Chapter 22
Invasive species

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Keynote points

- Globally, about 2,000 marine non-indigenous species (NIS) have been introduced to new locations through human-mediated movements. A few of those have economic value, but most have had negative ecological, socioeconomic or human health impacts. With increased trade and climate change, biological invasions are likely to increase.
- NIS can pose significant biosecurity and biodiversity hazards. Large-scale NIS surveys with broad taxonomic coverage are lacking, as are studies documenting the range of potential impacts in recipient environments.
- Major invasion vectors (i.e., ballast water, biofouling, aquaculture, trade in live specimens, canals and plastic or other debris) lack characterization and understanding at the global, and often regional, levels and, other than for the management of ballast water and sediments, there is an absence of regulation. Given the multi-vector nature of both the introduction and the spread of NIS, there is a need for comprehensive and integrated legal instruments with robust enforcement to mitigate the movement of species and holistic monitoring programmes that can detect them.
- Better tools are urgently required to assess the potential risks of NIS under changing environmental conditions, to identify the native species and ecosystems most at risk and to determine the best way to respond (i.e., through early detection and rapid response). That is especially true for species with no previously documented invasion history.

1. Introduction

Invasion by non-indigenous species (NIS) is a major driver of biodiversity change that can reduce biodiversity, alter community structure and function, diminish fisheries and aquaculture production and impact human health and well-being. It is exacerbated by climate change, including extreme events, and other human-induced disturbances (Bax and others, 2003; MEA, 2005; Ojaveer and others, 2018). NIS are those species, including microbes, that have overcome a natural dispersal barrier to become established in a new biogeographical area outside their native range as an intentional or unintentional result of human-mediated activities (Carlton, 1999). Those species can then spread in the newly invaded area, either naturally or by means of additional human-mediated activities, through a wide range of invasion vectors (i.e., the physical means by which individuals are moved, including biofouling, aquaculture, trade in live specimens and canals) (Carlton and Ruiz, 2005; Richardson and others, 2011). Invasion pathways represent a combination of processes and opportunities that allow individuals to be moved from a source location to a recipient (non-native) one and include some elements of invasion vectors (the term "invasion pathway" has sometimes been used interchangeably with "invasion vector") (Carlton and Ruiz, 2005; Richardson and others, 2011). Species that undergo distributional changes owing to ecosystem regime shifts or in response to climate change in their native range are not considered to be NIS, and neither are cryptogenic species (those whose native range is unknown) (Carlton, 1996). A subset of all NIS, often identified as "invasive alien species", have significant biological, economic or human health impacts (Williamson, 1996; UNEP, 2002). Given that it is often impossible to predict which NIS will become invasive in which area and under which circumstances, the precautionary approach has been followed in the present chapter, which therefore covers all NIS from marine and estuarine systems.

NIS are drivers of change in invaded ecosystems. They are influenced by the ecosystems that they are invading and the activities and events that have allowed them to be moved from their native range. Moreover, there is increased recognition that NIS are a critical component of multiple stressors, especially in coastal marine habitats, and that developments in the global economy and improved transportation are contributing to the spread of NIS (MEA, 2005). Marine ecosystems that are already stressed or degraded as a result of other human-caused impacts, such as overfishing, eutrophication, ocean acidification and habitat alteration, have been shown to be favourable to the establishment of NIS (Crooks and others, 2011). Thus, changes in native biodiversity (including in relation to species included in the appendices to the Convention on International Trade in Endangered Species of Wild Fauna and Flora),[1] productivity (including fisheries), harmful algal blooms and ecosystem structure and function (chaps. 6, 7, 10 and 15) can all directly affect marine invasion success, including where NIS are pathogens. In addition, expected increases in artificial habitats (chap. 14) that allow fouling species to become established in otherwise unsuitable environments may facilitate the introduction and the spread of NIS, the range of which is also extended by human-mediated activities such as marine transport and shipping, aquaculture- and fishing-related movements and stocking, habitat restoration, canals and diversions, marine debris and litter (especially plastics, which do not degrade rapidly and can thus persist as a transport vector) and research activities (chap. 16) (Ruiz and others, 1997; Carlton and others, 2017; Galil and others, 2018; Therriault and others, 2018).

NIS have the potential to affect, directly or indirectly, the biota and ecosystems that support healthy and productive human communities. Although NIS unintentionally introduced or escaped to the wild after an intentional introduction have been occasionally exploited (e.g. the Pacific oyster (*Crassostrea gigas*), the Red Sea prawn (*Penaeus pulchricaudatus*), the Asian tiger shrimp (*P. monodon*), the blue swimming crab (*Portunus segnis*) and the Manila clam (*Ruditapes philippinarum*)), the longer-term impacts tend to be negative, with reduced native diversity. Impacts also extend to coastal communities, directly or indirectly, by reducing the overall productivity and resilience of marine systems that traditionally support sustainable fisheries or aquaculture (Molnar and others, 2008; Schröder and de Leaniz, 2011).

For an improved understanding of invasions at the global scale, there is a need for validated, detailed georeferenced inventories of NIS accessible in searchable databases that can be used to better understand the distribution of such species and the potential mechanisms by which their range is extended. Currently, there is limited, incomplete or no understanding of NIS in many locations around the world, including in relation to the date of their first arrival (or detection) and the likely introduction vectors. Although progress has been made in terms of biodiversity assessments (Costello and others, 2010; Narayanaswamy and others, 2013), especially with advances in molecular techniques (Darling and others, 2017), critical gaps remain with respect to NIS. Specifically, not only does the taxonomy need to be fully resolved for each species, especially where NIS and sibling native species overlap, but an understanding of the native range of such species is also required. Similarly, there is a need for an improved geospatial and temporal understanding of invasion vectors and pathways. Although some regional studies have been conducted in relation to ballast water, there is

1 United Nations, *Treaty Series*, vol. 993, No. 14537.

in general limited information on the NIS transported by many invasion vectors. In addition, there is an incomplete understanding of, inter alia, the characteristics, routes, frequency and intensity of important invasion pathways. Collectively, such information is essential to inform NIS policy and management.

2. Documented baseline and changes in non-indigenous species

Since the first *World Ocean Assessment* (United Nations, 2017) did not contain a formal assessment of the status of NIS and related trends, it is not possible to evaluate changes since its publication. However, there are multiple lines of evidence confirming that NIS continue to spread globally, with new introductions reported in new locations, as a result of a general lack of management and control. Although the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004,[2] came into force in September 2017 (International Maritime Organization (IMO), 2019), the degree to which it has been implemented globally and its effectiveness in reducing marine invasions at the regional level are not clear. However, the current experience-building phase may provide important information for future assessments. Similarly, some States have implemented the International Council for the Exploration of the Sea (ICES) Code of Practice on the Introductions and Transfers of Marine Organisms (ICES, 2005) to reduce the threat posed by NIS when intentionally introduced to new areas for cultivation, but invasions have still occurred. Recognizing the growing importance of hull fouling as a vector, ICES has recommended four actions to evaluate and mitigate biofouling introductions (ICES, 2019). However, there are still many invasion vectors that are not globally regulated at present (see below).

Globally, the information available on NIS is quite variable spatially, temporally and taxonomically. NIS are not routinely surveyed or monitored in many locations. There are also strong biases in the breadth and depth of taxonomic coverage and expertise, with significantly better information available on larger, more conspicuous species (i.e., fishes and large crustaceans) than on smaller, less conspicuous ones (i.e., worms and other small invertebrates).

It is important to note that the consequences of marine invasions can take a considerable time to manifest and are notoriously difficult to quantify. There are often time lags between when an NIS is introduced to a new location and when the species is detected or impacts are noted. Furthermore, important pre-invasion baseline data are often not available. Thus, it is difficult to attribute observed ecosystem changes to NIS specifically, especially when so many other external stressors are affecting marine ecosystems. However, if global or regional baseline inventories are established, as suggested by Tsiamis and others (2019) for European Union countries, it will be possible to gain a better understanding of both the changes in NIS over space and time and their impacts on ecosystems and human well-being, recognizing that critical validation of those inventories will be required to ensure that they are fit for purpose. The first comprehensive region-specific analysis of baseline status and trends for multiple taxonomic groups is provided below (see sect. 4).

2 International Maritime Organization, document BWM/CONF/36, annex.

3. Consequences for human communities, economies and well-being

Not only do NIS affect the realization of Sustainable Development Goal 14 (Conserve and sustainably use the oceans, seas and marine resources for sustainable development) by contributing to the degradation of coastal habitats and the ecosystem goods and services associated with them, but they may also directly or indirectly affect that of many other Goals[3] (see International Council for Science (ICSU) and others, 2017). The achievement of Goal 1 (End poverty in all its forms everywhere) may be hindered by the continued spread of NIS that negatively affect fisheries and aquaculture directly or indirectly by altering the structure and function of ecosystems, especially in the case of small island developing States and least developed countries, which lack NIS regulations, policies, and monitoring and early detection and rapid response plans. Similarly, NIS could jeopardize the achievement of Goal 2 (End hunger, achieve food security and improved nutrition and promote sustainable agriculture) by compromising seafood safety and security by means of the same mechanisms. In many cases, NIS, especially those with the potential to affect human health, can be considered as a biological contaminant. Thus, the continued global spread of NIS, especially human pathogens such as *Vibrio cholerae*, also affects the achievement of Goal 3 (Ensure healthy lives and promote well-being for all at all ages). Some NIS have the potential to dramatically alter marine coastal environments and communities and, as such, could negatively influence the achievement of Goal 6 (Ensure availability and sustainable management of water and sanitation for all). There is growing evidence that many biofouling marine NIS are able to exploit anthropogenic structures, including docks, oil platforms and wind farms. As growing energy demands result in the development of coastal and offshore infrastructure, NIS could also hinder the achievement of Goal 7 (Ensure access to affordable, reliable, sustainable and modern energy for all). Sustainable growth in fisheries and aquaculture could be compromised in areas where NIS continue to spread unchecked. Thus, NIS also have the potential to compromise the achievement of Goal 8 (Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all) and Goal 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation).

Good ocean governance, associated with Goal 16 (Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels) could play an important role in improving the understanding of marine NIS and their impacts globally. Such governance could include the development of a reporting framework or database that would allow the ever-changing distributions of NIS to be documented, so as to allow informed management or policy development in areas beyond national jurisdictions. Furthermore, there are many marine ecosystems in respect of which even basic information on NIS is lacking (see sects. 2 and 4). In that regard, global partnerships and capacity-building may be possible under Goal 17 (Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development). If progress on achieving the Sustainable Development Goals is slow, then the spread and impacts of NIS could be exacerbated. For example, without progress on Goal 13 (Take urgent action to combat climate change and its impacts), the few marine

[3] See General Assembly resolution 70/1.

ecosystems that currently have only a limited number of NIS, such as the Arctic Ocean and the Southern Ocean (see sect. 4), are likely to see invasions proceed at a much faster rate as those environments become more suitable for a wide variety of taxa, and abiotic and biotic barriers to invasion are degraded or removed.

NIS are also addressed by other global policy documents, especially those pertaining to biodiversity, given the negative relationship between the two. For example, the Convention on Biological Diversity[4] recognizes the threat of NIS and article 8 (h) thereof provides that each contracting party shall, as far as possible and as appropriate, prevent the introduction of, control or eradicate those alien species that threaten ecosystems, habitats or species. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has also recognized the negative impacts of NIS around the world and has started a process for the assessment of those species.

Some NIS have the potential to impair human health and well-being. For example, introduced *Vibrio* bacteria and harmful algal species (dinoflagellates, diatoms and cyanobacteria) that create toxins can have a negative impact on marine biota and human consumers. Their effects are expected to worsen as they benefit from climate change (Ruiz and others, 2000; Paerl and Huisman, 2009). In the highly invaded Mediterranean, nine venomous and poisonous NIS from the Indian Ocean or the Western Indo-Pacific pose human health risks (Galil, 2018). In addition, the Indo-Pacific lionfish *Pterois volitans* produces a toxin that is dangerous to humans, although it rarely results in death. However, only fragmentary information is available concerning the spatial and temporal trends in those impacts on human health, as underdiagnosis and underreporting hamper the quantitative assessment of the global incidence of medically treated cases, and ignorance of the extent and severity of, and trends in, those emerging public health risks may hinder risk analyses.

Some NIS, whether introduced intentionally or not, have provided economic benefits, but there is often a trade-off between such benefits and the ecological consequences. For example, the Pacific oyster has been introduced in coastal environments around the world, including in North America, South America, Africa, Australia and Europe, resulting in economic opportunities with global production in excess of 4 million tons (Shatkin, 1997; Food and Agriculture Organization of the United Nations (FAO), 2019). However, in many places, that species has spread beyond culture locations and has had a negative impact in some areas on native biodiversity and ecosystem functioning, and human well-being (Molnar and others, 2008; Herbert and others, 2016). The Atlantic salmon (*Salmo salar*) has also been used to create economic opportunities in countries around the world, but large-scale escape events can have negative ecological and socioeconomic impacts (Schröder and de Leaniz, 2011). In the Barents Sea, the red king crab (*Paralithodes camtschaticus*) was introduced intentionally for fisheries but has rapidly spread to adjacent waters and increased in abundance, thus creating conflicts among various user groups and having a negative impact on biodiversity and ecosystem functioning, especially in coastal fjords (Falk-Petersen and others, 2011). The establishment of fisheries of NIS has longer-term implications, especially given the push to ensure that fisheries are sustainable. Furthermore, some NIS, such as the salt marsh grass (*Spartina alterniflora*), which was intentionally introduced to China as an ecosystem engineer, have significantly changed the ecosystems that they have invaded (Wan and others, 2009). Schlaepfer and others (2011) suggest that some NIS may provide ecological or conservation benefits, but predicting those is often complex and dependent on context.

[4] United Nations, *Treaty Series*, vol. 1760, No. 30619.

4. Key region-specific baselines, changes and consequences

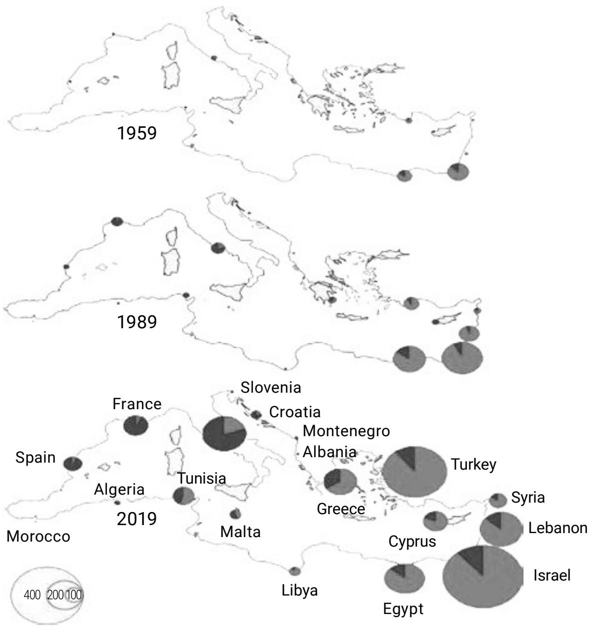
4.1. Arctic Ocean

Although basin-wide assessments of NIS in the Arctic Ocean are lacking, there appear to be relatively few invaders at present (Molnar and others, 2008; Chan and others, 2013). However, with rapid environmental changes, including increased temperatures and reduced sea ice, those waters could become suitable for a number of potential invaders in the future (Ware and others, 2016; Goldsmit and others, 2018). Furthermore, those environmental changes could lead to changes in the presence of human-mediated invasion vectors in the Arctic Ocean, especially marine transport, which could result in increased propagule pressure in the future (Miller and Ruiz, 2014).

4.2. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

The Mediterranean has a long history of invasions, with 22 NIS recorded before 1900 (Galil, 2012). By the early 2000s, country-level NIS inventories had been initiated and, as of 2011, a total of 787 NIS were listed as being present in European Union marine waters (Macaronesia included), with the highest number (242) reported in the western Mediterranean (Tsiamis and others, 2019; see also Gómez, 2019, regarding 52 microalgal species). However, the omission of data from the eastern and southern Mediterranean induced a major bias, since the number of NIS is substantially greater in the eastern than in the western Mediterranean (over 400 NIS recorded along the coast of Israel alone). There are 727 metazoan NIS in the entire Mediterranean, and the number is rapidly increasing (Galil and others, 2018) (see figure below), while, as of 2018, 173 NIS and cryptogenic species had been reported in the Black Sea. Despite the growing awareness of the role played by the Suez Canal in Mediterranean invasions, measures to mitigate probable NIS propagule increases have yet to be considered for the "New Suez Canal" project, which was launched in 2014 to substantially increase the depth and width of the original canal (Galil and others, 2017). Thus, the main invasion vectors for the Mediterranean include the introduction of Red Sea biota through the Suez Canal; shipping, both commercial and recreational; mariculture; and the aquarium trade. Although the latter vectors contribute fewer NIS, some have had disproportionate impacts, including the green alga (*Caulerpa taxifolia*) introduced with aquarium spillover (Meinesz and Hesse, 1991) and the brown alga (*Fucus spiralis*) introduced in the packaging of fishing bait (Sancholle, 1988).

Changes in non-indigenous species reports over time for the Mediterranean



Source: Agnese Marchini and Bella Galil.
Note: Red indicates species introduced through the Suez Canal and blue represents species introduced by other vectors.

Since the beginning of the twenty-first century, the apparent rate of introductions into the Baltic Sea has been 3.2 species per year, almost twice as high as the 1.4 species per year recorded between 1950 and 1999 (ICES, 2018). Ballast water and hull fouling are the main vectors for primary introductions, followed by the natural spread of NIS introduced by rivers and the North Sea. Most NIS in the Baltic Sea originate from North America, the Ponto-Caspian region and East Asia but introductions of subtropical NIS have recently been increasing, such that a total of 174 NIS and cryptogenic species have been recorded in the Baltic Sea (AquaNIS, 2019; Ojaveer and others, 2017; ICES, 2018). However, there remains considerable uncertainty about the direction and magnitude of the impacts of even the most widespread NIS on the structure and dynamics of Baltic Sea ecosystems (Ojaveer and Kotta, 2015).

Although there is some overlap in the studies, NIS reported in the eastern Atlantic include at least 80 species in the North Sea (Reise and others, 2002); 90 in waters around the United Kingdom of Great Britain and Northern Ireland (Minchin and others, 2013); 104 in French Atlantic waters (Goulletquer and others, 2002); and more than 100 in the English Channel (Dauvin and others, 2019). There are at least 189 NIS reported in the western Atlantic (Ruiz and others, 2015) but their number is likely to be higher. For policy and management, validated regional lists are required.

4.3. South Atlantic Ocean and Wider Caribbean

Records of NIS in the South Atlantic Ocean and Wider Caribbean are incomplete both spatially and temporally. The earliest historical compilations are from South Africa, where 12 NIS were reported in the early 1990s, including two global invaders, the European green crab (*Carcinus maenas*) and the blue (Gallo) mussel (*Mytilus galloprovincialis*) (Griffiths and others, 1992). Mead and others (2011) reassessed NIS occurrences in the region and identified 86 NIS, singling out ballast water and ship fouling as the main vectors. Apart from South Africa, the South-East Atlantic coast remains largely unstudied with regard to NIS, although a recent study from Angola reported 29 NIS (Barros Pestana and others, 2017). In the South-West Atlantic, the earliest compilations, which were for Argentina and Uruguay, identified 31 NIS, including one intentionally introduced species (the Pacific oyster) (Orensanz and others, 2002). A recent reassessment for that region identified more than 120 NIS from diverse taxonomic groups (from viruses to plants and fishes), including 33 new detections since 2002 (Schwindt and others, 2020) and, as in the case of South Africa, ships were the main vector for species introductions. The most recent surveys from Brazil identified 73 NIS (Lopes and others, 2009; Teixeira and Creed, 2020), along an extensive coastline with a long history of shipping, which suggests that that number could be underestimating the true richness of NIS. A data gap exists for the North Atlantic coast of South America (from French Guiana to Guyana), where there has been little attention to NIS (Schwindt and Bortolus, 2017), and no extensive compilations are available for the wider Caribbean region, although smaller-scale information is available for the Bolivarian Republic of Venezuela, where 22 NIS have been identified (Pérez and others, 2007), and Colombia, with 16 NIS recorded (Gracia and others, 2011). The lionfish *Pterois volitans* is one of the most problematic and studied NIS in the Caribbean region. Similarly, two invasive sun corals, *Tubastraea coccinea* and *T. tagusensis*, have spread rapidly in the tropical Western Atlantic and the Gulf of Mexico, outcompeting, overgrowing and replacing native corals (Creed and others, 2017).

4.4. Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Regional records of NIS are incomplete, both spatially and temporally. Despite the size and diversity of the Indian Ocean, studies on marine NIS in that area are scarce, mostly qualitative and geographically scattered, resulting in significant knowledge gaps (Indian Ocean Commission, 2016). For example, two red algae (*Eucheuma denticulatum* and *Kappaphycus alvarezii*) native to the Philippines were introduced for mariculture along the East African coastline (Kenya, Mozambique and the United Republic of Tanzania), resulting in deleterious impacts (Bergman and others, 2001; Halling and others, 2013). *K. alvarezii* was also introduced along the western coast of India and has spread into the Gulf of Mannar Biosphere Reserve, where it has had an impact on native corals (Chandrasekaran and others, 2008). As elsewhere, intentional introductions have been attributed to mariculture activities developed to address food insecurity and to the aquarium trade, for economic benefit, while unintentional introductions are mostly due to maritime shipping activities or transport on floating objects (Indian Ocean Commission, 2016; Anil and others 2003).

4.5. North Pacific Ocean

The North Pacific Ocean is large and biogeographically diverse and, as in other regions, NIS reporting is incomplete. However, as of 2012, at least 747 NIS had been reported in the 23 ecoregions studied (which include Hawaii, United States of America, and the northern Central Indo-Pacific), a similar number to that reported in the Mediterranean. More than 70 per cent of those NIS belong to four phyla, namely, Arthropoda (224), Chordata (tunicates and fishes) (114), Mollusca (110) and Annelida (89) (Lee and Reusser, 2012; Kestrup and others, 2015). While 32 per cent of them were native elsewhere in the North Pacific Ocean, 48 per cent were native to regions outside the North Pacific Ocean and 20 per cent were cryptogenic (Lee and Reusser, 2012; Kestrup and others, 2015). The North-East Pacific (368 NIS) and Hawaii (347 NIS) had similar numbers of invaders, while lower numbers were observed in the North-West Pacific (208) and the northern Central Indo-Pacific (75), possibly owing to different levels of sampling effort. Furthermore, it is important to note that, as there is no systematic survey effort in at least 27 other ecoregions in the North Pacific Ocean, predominately in South-East Asia (Spalding and others, 2007), the number of NIS is expected to be higher for the North Pacific Ocean as a whole. Some more comprehensive studies have been conducted at smaller spatial scales or focused on specific taxonomic groups. For example, there are at least 6 planktonic and 10 algal NIS in the Bohai Sea and port locations in China (Qiao, 2019) not previously reported in baseline surveys (Liu, 2008; Wang and Li, 2006), and San Francisco Bay has more than 234 NIS (Cohen and Carlton, 1998).

As in the case of other regions, ballast water discharges, hull fouling, intentional stocking, aquaculture escapes, aquaculture-associated species and the aquarium and plant trade were all important vectors for the North Pacific. Intentional stocking and aquaculture escapes were more prominent vectors in the North-West Pacific than in the North-East Pacific or Hawaii, which probably reflects the larger scale of aquaculture efforts in Asia. Another difference between the North-East and North-West Pacific was the greater importance of aquaculture-associated NIS in the North-East Pacific (about 42 per cent of NIS), probably reflecting the large number introduced through the import of the Atlantic oyster (*Crassostrea virginica*) from the Atlantic coast of North America and the Pacific oyster from Asia, which resulted in many “hitchhikers” becoming established outside their native range. Increased regulation in recent decades has been effective in reducing the number of inadvertent aquaculture-related movements of NIS. In 2011 the great east Japan earthquake and the resulting tsunami provided a unique vector for species indigenous to Japan to be transported across the North Pacific to Hawaii and North America (Carlton and others, 2017; Therriault and others, 2018).

4.6. South Pacific Ocean

There have been no synthetic assessments of the status of marine bioinvasions across the geographically, culturally and ecologically diverse area of the South Pacific. Most existing information comes from literature and field studies undertaken since the late 1990s in Australia, New Zealand and Chile. A literature review combined with NIS surveys in 41 Australian shipping ports between 1995 and 2004 identified 132 NIS throughout Australia (Sliwa and others, 2009), with 100 NIS detected in Port Phillip Bay alone (Hewitt and others, 2004). There were more NIS in southern temperate Australia than in tropical northern Australia (Hewitt, 2002) but such patterns are confounded by poorer taxonomic resolution in the tropical environments and by the larger urban centres and longer history of shipping in southern Australia (Hewitt and Campbell, 2010). Forty-three similar baseline surveys conducted in New Zealand between 2001 and 2007 (Seaward and others, 2015), combined with published records, museum holdings and submissions to the Marine Invasives Taxonomic Service (Cranfield and others, 1998; Kospartov and others, 2010), show that, as of March 2018, 377 NIS had been recorded in that country's marine waters (214 species are considered established in recipient systems, while the remaining 163 have been recorded only from vessels or transient structures or were failed introductions). Forty-six new NIS were recorded between 2010 and 2018, only 15 of which appear to have become established (Seaward and Inglis, 2018).

At least 53 marine NIS have been reported in Chile (1 seagrass, 15 algae, 26 invertebrates and 11 fishes) (Castilla and Neill, 2009; Turon and others, 2016). However, that is likely to be an underestimate, as there appear to have been few studies of biofouling assemblages in ports and harbours, where introduced species tend to be more abundant. For example, 53 NIS marine invertebrates were recently reported in the Galapagos Islands, Ecuador (Carlton and others, 2019), of which 30 species (57 per cent) were first recorded in fouling plate and shoreline surveys undertaken around shipping docks and infrastructure. Cárdenas-Calle and others (2019) have identified 6 NIS in mainland Ecuador.

There is limited information about the distribution and impact of NIS in the Pacific Island Countries and Territories, as relatively few systematic studies have been done in the region. Surveys undertaken in American Samoa, United States, in 2002 identified 17 NIS, most of which were restricted to Pago Pago harbour and were species known to occur across a broad geographical range (Coles and others, 2003). Forty NIS have been identified in Guam, United States (Paulay and others, 2002) and a preliminary survey of fouling assemblages in Malakal Harbour, Palau, identified 11 NIS (Campbell and others, 2016), in each case comprising mostly ascidians, bryozoans, hydroids and bivalve molluscs. Six NIS, comprising five invertebrates and one alga, have been recorded from the remote Palmyra Atoll, United States (Knapp and others, 2011). Nuisance blooms of fucoid algae, possibly spread by shipping, have been reported in Tahiti, France, (Stiger and Payri, 1999) and Tuvalu (De Ramon N'Yeurt and Iese, 2013).

More than 80 per cent of known NIS in Australia and New Zealand have been associated with incidental transport in ballast water or biofouling (Hewitt and Campbell, 2010; Kospartov and others, 2010) while deliberate introductions of aquaculture species have accounted for less than 2 per cent of records. Introductions of aquaculture species have been more numerous in Chile and Peru (Castilla and Neill, 2009), as well as in the Pacific Island Countries and Territories, throughout which at least 38 NIS have already been transported deliberately over the past 50 years in attempts to establish fisheries or small-scale aquaculture ventures (Eldredge, 1994). In the 1970s and 1980s, the green mussel (*Perna viridis*), sourced from the Philippines, was successively introduced to New Caledonia (France), Fiji, Tonga, the Society Islands (France), Samoa and the Cook Islands (Baker and others, 2007).

4.7. Southern Ocean

The Antarctic Circumpolar Current acts as a strong barrier to natural dispersal that has probably contributed to the uniqueness of Southern Ocean communities. Furthermore, the Southern Ocean has limited shallow-water continental shelves and a poorly described fauna (Brandt and others, 2007). It appears that the most likely vectors for NIS to those waters would either be direct human-mediated transport, such as shipping, or indirect transport by means of longer-distance rafting on artificial marine debris (Lewis and others, 2003; Barnes and others, 2006; Hughes and Ashton, 2017). In addition, any NIS that reached those environments would face challenging environmental conditions. However, with increased rates of climate change, they may become more prone to invasions. To date, only the North Atlantic spider crab (*Hyas araneus*) appears to have been introduced to the Southern Ocean by human activities (Tavares and de Melo, 2004), but it is likely that that will change in the future. Potential future invaders include the blue mussel (Lee and Chown, 2007), the predatory sea star (*Asterias amurensis*) (Byrne and others, 2016) and the kelp (*Undaria pinnatifida*) (James and others, 2015). Owing to its relatively low biodiversity, simple ecosystem structure and unique assemblages dominated by soft-bodied organisms, the Southern Ocean system may be especially vulnerable to introductions of NIS, in particular predatory species that could have a significant impact.

5. Outlook

While introductions of NIS continue as a result of human activities, there are many regions where temporal analyses have not been possible because information on NIS is either very poorly documented or completely lacking. Furthermore, climate change will add to other drivers of ocean change, including water pollution, severe storm events and overfishing, to potentially increase the abundance, ranges and impacts of NIS by altering recipient ecosystems in which native species will be increasingly stressed and by changing human-mediated connectivity through shifts in vectors and pathways. About 40 per cent of the world's population lives in coastal communities, increasing pressure on coastal marine ecosystems through multiple activities and their consequences that contribute to the introduction and spread of NIS, including shipping, boating, marine farming, land-based pollution and marine litter, coastal installations and development, energy production and multiple extraction activities (oil and gas, sediments and fish). It has been predicted that, in regions such as the Arctic, changing environmental conditions will increase the likelihood of new invaders from a variety of taxa (e.g., Goldsmit and others, 2018). They may also lead to changes in shipping patterns, with traffic expected to increase along the Northern Sea Route and become possible along the Northwest passage, which could in turn increase the supply of propagules (Miller and Ruiz, 2014).

Despite the risks posed by NIS, they are substantially underrepresented in existing databases and registries, such that many of the challenges inherent in dealing with such species stem from the limited or incomplete nature of the knowledge base. The magnitude and breadth of that knowledge gap is difficult to assess. It varies among taxa, habitats and regions, and owes much to the inaccessibility of marine ecosystems, caused by such factors as the higher costs of research relative to other ecosystems, the lack of expertise and the lack of interest in NIS that do not benefit or interfere with human needs. Generally, impacts are not well documented unless the NIS is profitable or highly destructive. Thus, the impacts of the vast majority of marine NIS have not been quantitatively or experimentally studied across sufficiently large time periods and spatial scales and remain unknown, as do their cumulative and synergetic connections with other drivers of change affecting the marine environment (Ojaveer and others, 2015).

Vector management is the most effective strategy for preventing the translocation of plants and animals, thereby reducing the introduction and spread of marine NIS. Given the lack of effective control of propagule transfer by the major vectors, management is limited to eradication, removal and control efforts that are frequently futile. NIS that are known or suspected to cause harm, and are identified while they are spatially confined, should be removed in order to mitigate long-term, ongoing management costs. Once NIS have spread widely, eradication or removal is virtually impossible, and attempts to reduce the population to an economically or ecologically acceptable level over the long term are rarely successful (Forrest and Hopkins, 2013). Legislation, regulations and policies to date have been reactive and fragmentary, often following disastrous and costly NIS outbreaks. The United Nations Convention on the Law of the Sea[5] was the first global legally binding instrument that addressed the intentional or accidental introduction of marine species. While guidelines for preventing the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediment discharges were established in 1991, and the International Convention for the Control and Management of Ships' Ballast Water and Sediments[6] entered into force in 2017, the management of ships' biofouling is not yet required, despite the IMO guidelines adopted in 2011 (IMO, 2019; IMO resolution MEPC.207(62)). Moreover, in its Strategic Plan for Biodiversity 2011–2020 and the Aichi Biodiversity Targets,[7] the Conference of the Parties to the Convention on Biological Diversity called for invasive alien species and pathways to be identified and prioritized, for priority species to be controlled or eradicated and for measures to be taken to manage pathways by 2020 – a target that will be missed. The goal of the European Union Marine Strategy Framework Directive to ensure, inter alia, that, by 2020, NIS are at levels that do not adversely alter the ecosystems is also likely to be unattainable. Regulation (EU) No.1143/2014 of the European Parliament and of the Council on the prevention and management of the introduction and spread of invasive alien species, which focused only on widely spread species and those of "Union concern", is also unlikely to succeed in marine ecosystems, given that only one marine species has been listed so far. Notwithstanding the existence of some national-level regulations, including in Australia, Canada, New Zealand and the United States, there are still no legally binding and strictly monitored frameworks and tools for addressing major global and regional introduction vectors, such as biofouling, the cultivation of and trade in live organisms, and maritime canals.

5 Ibid., vol. 1833, No. 31363.
6 IMO, document BWM/CONF/36, annex.
7 United Nations Environment Programme, document UNEP/CBD/COP/10/27, annex, decision X/2, annex.

6. Other

Although NIS have long been recognized as a major threat to native biodiversity (Bax and others, 2003), they have been largely overlooked in conservation and protected area planning, regulations and management (Giakoumi and others, 2016; Mačić and others, 2018). In view of global commitments to establishing and extending conservation areas (i.e., Aichi Biodiversity Target 11, article 8 of the Convention on Biological Diversity and Sustainable Development Goal 14), that omission may undermine conservation efforts, including the effectiveness of marine protected areas, in regions overrun by NIS (Galil, 2017; Iacarella and others, 2019). In the Caribbean and the Gulf of Mexico, large populations of Indo-Pacific lionfishes (*Pterois volitans* and *P. miles*) have been documented in marine protected areas, where they have impaired native biodiversity (Ruttenberg and others, 2012; Aguilar-Perera and others, 2017). Similarly, in the Mediterranean, many Erythraean species have become the most conspicuous denizens of marine protected areas, having displaced and replaced native species, thereby reversing marine conservation efforts and hampering stock recovery of economically and ecologically important species (Jimenez and others, 2016; Galil, 2018; Stern and Rothman, 2019).

Thus far, few NIS have been reported in areas beyond national jurisdiction. It is possible that that is because survey efforts to detect NIS in those ecosystems have been limited, but it is also likely that most NIS reported globally are primarily found in coastal waters (those of all continents). In addition, as oceanic abyssal communities have been poorly described, it is possible that, even if potential NIS were to be detected, they would not be recognized as such and might be classified, at least initially, as native species. That is what occurred in South America in the case of the smooth cordgrass (*Spartina alterniflora*), where "ecological mirages" masked the true situation (Bortolus and others, 2015).

Globally, marine NIS pose significant biosecurity and biodiversity hazards, but the identification and mitigation of those hazards lag behind comparable efforts in terrestrial systems, where there has been a longer history of dealing with agricultural and forest pests. Greater efforts must be made to document NIS, their vectors and pathways, and their impacts at larger spatial scales, given that existing marine NIS data are often sparse and incomplete, possibly because of logistical and capacity constraints. Policies aimed at preventing introductions, and the development of early detection and rapid response plans, can reduce the potential impacts of NIS. Earmarked funding, political will and capacity-building related to invasion science are required to effectively understand and ultimately manage marine NIS and their vectors globally. Only then can the sustainability of marine ecosystems be ensured.

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