing laws and regulations that set a strong context for preparing and implementing these plans. These include; section 14 of the Wildlife and Countryside Act (2011) and the accompanying Code of Practice On NonNative Species,[15] which have significantly strengthened the law, particularly in Scotland, where NIS legislation is now viewed as the most progressive in Europe.[45] Specifically, the strengthening of the existing offense of releasing a nonnative animal from captivity and including two further offenses; allowing an animal to escape from captivity outwith its native range; and causing an animal to be in a place outwith its native range.

The Scottish offences in relation to NIS plants and animals are "strict liability offenses" so intention, recklessness, or negligence do not have to be proved. A legal defense that all reasonable steps were taken to prevent the offense and that all due diligence was exercised to avoid committing the offense that can be made. The Code of Practice on Non-native Species sets out in broad terms what "reasonable steps" mean in this context and the advice includes; adopting a precautionary approach and not carrying out operations that might lead to the spread of NIS until there is a clear understanding of the situation; carrying out risk assessments to understand the risk of spreading NIS, setting out how to avoid it happening; seeking advice and following good practice; and reporting the presence of NIS. Although the code stops short of specifying

the need for a biosecurity plan, many of the main elements of this type of plan are set out as good practice.

The amended Scottish legislation also provides powers to relevant public bodies to enter into voluntary Species Control Agreements and, if an Species Control Agreement is refused, statutory Species Control Orders (SCOs).[15] SCOs are intended for situations where a species has already been introduced and must specify which operations should be carried out, who is to carry them out and when they must be carried out. SCOs can, therefore, form a legal compulsion for two major elements of a biosecurity plan – rapid response and containment. SCOs and Emergency SCOs can operate on the "polluter pays" principle. If government agency staff or their contractors have to carry out the control and containment work, then the cost of this work can be recovered from the site operator.

The EU Marine Strategy Framework Directive[46] and the Water Framework Directive[47] set a wider strategic and operational context for preventing the spread of NIS and their control, which feeds down to the national and regional legislation, but do not act as direct drivers for the preparation of biosecurity plans. Unfortunately, the EU Regulation on Invasive Alien Species[48] does not explicitly use the term "biosecurity" at any point. However, the components of the marine biosecurity planning (risk assessment, pathway recognition, pathway management, prevention, containment, early detection) are all mentioned and discussed. Member States are currently in the process of compiling an initial list of Species of Union Concern (SUC). Growing, breeding, selling, or intentionally releasing these species will be banned. Member States will also be able to list Invasive Alien Species of Member State Concern for similar bans.

Member states must also analyze the pathways of unintentional introduction and spread; identify "priority pathways" based on the volume or the impact of the species moved by that pathway and provide a pathway action plan with a timetable and measures to prevent the spread into or within the EU of the SUC. This plan will include awareness-raising measures, regulatory measures to minimize contamination and transport, border checks, and the existing ballast water conventions. At this stage, with no transposition to domestic law drafted, it is not easy to predict what impact this regulation will have in driving the need for biosecurity at the regional, site or operation level in the Member States.

In the UK, however, there are The Aquatic Animal Health (Scotland) Regulations 2009[49] and the equivalent Regulation for England and Wales, which implement the Council Directive 2006/88/EC[50] on animal health requirements for aquaculture animals and products. These regulations require Aquaculture Production Businesses including shellfish and finfish farmers, as a condition of their authorization, to produce and implement a Biosecurity Measures Plan to restrict the spread of disease to their site(s) of operation. Although not intended to cover NIS, the plan preparation process, as well as, the actions and precautions specified by the plan for diseases, could potentially be expanded and used by other maritime industries, the aquarium trade and government agencies to prevent the introduction and spread of SUC.

# Biosecurity planning

## Biosecurity – a survey of existing NIS plans

Biosecurity, as a term applied to NIS to describe measures to prevent their introduction and stop their spread, is still relatively new. Consequently, plans which have a range of titles including Invasive Species Action Plans, Non-Native Species Plans, Invasive Species Management Plans or Species Response Plans may well be, at least in part, biosecurity plans for NIS. These plans have been prepared in a variety of formats ranging from the more numerous countrywide strategic documents to the less frequent plans for small sites and individual operations (Table 1).[20,21,51] National and catchment plan preparation has predominantly been driven by central government, environment agencies, and non-governmental organizations, hence the greater number of these plans compared with the site and operation level plans, where there is no regulatory requirement (apart from the aquaculture industry for disease) for their production. A range of biosecurity guidance and Codes of Practice do exist, however, but they typically lack a plan structure, sign-off, and accountability at an operational level, so there are no clear means to ensure that the guidance and codes are followed.

There are some NIS plans that include "biosecurity" in their title. These plans generally include actions on the long-term, strategic control, and eradication of a well-established NIS rather than on preventative measures, which would usually be included in a biosecurity plan. As long-term strategic control and eradication are almost always technically impossible or not viable economically in the marine environment,[52] it is critical to be aware though that preventative measures are a key component of any biosecurity planning process.

# Pathway analysis

## Pathway and vector identification

The need to understand the pathways (ie, route between the source region and the region of release) of invasion by NIS

**Table 1** Biosecurity plans for invasive nonindigenous species by category

| Biosecurity plan type | Typical scope/content | Examples of plans | Examples of planning guidance |
|---|---|---|---|
| National plans | Strategic plans at a country or regional scale with actions specified at a sector level | GB Framework Strategy[53]<br>New Zealand Biosecurity Management Action Plan[54] | A Toolkit for Developing Legal and Institutional Frameworks for Invasive Alien Species[55] |
| Sector plans | Strategic plans covering an industry or activity across at a country-wide scale | Biosecurity plan for sea angling and bait[56] | Oil and Gas Industry – Guidance for Prevention and Management[57] |
| Area plans | Plans for a defined geographic area, often a catchment, estuary or coastal zone | Clyde Biosecurity Plan,[16] Solway Biosecurity Plan[17] | None encountered – new plans tend to use previous examples as a template |
| Site plans | Plans to manage the risk of a range of ongoing and long-term activities within a described site or facility. These plans may contain sections dealing with contingency and rapid response to a range of species threats | Pathogen Biosecurity Measures Plans shellfish and finfish | Cefas Biosecurity Measures Plan – Guidance for Shellfish farmers[21]<br>Invasive species management for the construction industry[51] |
| Operation plans | Plans covering a defined short or medium term operation | Planning by the Environment Agency and Port of London Authority for the influx of recreational boats to the Thames for the 2012 Olympics | Risk assessment protocol system for the transfer of mussel seed[58]<br>Event Biosecurity Support Pack[59] |
| Species plans | Plans for the exclusion or containment of an individual species. This plan category also includes rapid response and contingency plans for single species | UK wide contingency planning for the salmon parasite *Gyrodactylus salaris* | Asian Hornet Response Plan[60] |

**Abbreviation:** GB, Great Britain.

and the vectors (ie, specific means by which an invasive species moves within a particular pathway, for example, shipping (commercial and recreational), intentional stock, or aquarium trade movements) to prevent the introduction of NIS from one region to another is paramount in preparing a marine biosecurity plan. In the UK, a study found that the majority of NIS species introduced to British waters since 1850s originated from the North Pacific, particularly the north-west (eg, Asia and Japan) followed by the Northwest Atlantic (eg, east coast of the US).[8] This result is consistent with the findings of previous studies,[61,62] suggesting that NIS from regions with similar temperature regimes to the recipient region are more likely to become established and widespread, as species would be physiologically adapted to the environmental conditions experienced in these waters. Of course, there are always species that are able to tolerate a wide range of environmental conditions (eg, Zebra mussel *Dreissena polymorpha* and tubeworm *Ficopomatus enigmaticus*), enabling them to survive in conditions outside the conditions typically experienced in their native range.[8]

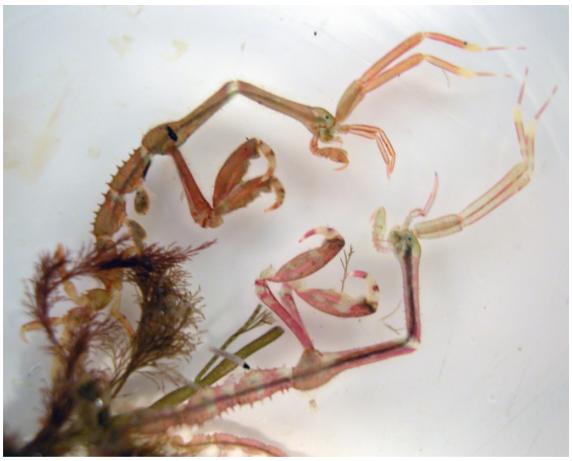

**Figure 1** The Japanese Skeleton Shrimp, *Caprella mutica*.
**Note:** Photo courtesy of E Cook, Scottish Association for Marine Science, Argyll, UK.

**Figure 2** The Japanese wireweed, *Sargassum muticum*.
**Note:** Photo courtesy of E Cook, Scottish Association for Marine Science, Argyll, UK.

There are also a number of species where their introduction into British waters was likely to be a result of secondary spread, where a species is transferred from the initial point of introduction by various more localized vectors (eg, coastal or local shipping, fisheries, stock movements, or by natural mechanisms). For example, the Japanese skeleton shrimp *Caprella mutica* (Figure 1)[63,64] and the non-indigenous bryozoan, *Tricellaria inopinata,*[65] were first recorded in mainland Europe prior to their appearance in the UK and secondary spread via hull fouling and aquaculture activities is likely to have contributed to the rapid expansion of their distribution throughout the region.

Major vectors currently identified for marine NIS include vessels (ballast water and hull fouling – particularly slow-moving vessels, such as barges, semi-submersible oil rigs, or vessels berthed in one place over long periods); aquaculture activities, including intentional stock transfer and unintentional introductions via escapes and hitchhikers;[66–68] the aquarium trade[69] and canals, such as the Suez Canal, which are a major conduit for the spread of alien species between separate biogeographical regions.[70,71] In British waters, where only a single vector was identified, vessels and aquaculture activities were considered responsible for at least 47% and 30% of NIS introductions, respectively.[8] Where the mode of arrival could have been via more than one vector, then vessels and aquaculture activities were still cited as major vectors along with other modes of transmission. The natural spread of NIS, can also be an important vector for the dispersal of certain species (eg, Japanese wireweed, *Sargassum muticum*) (Figure 2) [72,73] and nonindigenous plankton species, although this vector has received significantly less attention to date than ballast water and hull fouling, with the exception of monitoring for the nonindigenous phytoplankton, *Karenia mikimotoi*.[74]

The majority of studies to date have identified the high-risk pathways for a particular geographical region, rather than on a site or operational level, based on literature reviews and expert knowledge. A study identifying the high-risk pathways for the introduction and establishment of marine NIS across the UK and Ireland demonstrated the application of pathway analysis at this wider scale.[62] It is critical, however, that the pathways and vectors are identified and prioritized, based on their potential for transferring NIS, at a site and operation level, so that the high-risk pathways can be reduced or intercepted to remove any NIS.

## Risk analysis

Risk is the likelihood of a harmful event (or impact) occurring, multiplied by the magnitude of the consequences if the event occurs (eg, economic loss, ecosystem damage etc).[75] Conventional risk analysis typically involves three stages, which culminate in risk calculation and evaluation. Each stage includes measures of uncertainty in its results;

1. Likelihood of introduction – Based on the intensity of pathways/vectors previously identified and previous knowledge on major pathways/vectors of introduction for particular groups of NIS, if known.
2. Likelihood of establishment and spread – Based on environmental parameters and the suitability of available substrate in the recipient environment and natural and anthropogenic means of dispersal.
3. Potential impacts – Based on the potential harm that the NIS could cause in the recipient environment.

Risk can be estimated using a variety of methods, from inexpensive qualitative assessments, which can produce subjective results to more expensive semi- and qualitative methods, which focus on specific routes or taxa with known harmful characteristics and require detailed information that does not always exist.[76] The following sections highlight some of the problems experienced in performing these assessments.

## Likelihood of introduction

The greatest "likelihood of introduction" or highest risk is typically where the vector has arrived from another ocean basin in the same hemisphere[8] or from another port/aquaculture site where NIS have been previously identified.[77,78] For example, in the case of the later, the movement of mussel "seed" from an area known to contain the slipper limpet *Crepidula fornicata* in the UK, resulted in the transfer of this nonnative limpet in to an important seabed lay mussel producing region of North Wales.[79] A major issue with this, however, is the lack of baseline data throughout Europe to provide reliable evidence of the presence and distribution of NIS for this analysis.[75] At present, only ten European ports out of 1,200 from 22 coastal Member States have been surveyed and most of these have been comprised of a single survey, which provides an insufficient basis for pathway-risk analysis.[75]

It has also been suggested that regions with experience large volumes of shipping movements (eg, cross-channel ferries, commercial, and recreational vessels) and importation of stock for aquaculture purposes, over many years, are likely to be high-risk sites for NIS introductions.[8] However, a study of 16 large bays in the US, found that there was no relationship between the quantity and frequency of ballast water discharges from foreign vessels and the number of NIS.[80] The volume of ballast water discharges was, therefore, not

considered in a process of risk assessment for ballast water management[75] and although not proven for hull fouling or aquaculture activities, it should be considered that even small quantities of NIS could result in a successful introduction.

## Likelihood of establishment and subsequent spread

The greatest "likelihood of establishment and subsequent spread" of a NIS in a recipient environment will be predominantly based on the environmental characteristics (eg, temperature, salinity, etc) and the availability of suitable substrate at a site, if required, based on the premise that the species will be able to survive the voyage. If environmental conditions are similar to the donor region and suitable substrate is provided, then there is a greater likelihood that NIS will survive and become established.[11,75] In previous risk assessments, based on "environmental matching", a variety of environmental variables have been used,[81–83] however, due to the general lack of baseline data and life history knowledge for many NIS, it was suggested that salinity is the most "straight forward" parameter to use in the process of risk analysis.[75] For example, the likelihood of a marine NIS becoming established in a freshwater environment (<0.5 PSU) is highly unlikely. The likelihood of NIS surviving does increase, however, as the salinity increases, and it has been suggested that as salinity reaches 18 PSU, the likelihood of establishment will increase.[75] For example, the Japanese skeleton shrimp, *C. mutica*, is typically found in fully marine environments (>30 PSU), but a 100% mortality was found at salinities below 16 PSU.[84] There are exceptions though, particularly for brackish water species, such as the Zebra mussel, *D. polymorpha*,[85] and species, such as the Chinese mitten crab, *Eriocheir sinensis*, which migrates from freshwater to marine to spawn and complete their life-cycle.[86]

## Potential impact

The potential impact from NIS is considered to be greater if the species has already been shown to have had a deleterious effect on the environment, economy, human health, property, or resources in another region in which it has been introduced. If the impact has also been considered "severe", then this species could be classified as "high impact".[75] For example, the slipper limpet, *C. fornicata* was classified in a risk assessment commissioned by the GB Non-Native Species Secretariat, as likely to have a "massive impact" both economically and environmentally, effecting fisheries and aquaculture, as well as, significantly modifying habitat and out-competing native species.[87] The main issue, however, is that for many NIS across Europe, there is a distinct lack of understanding of their life history strategies and impacts on native species, thus considerably increasing the "uncertainty" in the process of risk assessment.[88]

Methods for understanding the risks of NIS introduction and establishment are becoming more refined all the time,[66] as critical data gaps are filled via research and documented evidence. Earlier work assessing the risk of NIS in aquaculture at a European scale is a good example of this.[67] However, with so many "unknowns" and the difficultly in determining the potential "harmfulness" of a particular species, it has been suggested that a precautionary approach must be adopted, treating all known and suspected NIS as potentially harmful and equally unwanted.[89]

One particular method of assessment, Hazard Analysis and Critical Control Point (HACCP) planning, however, has been produced that enables the production of biosecurity plans for specific activities and has been applied to managing the risk of spreading NIS between water bodies.[90] HACCP was originally created for the food standard industry.[90] This procedure takes each activity on a site or within a wider operation, looks at it in detail and breaks it down into a series of tasks. At the heart of HACCP is the precautionary principle, so the method of risk calculation, which follows as the next stage in the process, does not attempt to ascribe a value or rating to the severity or the potential impacts. The likelihood of invasion is considered, but the emphasis is not on the overall risk, but on developing control measures for each activity to prevent the spread of NIS and defining the Critical Control Points when they are best applied.

These control measures are actions that can be used to reduce the probability that NIS may be introduced to a new area. To ensure that such control measures are functioning as intended, it is important to attach a set of measurable prescribed ranges, limits, and/or criteria for control measures and detail corrective actions to use to safeguard against any mishaps.

The development of effective control measures, however, does require the pooling of resources from a number of sources. Perhaps the most important of these are informed personnel with the practical knowledge of the process involved in the activity, along with any constraints imposed. Knowledge of existing preventive measures required by law is also essential to include in control measures listed. A degree of specialized knowledge of potential nontarget species is also required. Such knowledge might include the range

of certain conditions that undesirable species can tolerate. Applying this type of information to the control measures included as part of the biosecurity plan greatly strengthens its effectiveness. HACCP has already been used as the basis for pathogen biosecurity and NIS in mariculture.[58] It could be simplified and combined with pathway management to become the basis for marine biosecurity planning at a site and operation level.

## Contingency and rapid response plans

The need to be prepared to act if biosecurity measures for NIS fail has been widely acknowledged and should be included in biosecurity plans. Rapid response and contingency plans have been produced, drawing partly on experience from the response to pathogen threats, such as foot and mouth disease and avian influenza, and environmental threats such as oil spill planning. In practice, most rapid responses to the discovery of NIS are actions which get under way immediately and planning the activity only follows at a later stage if the process starts to stretch into the longer term.[91–93]

## Practical marine biosecurity measures

Various practical measures have been undertaken to reduce the likelihood of a NIS being introduced or spreading from a site of introduction. These measures have predominantly used freshwater as either a preventative measure or as a control (ie, through washing of structures). However, aerial exposure, chemicals, smothering, and mechanical-based measures have also been used, depending on the particular activity.

### Freshwater source

The proximity of the site/operation to a freshwater source can significantly influence the likelihood of the successful establishment of a marine NIS. Studies have shown that many marine NIS have a broad tolerance to temperature, but will only tolerate a much smaller salinity range.[94] For example, the Japanese skeleton shrimp, *C. mutica,* has been found to tolerate temperatures ranging from 2°C to 20°C, whereas high mortalities are experienced when salinities fall to 16 PSU.[95] It is, therefore, likely that a large proportion of marine NIS associated with shipping (ie, transported either in ballast water or as hull fouling), will be excluded from sites with high freshwater input.[95] In a survey of 88 UK marinas which contained NIS, high freshwater input into the marina basin was highlighted as a significant feature in reducing the likelihood of NIS establishment. More specifically marinas located within 20 m of a freshwater source had significantly fewer NIS than those sited over 1 km away.[96]

### Removal and prevention of biofouling

NIS are highly opportunistic and robust, surviving for extended periods of time in the hostile environment of a ballast tank[97] or out-competing native species in highly disturbed environments on a wide variety of artificial structures, as native species are often poorly adapted to the altered physical and biological environment both on and around these man-made objects.[98] Ballast water, vessel hulls, floating pontoons, navigation buoys, fin- and shell-fish cultivation infrastructure are particularly prone to inoculation by NIS,[99] as they all provide a unique habitat for a variety of reasons, including isolation from surrounding waters or seabed, novel materials (eg, plastics), and shading.[100] The Japanese skeleton shrimp, *C. mutica,* for instance, occurs in exceptionally high densities on artificial structures such as pontoons and aquaculture infrastructures, which are raised from the seabed where they are able to avoid benthic predation pressure.[95] The likelihood of the successful establishment of a NIS, therefore, would be significantly increased by a reduction in the duration of the passage time or the presence of artificial structures. Therefore, any design features or maintenance practices that prevent the survival of NIS in ballast water and the accumulation of bio-fouling or can remove fouling from these artificial structures, without causing unintentional dispersal of the NIS, would reduce the risk of NIS establishment and spread.[45,52,101]

### Aerial exposure

Aerial exposure is a practical measure that has been shown to successfully remove biofouling, including NIS from a wide variety of artificial structures for many years.[102] Novel designs, such as rotating pontoon floats are currently being trialed in North Wales, which would allow surfaces exposed above the water line to be air dried in sections for prolonged periods, thus killing the any fouling organisms attached to the floats.[52] Locking pontoons are also in the conceptual phase. These could be "locked" at the top of high tide, exposing the underside of the pontoon surface to the air when the tide drops.[52] In addition, modular structures, which can easily be removed for air drying would also provide a practical solution for reducing the risk of NIS establishment.

## Jet washing

Artificial structures that can be removed from the water, such as vessels, pontoon floats, navigation buoys, and aquaculture infrastructure can be jet washed, preferably with fresh water to remove any biofouling. To minimize the likelihood of spreading NIS, any washing must be done in an appropriate enclosed area where there is no risk of runoff reaching the sea and that all debris is safely disposed of according to guidelines for biological waste. It is paramount that any washing is done on land and that the "in-water" cleaning of anything beyond a light algal coating on the structures is discouraged, as certain NIS damaged by physical abrasion may be induced to spawn, while others can survive being dislodged or broken into fragments.[72,103,104]

## Chemical treatments

Chemical treatments, such as biocides, chlorine, ozone, hydrogen peroxide, chlorine dioxide, acetic acid, etc, have been used to directly and indirectly treat for NIS. For example, a "BioBullet" in which the biocide is encapsulated within a particle that is ingested by the NIS has been successful at eradicating the Zebra mussel *D. polymorpha* and the sea squirt *D. vexillum*[105,106] from enclosed environments. Chemical treatments have also been used to indirectly eradicate NIS, either via addition to ballast water or by the spraying or dipping of aquaculture infrastructure and stock.[107,108] Dipping seed mussels, coated with a nonnative sea squirt *Didemnum* spp., in a 0.5% solution of bleach for 2 minutes was a 100% effective method of treatment for the invasive sea squirt and it left the mussels relatively unaffected.[107] Trials in New Zealand, also found that acetic acid sprayed over a colonial sea squirt, *Eudistoma elongatum*, was particularly effective at removing the sea squirt from oyster racks exposed at low tide. Spraying or immersion of infested structures with a saturated solution of hydrated lime (calcium hydroxide) or 5% acetic acid was also effective against the invasive solitary tunicate, *Styela clava* in Prince Edward Island, Canada, which grows in dense aggregations on mussel lines and oyster racks.[108] The dipping of dredged oysters, and associated species, in saturated or strong salt solutions is also a cheap, safe, and effective treatment for nonnative sea squirts and the macroalga, *Sargassum muticum* without harming the oysters.[109] The main drawback of using certain biocides, however, is their potential effect on nontarget organisms within the wider environment and, therefore, careful regulation of their use is required.[108]

## Enclosure of artificial structures

For structures that are fixed to the seabed, or are unable to be removed from the water for logistical or other reasons, then enclosure with plastic film/bags has been shown to be effective at removing biofouling, including NIS.[52,110] The enclosure technique prevents a supply of clean water to the biofouling and smothers it through lack of oxygen. A chemical accelerant has been found to be effective at reducing the application time, such as sodium hypochlorite, acetic acid, chlorine, or freshwater for the invasive carpet sea squirt *D. vexillum*.[106,107,111] The freshwater method is considered particularly effective though, since it reduces any risk of spillage and effect on the environment.[106] On a much larger scale, this enclosure technique is currently in the developmental phase for the pontoon floats of semi-submersible oil rigs and associated supply vessels in New Zealand.[112]

## Site enclosure

For sites, such as harbors, marinas, and canal systems, which have their own lock gates, then there have been examples where the gates have been closed to allow for the rapid isolation and eradication of NIS. For example, when a nonnative bivalve *Mytilopsis* sp. was identified in three Australian marinas, all the sites were quarantined by closing their lock gates and treated rapidly using chemicals, allowing the invasive species to be eradicated before it became established in a more open environment.[92] This follows a similar procedure used to successfully eradicate fresh and brackish water NIS from enclosed bodies of water, such as flooded quarries, reservoirs, and cooling pipes.[105,113] As illustrated by the £4.2 million project at Bury Marina, Wales, although it is a costly process, it is also possible to adapt existing enclosed harbors and marinas to have lock gates.[114]

## Mechanical clearance

Filtration is the most commonly used treatment for the removal of NIS from ballast water, and it can be accomplished during ballasting operations using a shipboard filtration system. The physical separation and removal of organisms can be undertaken either whilst loading ballast water or during the voyage. Cyclonic separation can also be used. Depending on the design and application, the hydrocyclones require less pump pressure than screen filters and allow separation of sediments and other suspended solids to approximately 20 µm.[115] A combination of filtration and cyclonic separation have been shown to be over 90% effective at removing micro- and macro-zooplankton from the ballast water. However, phytoplankton removal was only 30% effective.[116]

Following the unintentional introduction of the slipper limpet, *C. fornicata*, to the Menai Strait, North Wales with seed mussels from a site in the English Channel in 2006, a successful eradication of this species was undertaken. This procedure involved; the removal of the mussel lay and as much of the associated material as practicable by dredgers, followed by the smothering of any remaining *C. fornicata* in the affected area, with a dense layer of mussels sourced from an unaffected area. As this species is unable to either burrow or reposition themselves once covered, it was highly unlikely that they would survive the smothering. Subsequent monitoring surveys have since found no sign of live limpets.[91]

The mussel industry in New Zealand has also found that the mechanical stripping, grading, and restocking process that occurs between 6 and 12 months in the growth cycle is sufficient to control the growth of fouling organisms, including invasive tunicates. Occasionally, this process has had to be repeated later on in the cycle if a NIS is particularly abundant, but farms are generally reluctant to do this due to cost and difficulties in getting the larger mussels to reattach securely to the lines (B Forrest, personal communication, 2013). In Ireland, the rope-grown mussel industry has also successfully conducted a removal program during the grading and harvesting process, when small quantities of the invasive sea squirt *D. vexillum* was found on the mussel ropes.[106]

## Anti-fouling systems

Once the surfaces have been cleaned of fouling, paints are generally applied to vessel hulls and finfish aquaculture cage netting which contain antifouling biocides.[117] These paints prevent the settlement and growth of fouling organisms through the continual leaching of biocides, predominantly heavy metals such as copper and zinc into the surrounding water.[118] Although such antifouling paints have proven to be effective, factors such as paint age, damage, or areas left unpainted can significantly decrease their efficiency. Studies have shown that paint age can have a significant influence on biofouling communities, with older paint allowing the establishment of greater quantities of fouling.[119] Unpainted surfaces, such as those that evade actual paint coverage, eg, regions covered by support frames whilst the vessel is in dry dock and niche areas such as the propeller shaft, may allow sufficient area to facilitate biofouling.[120] In addition, minor failures (<0.5 cm wide) in the anti-fouling system, as a result of accidental damage during daily operations (eg, anchor damage, vessel groundings or minor collisions) can also lead to the rapid establishment of fouling species, including NIS on the unprotected areas.[120] The application of anti-fouling paints to structures that are likely to remain in the water for extended periods of time, following manufacturers', guidelines should be promoted by government agencies to reduce the likelihood of NIS establishment.

## Continuous surveillance and monitoring

Continuous surveillance and monitoring for NIS will allow for the early identification of an introduction event at a particular location and to provide reliable baseline data on the presence and distribution of a particular species.[75] This is vital, as the management options to eradicate or mitigate the impacts of NIS decreases over time as populations become established and spread.[98] It has been found that within as little as 6 months between surveys, a new NIS can establish and rapidly colonize a site. [92]

The standardization of sampling protocols, however, still needs to be improved between countries to enable the generation of reliable and comparable results.[75] In Australia and New Zealand, extensive surveys have been completed since the early 2000s in both international and domestic ports, including plankton, sedentary encrusting and benthic species and mobile species following the protocols developed by the Australian Centre for Research on Introduced Marine Pest for baseline surveys of NIS in ports.[121] These protocols have since been adopted by the IMO's Global Ballast Water Management Programme and variations of this protocol have been applied to port surveys in many other countries.[122] These surveys, however, are expensive and require expert taxonomic knowledge to complete. A cheaper, more targeted rapid assessment approach, in combination with a pre-survey literature review, has been used successfully for fouling NIS in marina surveys in the US,[123] UK,[124] and Ireland.[125] This approach, however, still requires expertise in taxonomic identification.

In addition to monitoring the site itself, closely monitoring the pathways of introduction (ie, vessel and stock movements) is also crucial in preventing the introduction of NIS. The aquaculture industry, already has a requirement to log any stock movements to restrict the spread of disease,[20,21] however this needs to be expanded to include NIS. The IMO voluntary guidelines for the control and management of ships' biofouling also include the requirement for each commercial[126] and recreational[127] vessel and associated industries (ie, shipbuilders, ship repair yards etc) to complete a biofouling management plan and record book, detailing anti-fouling systems used, their maintenance and inspection history, plus any periods when the vessel has been laid up or inactive for extended periods of time. However, as these IMO guidelines

are only voluntary, there is little evidence yet of their update by vessel owners.

In the meantime, one approach that has been developed for quarantine personnel in New Zealand was a ranking scale used to quantify hull fouling on recreational vessels entering from international waters.[103] This enables staff with minimal taxonomic expertise and training in the approach, to distinguish from a brief visual inspection of the hull from the surface, between vessels that carry, no, sparse or extensive fouling on their hulls. The staff member can then allocate each vessel a rank of 0–5 on arrival and those with a fouling rank of >2 (ie, small patches of macrofouling), can then be subject to further biosecurity measures.[103]

## Conclusion and future directions

Biosecurity is critical if the exponential increase in the spread of NIS around the world over the last few decades is to be tackled. National biosecurity plans have been produced by the UK and New Zealand, however, site-specific NIS plans are rare. With the introduction of new regulations and guidance in Scotland, a regulatory driver has been introduced for the first time to encourage maritime operators to produce their own biosecurity plans. It is crucial to encourage other countries to adopt a similar regulatory framework as Scotland to address the issue of NIS biosecurity.

The need to understand the pathways of invasion and the vectors which transport NIS from region to region, to be prepared to act rapidly if planned biosecurity measures fail and to undertake continuously monitoring, is also paramount in preparing a biosecurity plan and successfully preventing the introduction of NIS. The EU Regulation on Alien Invasive Species will enable Member States to critically evaluate pathways and vectors for a SUC, however, the impacts of many marine NIS are still either unknown or poorly understood leading to a high degree of uncertainty in the process of risk assessment. This can only, therefore, be addressed with further research on the environmental, as well as the socio-economic impacts that marine NIS may have on an introduced region.

Maritime operators can also undertake preventative measures to reduce the risk of NIS introduction, either through effective ballast water treatment and/or the prevention of biofouling accumulation on submerged structures. Increasing the efficacy of ballast water treatment to reduce filtration times, the development of novel in-water cleaning techniques, prolonging the effectiveness of anti-fouling systems on static and mobile structures and improving taxonomic expertise are all key challenges for the future.

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