114

REPORTS AND STUDIES

GESAMP
Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection

MARINE BIOFOULING: NON-INDIGENOUS SPECIES AND MANAGEMENT ACROSS SECTORS

GESAMP WORKING GROUP 44

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Contributors to the report: Nina Bloecher, Katja Broeg, Marnie Campbell, Joop Coolen, Jung-Hoon Kang, Hiroshi Kawai, Youna Lyons, Agnese Marchini, Koebraa Peters, Pei-Yuan Qian, Kamal Ranatunga, Evangelina Schwindt, David Smith, Mario Tamburri, Serena Teo, Pedro Almeida Vinagre, Andrew Want, Anna Yunnie

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EXECUTIVE SUMMARY

The biofouling of submerged anthropogenic surfaces and factors that contribute to the spread of non-indigenous species (NIS) have both received substantial attention from researchers, regulators and the private sector focused on understanding their economic, social and environmental consequences. This work has informed the development and implementation of sustainable management approaches, for the prevention of a range of harmful impacts. All marine commercial and recreational sectors deal with biofouling and its varied but typically undesirable consequences. Similarly, almost all marine resource managers, from local to global scale, are concerned with the threat of invasive species and their vectors. This review is an effort by the GESAMP WG 44 to look at the interface between these two pervasive challenges.

Various strategies and tools to prevent, reduce or manage biofouling have been developed and adopted. The intent of these efforts has been primarily to combat the direct negative consequences of biofouling communities on the performance and structural integrity of the surfaces to which the communities attach. The potential for biofouling to be a vector for invasive species has usually been a secondary consideration. Although the strategies, tools and associated regulatory measures are typically developed by experts working within a specific aquatic sector, uptake of successful actions by other sectors is common.

Currently, all of the strategies, tools or regulatory measures have both strengths and limitations, which can vary greatly with the context in which they are applied. This report first reviews the more general consequences of biofouling (Chapter 2) and the strengths and limitations of the most common strategies, technical measures and policies for preventing and managing biofouling (Chapter 3). This information sets the context in which to examine how effectively each commercial and recreational sector currently can deal with biofouling, its impacts and the potential unintended consequences of antifouling or biofouling removal approaches.

This examination was conducted sector by sector (Chapter 4), because some strengths or weaknesses of each individual measure or policy may affect suitability and performance differently in the various marine sectors. Moreover, although biofouling may present a pathway for movement of NIS in each sector, the primary risks associated with each sector may also differ. Thus, within Chapter 4, for each sector, the report examines which policies, measures and regulatory actions are commonly used, the rationales for the preferences, and how these choices affect the potential for the sector to manage the risk of transfer of NIS through biofouling. Opportunities to increase the effectiveness in preventing or reducing the transmission of invasive species through adapting improving existing policies, measures and regulations, or adopting additional ones, are highlighted. The sectors examined are vessels (subdivided into shipping, fishing and recreational sectors), aquaculture, marine offshore energy, offshore renewable energy, ocean-observing infrastructure (i.e. monitoring and research instrumentation) and marine debris.

The report finds that, for each sector, there is no single 'best solution'. Various combinations of policies, measures and regulations are necessary for the effective prevention or control of biofouling and NIS. Regulatory frameworks with clear standards can contribute to managing the risk of biofouling as a pathway for the spread of invasive species but must be appropriate for the sector. Effective frameworks also must be supported by adequate monitoring and capacity to ensure compliance, regularly updated as additional knowledge and innovations become available, and must not cause other unintended environmental consequences. Moreover, performance will remain context-specific even for combinations of measures, making ongoing monitoring, information sharing within and among sectors and adaptive management essential. Some of these emergent lessons and priority knowledge gaps are summarized in Chapter 5.

ACKNOWLEDGEMENTS

The GESAMP Working Group 44 is sponsored by the GEF-UNDP-IMO GloFouling Partnerships project, a joint global initiative between the Global Environment Facility (GEF), the United Nations Development Programme (UNDP) and the International Maritime Organization (IMO), with the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) as a partner. Working Group 44 is grateful for comments on a draft version of this report provided by the external peer-reviewers, the IMO GloFouling Program and several GESAMP Members, which greatly improved this report.

1. INTRODUCTION

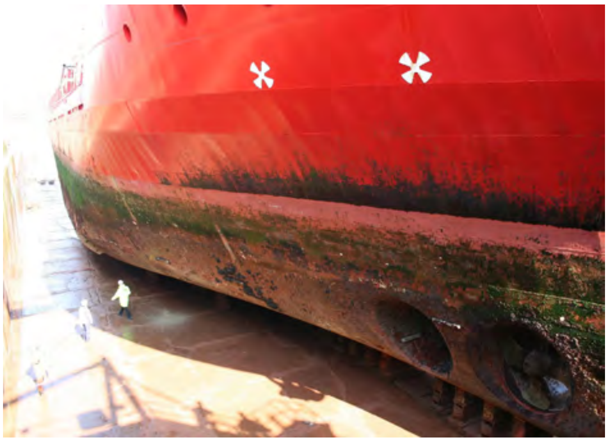


Figure 1.1 The microbial biofilm on a ship's hull provides a ready environment for the adhesion and growth of microalgae and bacteria.
Source: David Smith.

Figure 1.2 Macrofouling consisting of barnacles and mussels.
Source: Alejandro Bortolus, IPEEC-CONICET, Argentina.

1.1 What is biofouling?

When a surface is immersed in an aquatic medium, a ubiquitous series of reactions occur, particularly in natural seawater, which is an ionic solution containing a dense soup of particulate and living matter. Initially, a variety of microorganisms colonize the surface, forming first a biofilm (or slime layer), commonly called 'microfouling', composed mainly of bacteria and microalgae (Figure 1.1). Subsequently, macroorganisms settle, ranging from small-sized organisms, such as nematodes and ostracods, and other larger sized organisms, such as macroalgae and larger invertebrates, often culminating in a viable ecosystem which can include various sessile and mobile species (Figures 1.2 and 1.3; Railkin, 2004). This is the basis on which benthic marine communities develop and grow. When the accumulation of aquatic organisms such as microorganisms, plants and or animals occurs on anthropogenic surfaces and structures immersed in or exposed to the aquatic environment, it is termed as 'biofouling' (IMO, 2023). Biofouling can also include pathogens of concern to the health of exploited species, wildlife and humans (Georgiades et al., 2021). Macrofouling organisms are defined by the International Maritime Organization (IMO) as those individuals or colonies visible to the human eye and are also often separated into two categories, namely 'soft' (e.g. soft macroalgae, sponges, tunicates, anemones) and 'hard' (e.g. calcareous macroalgae, shelled invertebrates such as barnacles and mussels, calcareous bryozoans and tubeworms) (Railkin, 2004). In addition, the complex three-dimensional biofouling communities usually include motile invertebrates, such as crabs, amphipods, isopods and polychaetes (Schwindt et al., 2014).

In its negative connotation, the term 'biofouling' refers to the unwanted accumulation of biological matter on anthropogenic surfaces. Biofouling begins almost immediately on all submerged, floating or wet structures, from boats, ships and nets, to equipment, infrastructure and marine litter. It is a concern for all maritime activities, including some land-based human activities and constructions. These concerns, described in Chapter 2, have prompted the development of a number of methods for preventing, eliminating or reducing biofouling on marine structures, as reviewed in Chapter 3. The amount and type of biofouling and its development as well as species involved are dependent on a variety of biotic and abiotic conditions. It will also depend on other factors, such as the geographical location of submerged structures, as described below. The term 'biofouling' should not be confused with 'epibiosis' (see definition in the Glossary).

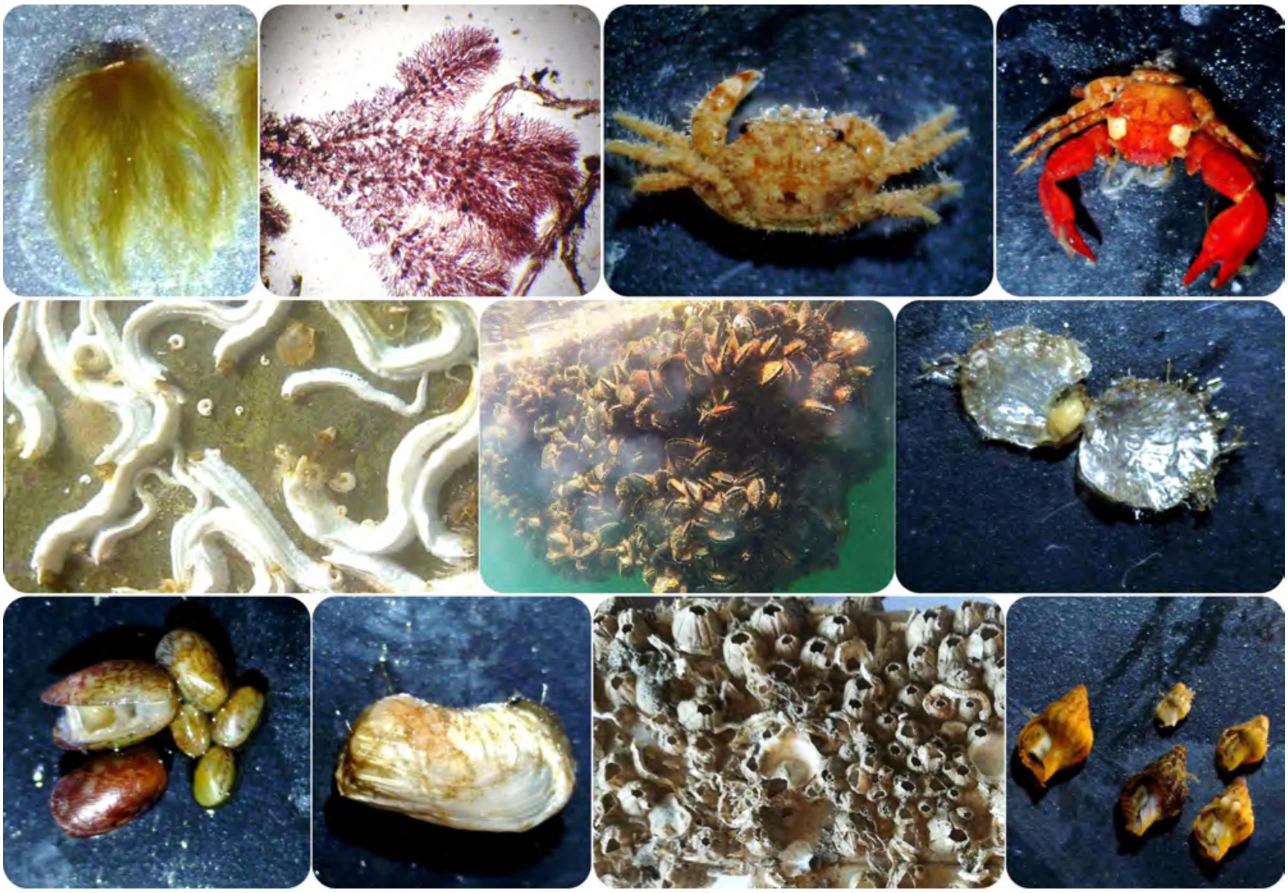


Figure 1.3 Examples of typical macrofouling species. From top-left to bottom-right: filamentous brown algae (cf. *Sphacelaria* sp.), filamentous red algae (cf. *Pterothamnion crispum*), decapods (*Pilumnus hirtellus*, *Pisidia longicornis*), calcareous tubeworms (*Spirobranchus* sp.), mussels (*Mytilus galloprovincialis*) and other bivalves (*Anomia ephippium, Musculus costulatus, Hiatella arctica*), acorn barnacles (*Perforatus perforatus*)and gastropods (*Nassarius* sp.)
Source: Pedro Almeida Vinagre/WavEC.

1.2 The role of biofouling as a vector for invasive aquatic species

Biofouling on anthropogenic structures has also been shown to be a significant pathway for the transport and introduction of non-indigenous species (NIS) (Galil et al., 2019; Bailey et al., 2020). Although species have been transported as biofouling on vessels for centuries, its importance as a pathway of NIS and the urgent need to establish management strategies was recognized only in the last few decades (Galil et al., 2019). It has been documented that between 56% and 70% of the currently established coastal and estuarine NIS globally were transported through a biofouling pathway (Hewitt and Campbell, 2010; Bailey et al., 2020). This is also reflected at regional level, for example in South Africa (48%, Mead et al., 2011), Argentina and Uruguay (45%, Schwindt et al., 2020) and the Galápagos Islands (55%, Carlton et al., 2019). Other non-intentional introductions, such as aquarium trade, escape from farms, research and fishery equipment and intentional introductions for recreational or aquaculture purposes, were documented in lower percentages, usually less than 20%, except for the eastern Mediterranean Sea where 90% of the NIS were introduced through the Suez Canal (Galil et al., 2020).

With the increasing awareness of impacts caused by NIS, there is a heightened awareness of how marine organisms are inadvertently transported across natural biogeographic barriers through the movement of anthropogenic materials. The introduction of NIS to new environments and their further spread within the regions represent a major threat to coasts and oceans worldwide and, thus, to the conservation of biodiversity. The recent IPBES Report (2023) lists invasions of NIS as one of the five direct drivers that have the strongest impact on environmental change. The impact of NIS results from their ability to survive in their new host environments, to establish reproductive populations and become invasive. Invasive aquatic species (IAS) can affect gene flow, population dynamics, community structure and ecosystem functioning, and introduce new pathogens (see Section 2.9). In addition, IAS can cause socio-economic impacts on fisheries, aquaculture, coastal infrastructure, tourism and other development efforts, as well as on the health of humans and other aquatic organisms (see Section 2.9).

Once established in the new aquatic habitat, the removal or eradication measures are extremely costly and the likelihood of complete success is very low (Locke, 2009; Lehtiniemi et al., 2015). One rare example of a successful aquatic NIS eradication effort was in the removal of *Caulerpa taxifolia* that occurred in a small and enclosed bay in California (Anderson, 2005). Often, reinvasion occurs once eradication efforts cease, as was observed in South Africa with the green crab *Carcinus maenas* (Mabin et al., 2020). Thus, the development and implementation of effective measures to avoid or prevent biofouling NIS is urgently needed to avoid environmental, economic and social impacts.

Long-range transport is the main mechanism responsible for the initial introduction of species. Because intercontinental maritime transport, which is known to be one major pathway, happens between ports, initial introductions of species mainly occur within or in the close vicinity of these locations (Leclerc et al., 2018; Hulme, 2021). Short-range movements mainly cause further secondary spread of introduced species within a region, which also includes spread to sensitive or otherwise high-priority marine and coastal areas, such as marine protected areas (Martínez-Laiz et al., 2019; Iacarella et al., 2020). Recreational craft, fishing activities and marine debris might act as vectors or facilitators in this context (see Sections 4.1.2, 4.1.3 and 4.6).

In addition to vessel transport, fixed surfaces such as pilings or floating platforms, aquaculture facilities and other structures such as shipwrecks provide substrata for potential invasive NIS to settle and establish in proximity to ships and boats (Giachetti et al., 2020; Castro et al., 2021). These surfaces thus can serve as 'stepping stones' and a source for living organisms which may attach to a ship and be translocated and introduced in new environments (Dafforn et al., 2012; Airoldi et al., 2015). By 2018, it was estimated that the total marine construction surface created (including gas and oil platforms, aquaculture and wind farms, recreational and commercial ports, wave and tidal farms, breakwaters, shipwrecks, artificial reefs) was 32,000 km^2 and projected to increase by 23% by 2028 (Bugnot et al., 2021). Ocean infrastructure is developing faster than marine spatial management and planning, which is struggling to include NIS management. Acting in synergy, many direct or indirect drivers of biodiversity change, such as climate change, can trigger new species introductions and range expansion of the species already introduced. Given the expected changes in climate conditions, species in the marine environment are expected to expand or contract their distributions much faster than in terrestrial ecosystems (Sorte et al., 2010). The expected changes by the end of the century as a result of ocean warming will produce new ecosystems and changes in the present communities (Goldsmit et al., 2018; Pack et al., 2022; Pecl et al., 2017). For these reasons, it is essential to address biofouling across the full range of biofouling sources and structures present in the aquatic environment.

Figure 1.4 The NIS *Mytilus galloprovincialis* populating rocky shores in South Africa.
Source: Koebraa Peters.

Because of the often complex nature of the biofouling pathways involved, the measures taken to counteract the detrimental effects of NIS can involve both intricate techniques and complex management strategies (See Chapter 3). In addition, understanding the full range of potential impacts caused by such NIS invasions is similarly challenging. These impacts not only range across evident detrimental effects on a local environment and ecology, but also include direct operational or production losses. There are also more indirect considerations, such as socio-economic consequences, together with the potential harm to human health and well-being (See Chapter 2 and references therein).

1.3 Invasive aquatic species as a problem for the environment, society and economy

NIS introduced via biofouling might have a variety of impacts in the recipient regions where they become established. These species can change the habitat for native species, by creating or modifying their existing environments. Many mussels, serpulid and barnacle species are habitat-forming organisms that can reach high densities, influencing the structure and functioning of local communities (Crooks, 2009). For example, the Mediterranean mussel *Mytilus galloprovincialis,* first detected in South Africa in 1979 (Mead et al., 2011), is now one of the most widespread species, covering 2,800 km of the shore (Figure 1.4). This species outcompetes native mussels and increases habitat complexity. Consequently, the density and richness of local benthic communities has substantially changed (Robinson et al., 2007, 2020).

IAS can also affect native communities by changing ecological interactions, for example through competition, e.g. between the invasive snail *Batillaria attramentaria* and the native mud snail, *Cerithidea californica,* in California (USA) (Byers, 2000), or predation, e.g. between the sea star *Asterias amurensis* and native clams *Fulvia tenuicostata* and *Katelysia scalarina* in the soft sediments of Tasmania (Australia) (Ross et al., 2003). Some IAS can have an impact on trophic interactions at multiple levels. For example, the green crab *Carcinus maenas* is a widespread predator invader (Carlton and Cohen, 2003) able to colonize a variety of habitats, from protected rocky shores to mudflats. Through predation as preferred prey, *C. maenas* (Figure 1.5) reduced the density of native clams *Nutricola* spp. five- to ten-fold within three years of arrival in California (USA) (Grosholz et al., 2000). Although native clam abundances were reduced, the non-indigenous clam *Gemma gemma* increased. Indirectly, other small native crustaceans and polychaetes also increased in abundance, most likely due to the removal of co-occurring green crab (Grosholz and Ruiz, 2009).

Figure 1.5 Green crab *Carcinus maenas* preying upon bivalves.
Source: Nicolás Battini, IBIOMAR-CONICET, Argentina.

Other invasive species affect not only biodiversity but also the dynamic of the physical environment. For example, the reef-building polychaete *Ficopomatus enigmaticus* is a well-studied IAS in Argentina (Figure 1.6). This serpulid is a suspension feeder able to reduce phytoplankton biomass significantly (Bruschetti et al., 2018). By creating reefs, *Ficopomatus* creates hard substrate and enhances the recruitment of macroalgae which favours the growth of the polychaetes during the warm season (Bazterrica et al., 2012, 2014). At large scale, the high abundance of reefs in the ecosystem alters the water flow, the sediment transport and increases the sediment deposition. At the same time, these novel habitats attract and offer refuge for the native predatory crab *Cyrtograpsus angulatus*, resulting in a reduction of native soft-bottom polychaetes (Schwindt et al., 2001).

Figure. 1.6 Reefs formed by NIS *Ficopomatus enigmaticus* on mudflats offer refuge for predatory native crabs.
Source: Alejandro Bortolus, IPEEC-CONICET, Argentina.

The tunicate *Ciona* spp., known to be a problem for the oyster aquaculture industry, has been continuously found at almost all subtidal zones of Korean waters, except in limited areas of the Yellow Sea coastal zone (Park et al., 2020). Filter feeding activity of *C. robusta* can have a negative impact on the richness of microzooplankton such as bivalve larvae and ciliates. In addition, resident *Ciona* species suppress settlement of oyster larvae on the substrate by larval predation (Osman et al., 1989).

Given the variety of environmental and biological variables interacting at local scales, when a non-indigenous aquatic species introduced via biofouling arrives at a given location, the direction and intensity of the impacts and ecological interactions are difficult to predict. These interactions among resident and invasive species might be different from site to site depending on, for example, the artificial structure (Figure 1.7). Communities growing on floating or suspended structures, such as buoys and ropes, are only affected by

Figure 1.7 Fouling communities growing on different artificial structures such as a shipwreck (top) and a floating rope (bottom).
Source: Nicolás Battini, IBIOMAR-CONICET, Argentina.

nektonic predators (Ashton et al., 2022), whereas structures connected to the sea bottom, such as piers, are also affected by benthic predators such as crabs, sea urchins, octopuses and sea stars (Giachetti et al., 2020; Leclerc et al., 2020). In consequence, fouling communities attached to suspended structures have a different composition and richness than structures connected to the sea bottom, such as piers. In general, artificial structures harbour most of the introduced species, compared to other natural hard and soft bottom habitats (Ruiz et al., 2009) and these structures help to maximize the establishment and spread of introduced species (Glasby et al., 2007; Airoldi et al., 2015; Giachetti et al., 2019).

To illustrate the potential magnitude of the economic consequences, the United States Naval Sea Systems Command estimated that biofouling on ship hulls accounts for speed loss of about 2% and subsequent fuel cost increases ranging from 6% to 45%, depending on the size of the ship (Nurioglu et al., 2015), accompanied by an augmentation of greenhouse gas (GHG) emissions (GEF-UNDP-IMO GloFouling Partnerships Project and GIA for Marine Biosafety, 2022; ICCT, 2011). The IMO reported that, without corrective action, gas emissions from world shipping fleets could increase from 150% to 250% by 2050, compared to the emissions in 2007. In particular, CO_2 emissions have been predicted to double by 2030, under extreme scenarios (IMO, 2009). Some species, like the golden mussel *Limnoperna fortunei,* can cause enormous damage to the shipping industry. This species can clog the water intake sieves and filters, pipes, etc. in many nuclear and hydroelectric power stations as well as distilleries and refineries along the Río de La Plata estuary (Boltovskoy et al., 2006). The maintenance and cleaning of all the infrastructure is usually carried out by the companies to an estimated annual cost of US$ 2,032,315 (Duboscq-Carra et al., 2021).

1.4 Global and regional policy responses to the introduction of NIS

The global awareness of the seriousness of ecological risks arising from the introduction of NIS is not new. Accordingly, international treaties that apply to the protection of the marine environment include specific provisions. First, the United Nations Convention on the Law of the Sea (UNCLOS), which was negotiated in the 70s, adopted in 1982 and entered into force in 1994,[1] requires States to take all measures necessary to prevent, reduce and control pollution of the marine environment resulting from the intentional or accidental introduction of species, alien or new, to a particular part of the marine environment, which may cause significant and harmful changes thereto. This clear and direct provision obligates States to

1 Available at: https://treaties.un.org/doc/publication/unts/volume%201833/volume-1833-a-31363-english.pdf

a duty of due diligence to adopt measures before the occurrence of damages or apparent threats. It therefore imposes a precautionary approach. This obligation applies to intentional and accidental introductions in any part of the marine environment, via biofouling or any other means. Second, States that adopted the Convention on Biological Diversity (CBD)[2] also committed to prevent the introduction of, control or eradicate species which threaten ecosystems, habitat or species (Article 8(h)). Implementation of this provision has been framed around the identification and management of introduction pathways and of priority species and sites.

Despite these commitments (UNCLOS and the CBD are adopted by 167 and 195 States Parties, respectively), this report shows that the development of international and domestic regulations, standards and practices required for the implementation of these provisions has been slow and insufficient for the different coastal and sea activities that create or contribute to the risk of introduction of NIS in the marine environment, and are still lagging. The most notable exception is the introduction of NIS through the ballast water of vessels addressed by the International Maritime Organisation (IMO). Of note also are the recently adopted IMO 2023 Guidelines for the Control and Management of Ships' Biofouling to Minimise the Transfer of Invasive Aquatic Species (IMO, 2023). See Section 4.1.1.6 for further details on the IMO regulations. Overall, the precautionary approach is not adequately implemented in the context of the risk of introduction of NIS. This overall weakness of the global body of law and policy is also reflected in the paucity of legal and policy publications on marine NIS. However, this is not to say that the topic has not been discussed by policy bodies and that there are no applicable rules and guidance. The two main bodies to have done so for several decades are the CBD and the IMO, respectively, with a focus on the impact of NIS on biodiversity conservation and the role played by shipping in the spreading of invasive species, including via biofouling.

The CBD has adopted a number of recommendations and decisions and established expert and working groups devoted to addressing threats on biodiversity from IAS (CBD, 2005), starting in 1998 (CBD, 1998). However, until the Programme of Work on Marine and Coastal Biodiversity focused on this topic, the work included both terrestrial and marine ecosystems, with a focus on the former. Decision VI/23 of the Conference of the Parties to the CBD adopted Guiding Principles for its work on this topic and encouraged cooperation, research and action by a number of international bodies, including the IMO and others who regulate the various activities at sea and/or are devoted to the protection of the marine environment (CBD, 2002). The CBD's Programme of Work on Marine and Coastal Biodiversity identifies shipping, mariculture and trade as pathways for which control mechanisms must be put in place. Other objectives are focused on research and data collection on the introduction of NIS (CBD, 2004).

The work streams of the CBD on invasive species have built on the work and outputs of the Species Survival Commission (SSC), originally established by the International Union for the Conservation of Nature (IUCN) in 1949 as the IUCN 'Survival Service' to preserve vanishing species of flora and fauna. The latter is still very much at the forefront of the development of assessments of threatened species population status and trends, as well as threats to them (Mainguy, 2012). The Global Invasive Species Database developed and maintained by its Invasive Species Specialist Group (ISSG) since the 90s, and the assessments and guidelines it prepares, have the authoritative scientific value needed to inform law- and policy-making aimed at preventing or reducing the adverse effects of NIS on native biodiversity and ecosystems (Pagad et al., 2015).

At the Earth Summit of 2012, the significant threats posed by IAS to marine ecosystems reached the highest level of the United Nations (UN). The UN General Assembly has since, in several resolutions, noted this threat and has 'committed to implement measures to prevent the introduction and manage the adverse environmental impacts of alien invasive species'. This impetus translated into the creation of new work streams for the development of policy guidance, rules and standards in the many institutions that contribute to the implementation of UNCLOS and the CBD in different activity sectors. The knowledge gap identified by international regulatory bodies is progressively becoming filled by key global initiatives that involve the IUCN ISSG and are established in coordination with and with the support of the CBD (if not under its auspices). Such bodies include the inter-agency Liaison Group on Invasive Alien Species (IALSG), the Ad Hoc Technical Expert Group on Invasive Alien Species (AHTEGIAS) and the Global Invasive Alien Species Information Partnership (GIASIP) with its Global Register of Introduced and Invasive Species (GRIIS); the latter was initiated by the ISSG.

Furthermore, in the newly adopted post-2020 agenda of the CBD, target 6 of the 2022 Kunming-Montreal Global Biodiversity Framework (GBF) (CBD, 2022) revised the earlier Aichi Target 9 (CBD, 2010), adding (i) a reduction target of 50% to the rates of introduction and establishment of other known or potential IAS and (ii) a focus on priority sites in addition to priority invasive species. CBD COP15 Decision XV/27 (CBD, 2022) on invasive alien species requests the organization of a peer-review process to solicit advice on the six draft guidance documents prepared by the AHTEGIA and make recommendations for CBD COP16. These draft guidance

2 Convention on Biological Diversity, 5 June, 1992 (entered into force 29 December 1993). Available at: https://www.cbd.int/doc/legal/cbd-en.pdf

documents include methodologies and tools for cost-benefit and cost-effectiveness analysis to manage IAS, including in the context of climate change, risk analysis of the potential consequences of the introduction of IAS on social, economic and cultural values, database and IAS management such as management-specific pathways (Essl et al., 2020). Despite this focus on the control of pathways since CBD Aichi Target 9 (CBD, 2010), these documents only mention biofouling in the context of maritime transport, with reference to the work of the IMO. The other sectors of activities examined in this report are not mentioned.

Although there are generally few specific legal instruments applicable to the introduction of NIS via biofouling at global level (Outhwaite, 2017; Riley, 2014), there are sectoral rules, standards and guidance in place or under development for activities that can act as a pathway for the introduction of NIS via biofouling in the marine environment. These are presented in the relevant sections below.

To complement regulations and policy measures adopted at global level, measures adopted in some regional seas also warrant mention. Most regional sea instruments adopted to protect and preserve the marine environment include provisions on risks from the introduction of NIS and measures to prevent them or mitigate their impact. These measures have been introduced in the text of regional sea treaties (e.g. SPAW, 1990) and in regional action plans, strategies and/or monitoring guidelines, including through the development of specific NIS indicators (UNEP-MAP-RAC/SPA, 2005; OSPAR NAES, 2021; Stæhr et al., 2023; HELCOM, 2018); most of these measures are part of the regional seas programme administered by UNEP. The measures generally fit within larger suites of measures on the protection of the marine environment and implementation of an ecosystem-based approach. The general approach followed focuses on (1) regulation to control introductions; and (2) monitoring, inventory and analysis of introduced species to inform a risk assessment approach to response measures (UNEP-MAP-RAC/SPA, 2005). This approach can be supported by regional activity centres such as the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC), administered by the IMO, which focuses more specifically on the introduction of NIS from shipping in the region. In the context of the implementation of the introduction of NIS from ballast water, OSPAR and HELCOM have included a joint natural dispersal and common risk area approach into their overall risk assessment approach. This more integrated approach may prove useful to the management of introduction of NIS via biofouling from ships as well as other vectors (OSPAR-HELCOM, 2020). However, specific acknowledgement in legal and policy documents of the risks created by biofouling in other activities than shipping could not be found.

1.5 GESAMP WG 44 and this report

The GEF-UNDP-IMO GloFouling Partnerships project (www.glofouling.imo.org) is a global initiative between the GEF, UNDP and IMO, launched in 2019. Its objective is to drive actions through technical cooperation and capacity-building for the implementation of the IMO Biofouling Guidelines. These efforts are intended to provide a globally consistent approach on how biofouling should be controlled and managed to minimize the risk of NIS introductions via ships. As part of its efforts to develop capacity for the implementation of the IMO Biofouling Guidelines, the GloFouling Partnerships project provided funds to facilitate the development and publication of a review of existing biofouling management practices across shipping and other maritime sectors, the impact of biofouling and how it contributes to the transfer of NIS. This work was undertaken by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), which established a Working Group on Biofouling Management (Number 44). GESAMP is an inter-agency body of the United Nations, providing authoritative and independent scientific advice to organizations and governments to support the protection and sustainable use of the marine environment.

Under the GloFouling Partnerships project, the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) provides scientific guidance and coordinates efforts to address ships and non-ship pathways, and acts as the lead agency under which experts are part of the GESAMP Working group (WG 44). The overall objective of the WG 44 on biofouling management and NIS is to build a broader understanding of the introduction and spread of aquatic invasive species via biofouling across all maritime industries.

The WG 44 worked to develop a one-stop scientific report focusing on IAS introduced via biofouling on ships and other wetted or submerged structures. The report is expected to support the mandates and programmes of the IMO and its GloFouling Partnerships project, as well as IOC–UNESCO and other agencies dealing with marine biofouling, with an emphasis on its role as a pathway of the transfer and introduction of NIS. It will also address data gaps, including those that have been highlighted through the respective relevant governing bodies of these organizations. The group will seek to identify areas of common scientific interest, monitor trends, provide consistency of scientific advice and facilitate the coordination of UN agency activities aimed at preventing the transfer of IAS through marine biofouling.

1.5.1 Terms of reference for this report

This report represents the results of that study which was conducted using the following terms of reference:

1. Identification and description of both primary and secondary pathways for the transfer of NIS by a range of means including shipping, fishing, off-shore operations and other identified pathways.
2. Description and assessment of the various impacts arising from NIS events, including effects on the environment, biodiversity, potential human health issues and economic and social consequences.
3. Overview of best management practices for biofouling control within the identified industries, including management approaches and innovative technologies.
4. Conclusions based on the collected information and observations on where improvements could be achieved, along with identified gaps in available knowledge.

The WG 44 has developed this report in parallel with other work coordinated by the GloFouling Partnerships project which resulted in several publications on best management practices in specific sectors and on some aspects of biofouling management (GHG emissions resulting from biofouling on ships; regulatory environment for biofouling management). Where themes explored by glofouling partnerships are relevant to themes addressed by WG44, their findings should also be considered along with the information found in this report.

1.5.2 Terminology used in the report

Across industry sectors and scientific disciplines, many different terms are used and sometimes interpreted in quite different ways to reflect the different contexts and histories in the various fields. As a consequence, the WG has prepared a Glossary which presents the definitions and interpretations of technical terms as they are used in this report. This is not an attempt to change established practices in individual sectors, but allows the content of this report to be interpreted clearly and consistently by readers who may have a variety of disciplinary backgrounds.

The WG also agreed to mostly use the term non-indigenous species (NIS) defined as a species, subspecies, or lower tax on forming a self-sustaining reproductive population occurring outside of its natural biogeographic range and beyond its natural dispersal potential, which has been transported by direct or indirect human activities into a region where they were previously absent. In some cases, the WG uses the term invasive aquatic species (IAS) for those animals, plants or other organisms that are introduced into places outside their natural range and are documented to negatively impact native biodiversity, ecosystem services or human well-being.

1.5.3 Structure of the chapters and sections

Following this introduction, the report is composed of four chapters and three annexes. Chapter 2 covers the consequences of biofouling other than NIS introductions, across all the main sectors developed in this report such as shipping (which includes all kinds of vessels and activities developed with vessels), aquaculture, marine offshore energy operations, ocean renewable generation, ocean-observing infrastructure and marine debris. Chapter 3 reports the strategies and approaches used to address and reduce biofouling in all sectors described in Chapter 2. Chapter 4 is divided into six sections in which each sector is discussed in relation to the sectoral problems and efforts at solutions and includes identified gaps, recommendations and policy-regulatory issues within the sector. At the end of each chapter or relevant section within the chapter, the WG has developed a series of key findings, main gaps and recommendations. Finally, Chapter 5 comprises a synthesis section with emergent cross-chapter issues. Below, there is a short introduction to the sections developed in Chapter 4.

1.5.3.1 Shipping

Due to the different activities performed and the various sizes of the different types of vessel, the section on shipping is divided into subsections covering vessels engaged in commercial shipping, recreational and commercial fishing, and recreational craft.

Shipping is one of the main and primary pathways of introduction of NIS, as it transports them across the ocean and into coastal areas (See Figure 1.1). It also acts as a secondary source of introduction by further dispersing already introduced species to coastal regions. Smaller vessels such as recreational craft (Figure 1.8) are often responsible for a secondary spread of NIS once introduced into a new region. However, they can also act as primary pathways depending on the circumstances of travel and the presence of NIS as biofouling.

1.5.3.2 Aquaculture

Aquaculture includes the production of freshwater and marine organisms such as finfish, algae, molluscs and crustaceans. Biofouling is a challenge to aquaculture structures as well as the cultured organisms (Figure 1.9) and is traditionally mitigated first and foremost to sustain ideal culture conditions. As such, aquaculture installations are at risk of harbouring and spreading NIS.

1.5.3.3 Marine offshore energy operations

Approximately 12,000 stationary fixed and floating offshore oil and gas platforms are present worldwide, plus over 130,000 km of pipelines. These installations can be either stationary, infrequently or periodically relocated, or mobile, meaning they are relocated regularly between sites for activities such as drilling or exploration. Mobile structures

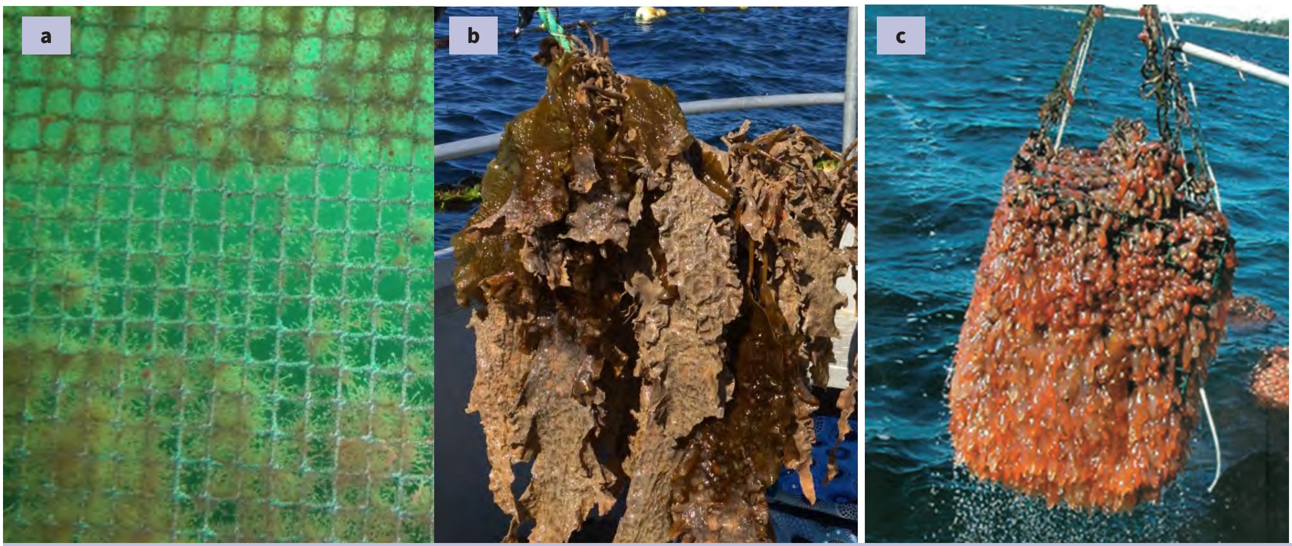


Figure 1.9 Examples of biofouling in aquaculture: a) The hydroid *Ectopleura larynx* on the net of a salmon sea cage in Norway. *Source:* Nina Bloecher; b) the bryozoan *Membranipora membranacea* overgrowing the sugar kelp *Saccharina latissima* cultured on ropes in Norway. *Source:* Silje Forbord; c) tunicates on shellfish cages in Canada. *Source:* Andre Mallet, IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships, 2022.

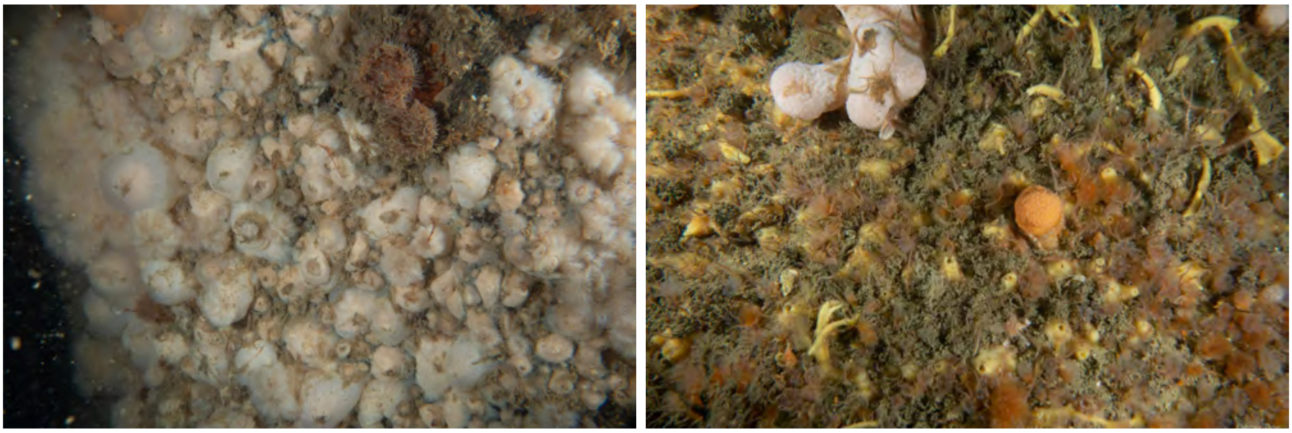


Figure 1.10 Biofouling as observed on submerged parts of marine offshore energy installations.
Source: Oscar Bos, Wageningen University & Research.

Figure 1.11 A floating tidal energy device deployed in Scottish waters.
Source: Orbital Marine Power.

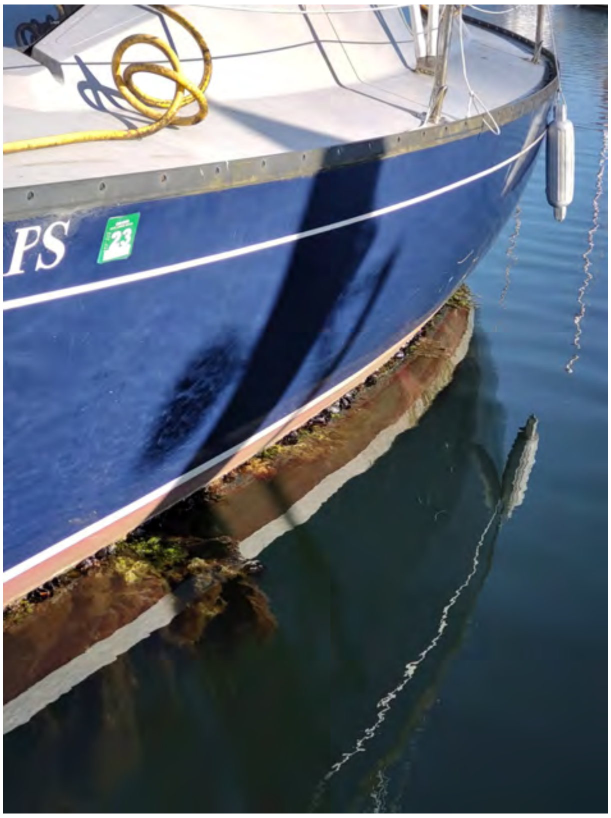


Figure 1.8 Recreational craft in a marina with biofouling.
Source: Evangelina Schwindt.

may be pathways that actively transport species outside their native range, when relocated between projects. Fixed platform installations may provide pathways as stepping stones for further distribution after NIS have been introduced to a region by creating habitats for NIS in otherwise unsuitable environments (Figure 1.10). Pipelines may offer novel habitats for fouling species, likely including NIS, when introducing steel and concrete hard substrates on sandy seabeds, that interconnect fixed offshore and coastal structures.

1.5.3.4 Ocean renewable energy generation

Efforts towards decarbonizing energy generation are gaining in importance and have seen a rapid increase in the deployment of renewable energy devices in waters globally. Currently, these technologies include offshore wind turbines, wave and tidal energy devices and floating photovoltaic arrays. Introducing ocean renewable energy (ORE) devices and infrastructure provides artificial hard substrates that facilitate the growth and spread of biofouling. From an industry perspective, biofouling is seen as a costly nuisance that may negatively impact the performance and survivability of structures (Figure 1.11). From an ecological perspective, ORE deployments in new regions and novel habitats have the potential to facilitate the connectivity of biofouling populations, including NIS.

Figure 1.12 Monitoring buoy after being cleaned, showing remains of barnacles not removed by standard cleaning practices.
Source: Pedro Almeida Vinagre/WavEC.

1.5.3.5 Ocean-observing infrastructure

Thousands of ocean-observing infrastructures are currently deployed around the world, for oceanographic monitoring, environmental monitoring (Figure 1.12), or specific projects including offshore renewable energy and aquaculture. Although they generally provide a small colonizable area compared to other infrastructure at sea, such as oil and gas (O&G) and wind energy, ocean-observing infrastructure might represent a greater number of 'stepping stones' for the propagation of NIS to broader geographical areas. Also, maintenance activities of ocean-observing infrastructure will require frequent use of vessels to conduct activities on site or to transport the infrastructure to ports, which may further increase the potential for introduction in coastal areas.

1.5.3.6 Marine debris

Marine debris includes persistent, solid material discarded, disposed of, abandoned or outflowed in the marine and coastal environments. In particular, those that are relatively large and drift on the ocean surface for long periods tend to serve as a substrate for various marine organisms and may assist transoceanic introductions of NIS. Among various examples, plastics – the production of which has increased dramatically since the 1970s – comprise a major portion of the rapid increase in marine debris. This section describes the types of marine debris and the diversity of biofouling that inhabit them, as well as a discussion of the risk of invasions caused by large marine debris associated with tsunamis. To prevent transocean transfer of marine NIS, it is extremely important to improve the treatment system of materials that may become marine debris, since most of them are derived from land-based solid wastes, but it is also essential to improve the monitoring of marine debris, which potentially may act as vectors of NIS.

2. CONSEQUENCES OF BIOFOULING OTHER THAN NIS INTRODUCTIONS

Both oceanic and freshwater biofouling have been recognized as problematic phenomena for over a century. For vessels, offshore structures and industrial plants, such as cooling water and desalination systems exposed to such waters, there are many undesirable consequences for the efficient and safe use and operation. Such consequences have led to efforts to reduce, eliminate or mitigate the formation and growth of biofouling for many decades. Although consequences of biofouling other than presenting potential pathways for NIS are not within the scope of this report, they have influenced the types of measures available to address the threats from biofouling and the regulations and industry 'best practices' that have developed. For those reasons, the other major consequences of biofouling are summarized briefly here, as they provide background and context for the measures and policies discussed in the rest of the report.

2.1 Increase in weight and drag

The attachment of biofouling organisms to surfaces can add considerable weight to a structure. In the case of a hull of a vessel, biofouling also creates roughness, which increases the hydrodynamic resistance to the ship movement through the water (i.e. increases 'drag'). A consequence of this is a loss of operational speed of the vessel or the application of more motive power to maintain the required speed (Schultz, 2007; Schultz et al., 2011). It has been estimated that even a layer of biofilm as thin as 0.5 mm covering up to 50% of a hull surface could result in a 25% increase in fuel consumption by a vessel, with an attendant rise in GHG emissions (GEF-UNDP-IMO GloFouling Partnerships Project and GIA for Marine Biosafety, 2022). In cases of advanced fouling, this can result in fuel consumption increases of up to nearly 50%.

Figure 2.1 demonstrates the potential increase in fuel consumption and attendant greenhouse gasses against a biofouling scale rising from slime formation to barnacle and weed growth.In aquaculture, the physical presence of biofouling on farm structures increases its weight and drag, which impacts stability and buoyancy of suspended culture systems and increases the risk of structural damage of suspended structures during storm surges, as well as reducing the lifespan of mooring lines. A recent study by Bi et al. (2018) demonstrated up to a 10-fold increase in hydrodynamic load and a 21.4% reduction in flow velocity in nets

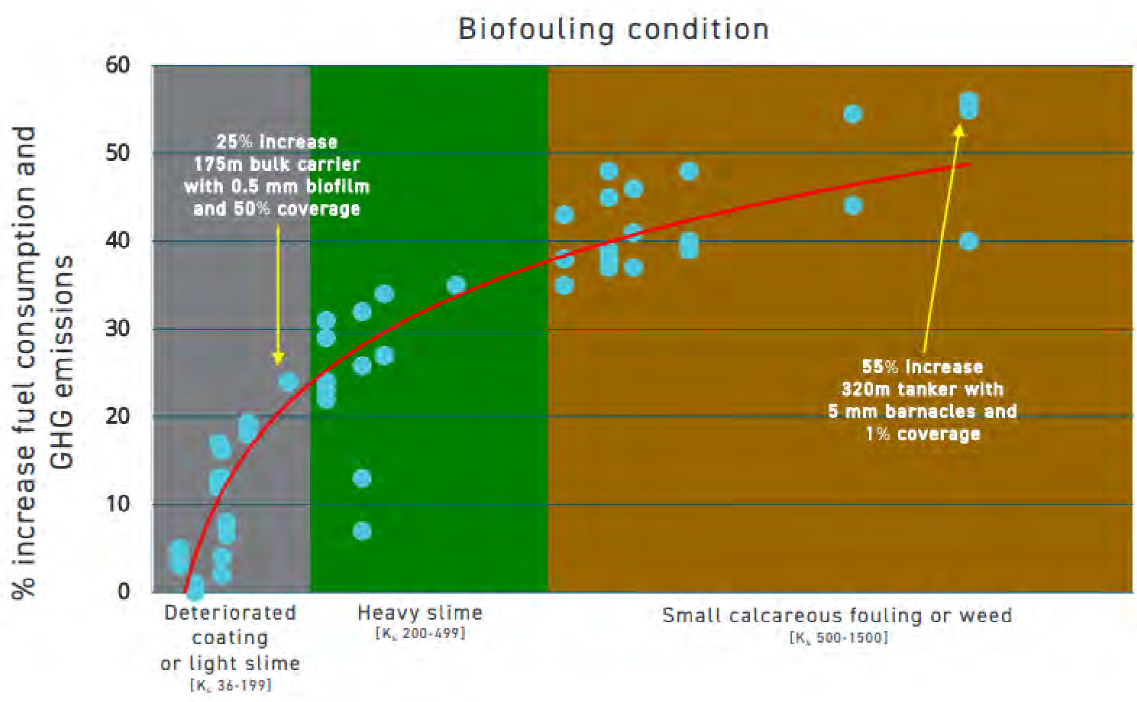


Figure 2.1 Impact of ship fouling on Fuel Consumption and GHG emissions.
Source: Glofouling Partnership.

heavily fouled by hydroids. Biofouling on the cultured organisms themselves may impact their fitness by adding weight and increasing drag, potentially causing loss of cultured organisms from, for example, mooring lines (Bannister et al., 2019). These consequences, and the labour costs to address them, have been influential on the industry practices discussed in Chapters 3 and 4.

In the offshore renewable energy sector, increased weight and drag from biofouling may compromise functioning and survivability of mooring systems and dynamic subsea cables by increasing structural loading (Langhamer et al., 2009; Taormina et al., 2018). Similarly, fixed structures for offshore renewable energy, as well as oil and gas installations, covered by fouling receive an increased drag from currents and wave action.

2.2 Compromised structural integrity

Biofouling assemblages can play host to and provide a haven for a multitude of organisms and microbes. Some of these can have deleterious effects on the structural integrity of man-made structures such as ships and other static fabrications related to the marine environment. These include harbour walls, wharves, shoreline stabilization features (groynes) and the burgeoning number of offshore renewable platforms (Bugnot et al., 2021). The cause and nature of the fouling-induced deterioration will vary with the type of material used in the construction, the environmental conditions and the accumulated biofouling loading. If left unchecked, the continued weakening of the structure may lead to complete failure (Tsinker, 2004).

The following is a brief overview of the nature of the harmful effects of biofouling on the archetypal construction materials of wood, steel and concrete.

2.2.1 Wooden structures

Wood is a material extremely vulnerable to attack by biofouling organisms. The species of bivalve mollusc genera *Teredo*, *Bankia* and *Lyrodus* are communally known as shipworms and have posed a serious destructive problem in wood over several centuries. These creatures have long slender worm-like bodies which give them their common name, along with the fact that the species *Teredo navalis* has been identified as the prime worm responsible for damage to the hulls and the loss of structural strength in both ships and other fabricated structures.

Shipworms settle on a wooden structure and begin to excavate their way into the wood primarily as larvae. They continue to burrow and consume wood after metamorphosis (Stravoravdis et al., 2021), eventually becoming a long worm-like animal approximately 30–45 cm in length with a drill-shaped shell on its head, which it uses to burrow into the wood substratum to produce minute wood shavings for ingestion as shown in Figure 2.2.

Figure 2.2 Illustration of shipworm burrowing into timber.
Source: Ekaterina Gerasimchuk/Shutterstock.

Given that these creatures have a rapid reproduction rate and can create high-density infestations, their combined efforts of wooden material removal for growth along with the deep cavities they create can eventually weaken the wooden host structure to a point where it will be susceptible to collapse.

As an example of the wholescale damage that these biofouling creatures can incur, the introduction of the *Teredo navalis* into the west coast of the United States reached epidemic proportions between 1880 and 1920, causing massive wooden infrastructure damage to wooden piers, docks and wharves. The estimated cost of renewal and/or remediation along with the lost trade totalled around half a billion dollars (Nelson, 2016).

Shipworms are a global phenomenon and remain a menace to any wooden construction. The management of this structural threat in relation to the type of wood used in construction has been studied, along with the infestation positioning on wooden supporting piles (Hernández and Angelini, 2019). The study was carried out to identify more resilient wood types for construction material and to inform where to concentrate antifouling treatments on wooden structures to increase their functional longevity.

2.2.2 Steel structures

The presence of biofouling organisms in marine and freshwater environments can degrade and compromise the surface integrity of steel structures through several processes. Of these, corrosion represents a particular hazard as it has the potential to lead to the catastrophic failure of steel structures (Eckert et al., 2021). The potential for corrosion and consequent decomposition of immersed material such as carbon steel represents a serious threat to the integrity of fabricated structures. These include ships and many other steel structures, such as those associated with offshore renewable energy and oil and gas industries. Although inorganic electrochemical reactions involving exposed material surfaces interacting with an electrolyte such as sea or brackish water may occur as a part of the corrosion process, other forms of surface wastage directly associated with the biofilm phase of the biofouling dynamic are also common.

One form of corrosion arises due to sulphate reducing bacteria (SRB), which are microorganisms found in both marine and freshwater environments, more particularly in polluted waters (Melchers, 2013). During biofilm formation on a newly immersed object, the adsorption of molecules such as proteins takes place. These molecules form a conditioning film where SRBs and other such bacteria can attach themselves and subsequently initiate the production of further film density and eventually create dense localized colonies of SRBs (Little and Wagner, 2002). Once established within the biofilm matrix, these colonies will actively reduce sulphate to sulphide via respiration. In this process, Hydrogen Sulphide (H_2S) is formed which promotes the corrosion of iron and steel under the anaerobic (lack of oxygen) conditions within the biofilm (Cord-Ruwisch et al., 1987).

The nature of this corrosion is termed 'microbiologically induced/influenced corrosion' (MIC) and is characterized by localized severe corrosion pitting of carbon steel with deep pits filled with black corrosion products such as iron sulphide, as shown in Figure 2.3. Although there is still some debate concerning the precise chemical and biological mechanisms surrounding this organic form of corrosion (Little et al., 2020a, b), its existence is directly linked to biofouling and thus its control is based on biofouling mitigation measures.

Figure 2.3. Ship's Hull showing pitting corrosion.
Source: Gard P&I Club.

MIC occurs not only on surfaces such as ship hulls but can cause severe corrosion in other areas of marine structures such as within a ship's ballast and oil tanks, to the extent where catastrophic structural failure can occur (Cui et al., 2016). Similarly, the deleterious effects of MIC and resultant corrosion fatigue on higher strength steels used in offshore structures have been highlighted by the UK Health and Safety Executive (Robinson and Kilgallon, 1998).

2.2.3 Concrete structures

Concretes designed to meet the appropriate requirements of EN 206-1 and BS 8500 are used in the harsh environmental conditions experienced in marine and coastal applications. Both in situ and precast concrete are used in a wide range of applications along the coast. In ports and harbours, concrete often forms the main structural body of quays, used in caissons, blockwork or diaphragm wall structures. Whatever form of substructure construction is used, concrete is invariably used for the quay deck[3].

Such concrete structures are susceptible to biofouling (Figure 2.4) and there is continuing discussion as to the nature of concrete deterioration due to both microbial and macro biofouling. Overall, the fouling of concrete surfaces by organisms such as those found in biofouling can have negative effects which may accelerate deterioration of the concrete (Gaylarde and Morton, 1999).

Research into the use of fine aggregates mixed with concrete to create marine structures (Hughes et al., 2013) showed that the vast communities of common microorganism fouling group Chlorophyta (green algae) can often form green uniform microbial lawns, in some places several millimetres thick and localized at the surface of the concrete shell. These filamentous microalgae can actively bore into carbonate concrete substrates to produce networks of minute branching passageways which may connect to form cavities up to 25µm wide (Golubic et al., 1975). The effects of this tunnelling and algal colonization at the cement-aggregate matrix interface of a marine concrete structure were examined microscopically (Hughes et al., 2013). Biodeterioration of the concrete was noted as a result of the coiled algal filaments running through the structure.

3 See https://www.concretecentre.com/

Figure 2.4 a) A concrete marine structure with severe biofouling. *Source:* Vorathep Muthuwan /Shutterstock.com; b) Mussels on a pier pillar. *Source:* Mikeledray/Shutterstock.com

The mussel is a predominant macro fouling bivalve mollusc. It is found in both saltwater and freshwater habitats and can occupy large expanses of concrete structures as shown in Fig 2.4. Investigations have been carried out on the capability of the freshwater mollusc Limnoperna fortunei to cause both chemical and physical deterioration on concrete structures (Yao et al., 2017). This work highlighted the fact that the adhesive byssal threads holding the mussels onto concrete surfaces could effectively penetrate into the concrete layers, physically separating concrete constituents and causing fissures in the structure. The resultant porosity allows water to access and corrode the steel reinforcing bars contained within the concrete medium (Pérez et al., 2003).

Calcium carbonate is a substance added to help increase the strength of concrete. It also improves concrete's particle packing, provides concrete with a spacer effect and promotes self-compacting properties of concrete. In addition, calcium carbonate reduces porosity and air voids in concrete which improves pumpability and adds to smoother surfaces (NOAH Chemicals, 2023). The results of testing concrete samples colonized by Limnoperna fortunei and similar uncolonized concrete samples showed a significant reduction of calcium carbonate in the colonized test concrete with a resultant rise in the concrete deterioration. An increase in water absorption of 79–99% and a compressive strength loss of 21% was noted as a result of these tests (Yao et al., 2017). The loss in strength was ascribed to calcium being absorbed from the concrete by the mussels for building their shells (Silverman et al., 1983).

Yao et al. (2017) also highlighted that, although the research was carried out on a freshwater species of mollusc, the similarities in life processes between that species and marine molluscs such as the infamous Zebra and Quagga mussels would suggest that prolific marine molluscs may also contribute to accelerated concrete structure decay in saline waters.

A review of current biofouling management strategies across a variety of industries utilizing submerged artificial structures (Hopkins et al., 2021) concluded that the range of tools currently available to manage marine biofouling on static structures lacks sufficient proactive options to effectively limit the associated detrimental consequences to infrastructure and the environment. The review also highlighted the potential use of emerging technologies, such as those outlined in Chapter 3 of this report, along with their practical use when considering the cost–benefit analysis of biofouling control strategies for owners and operators of marine structures.

Some specific industries can suffer other unique surface degradation concerns, as described in the following sections.

2.3 Biofouling impacts on cooling water system circulation

The use of both fresh and marine water is a common method of providing a cooling medium for both ship machinery and industrial activities such as power generation, steel production and oil refining.

Large-scale activities of this nature are often sited in areas where there is access to large volumes of river or seawater available for use in a 'once through' or 'recirculating' heat exchange process[4]. In such systems, the local water supply is drawn up into the system by pipework and pumps and is then passed through a heat exchanger to absorb some of the heat generated by the manufacturing process before being returned to its original source at an elevated temperature.

The main impact of biofouling on industrial heat cooling water systems is the reduction in heat transfer efficiency. Biofilms forming on the surfaces of heat exchange mechanisms such as coils, condensers and plate heat exchange units can considerably reduce the overall efficiency of the cooling system. This reduction in efficiency can lead to increased energy consumption and higher operating costs due to internal mechanical and chemical cleaning of components (Melo and Bott 1997). In a similar manner, the build-up of biofouling material on internal pipework and pumping arrangements can reduce the flow of cooling water, requiring more pump output to maintain the internal components' operating temperatures.

This can be a consideration for vessel propulsion systems; aspects addressed as part of reduced functionality in Sections 2.5 and 2.7. During oil and gas operations, water is taken in for on-board cooling systems providing electrical power and also emergency services such as fire pumps, etc. In such cases, any restriction of flow due to biofouling can have severe repercussions. Wind energy does not rely on circulating water, but the impacts of biofouling on water circulation may increase in priority for wave and tidal energy production, as these sources of energy are developed further.

Biofouling can also cause enhanced corrosion in cooling water systems due to the presence of microorganisms and other fouling deposits, which can create localized areas of low oxygen concentration and high acidity leading to the formation of localized corrosion cells and deep pitting in the steel types employed in the cooling water system construction (Choudhary, 1998). The potential increase in corrosion rates can lead to partial failure of the overall cooling system and may consequently require more frequent periodic shutdowns of the cooling water plant for inspection and replacement of components (Sudhir et al., 2021).

2.4 Biofouling impacts on aquaculture

In aquaculture, biofouling obstructs the mesh, reducing water flow and removal of waste within the cage. This results in reduced water quality and increased risk of harmful algal blooms within the cages. Excessive biofouling may result in the depletion of dissolved oxygen within the cage, resulting in effects on the fish, ranging from a sudden reduction in feed consumption, to increased incidences of pathogens and disease outbreaks, up to the loss of the entire cohort of fish owing to anoxia. Fingerlings in cages with a small net-mesh size are the most vulnerable to catastrophic losses, especially if periods with low or no current occur at the site (Cardia and Lovatelli, 2015). The biofouling itself can also inflict direct damage on the nets due to the abrasive action of the fouling, whereby shells or other hard parts of invertebrates rub against the netting and ropes and cause damage, such as holes in the netting or severed ropes (Cardia and Lovatelli, 2015).

In shellfish, aquaculture biofouling can damage shells and may reduce fitness due to competition for food and oxygen or smothering, and can impede valve function. Algae are similarly impacted when overgrown by fouling organisms as this may reduce availability of light and nutrients and hinder metabolite exchange. In both cases, the added weight and physical damage will impact market value and may directly lead to growth reduction and loss of stock (reviewed in Bannister et al., 2019).

2.5 Biofouling impacts on industrial desalination plants

Biofouling also represents a significant threat to the efficient and safe operation of desalination plants. Desalination has become an increasingly important source of freshwater for arid and semi-arid regions where freshwater scarcity is a major issue. One of the most challenging factors to the use of desalination plants is the control of biofilm growth on the surfaces of the fitted reverse osmosis membranes, such as those used in the membrane distillation (MD) process which

4 See WNA (World Nuclear Association): https://world-nuclear.org/our-association/publications/technical-positions/cooling-of-power-plants.aspx

can generate high-quality water by combining the processes of conventional heat-driven distillation and membrane separation (Costa et al., 2021).

The membrane technologies used in desalination plants are particularly prone to the formation of recalcitrant biofilms being formed on the membrane surface by the presence of bacteria and their extracellular polymeric substances which the bacteria secrete to establish the functional and structural integrity of the created biofilm. This secreted film provides protection of the microbial communities from any local harsh environmental conditions and provides a haven for the proliferation of pathogens, bacteria and viruses which may be present in the incoming local water supply. Although the reverse osmosis process is designed to remove bacteria and larger pathogens, the membrane may become blocked or suffer breaches of integrity due to excessive biofouling. This in turn presents a potential risk to human health due to the possible concentration of marine toxins being carried over into the finished water quality. This latent threat can be increased during the presence of algal blooms in the supply water sources (Boerlage and Nada, 2015).

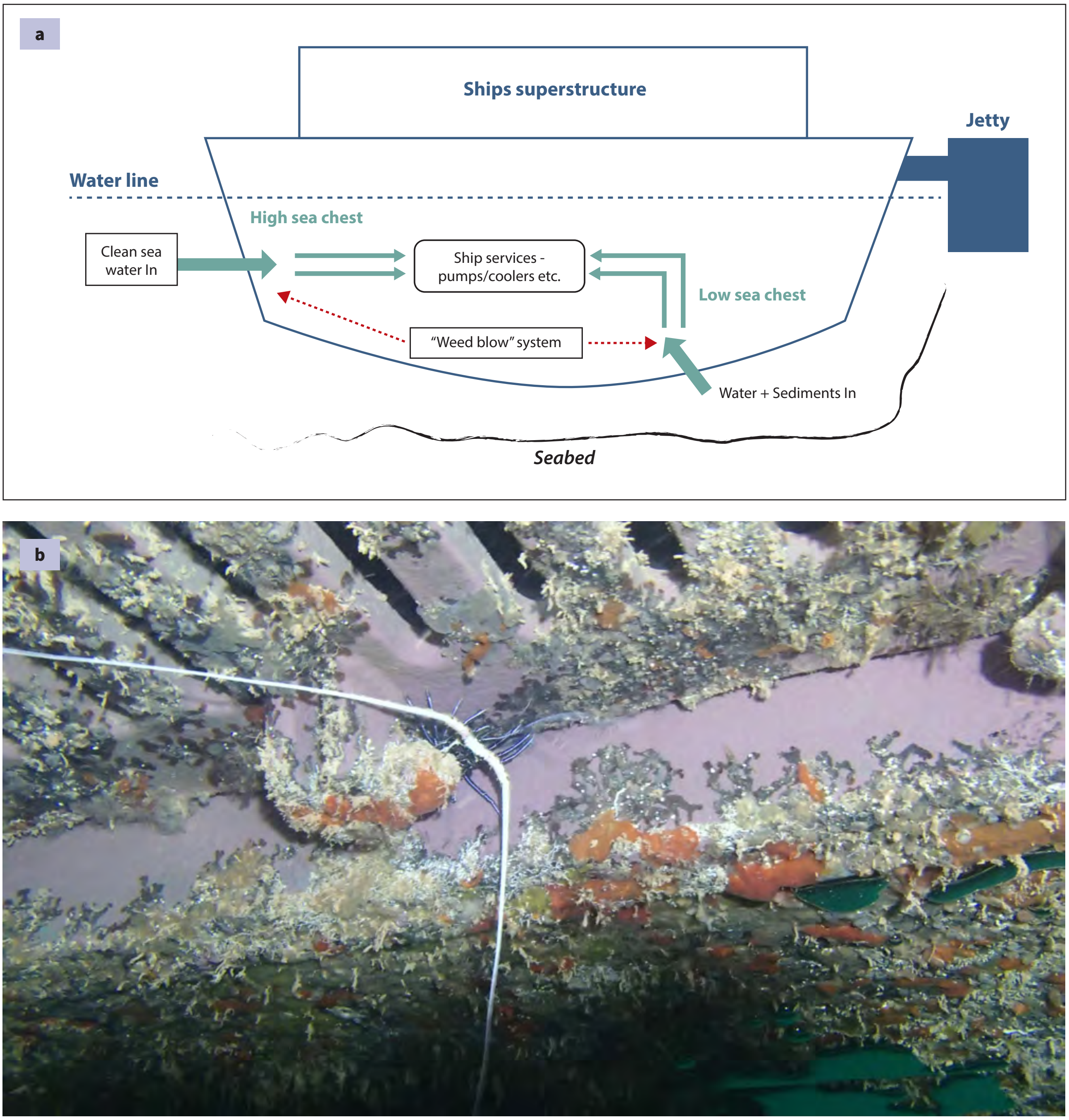


Figure 2.5 a) Typical sea chest arrangement showing sea chest location and fouling. *Source:* David Smith; b) Internal sea chest fouling. *Source:* Ashley Coutts (Biofouling Solutions Ltd).

In a similar manner to cooling water systems, there may be reduced efficiency due to partial blockage of pipes, and increased operating pressures to maintain the desalination process may be required, along with the potential for microbial corrosion, which can also lead to reduced quality water production and increased maintenance costs. Because biofouling can reduce the quality of the water produced by desalination plants by introducing bacteria, viruses and other pathogens, it can lead to health risks for consumers and increased post water production treatment costs to meet acceptable standards (WHO, 2011).

2.6 Direct impediment of functionality

Biofouling can impact functions associated with many of the structures in which these communities can form. For example, several functions involved in vessel performance can be decreased by biofouling. Biofouling on the surface of a ship's propellor can make the propellor less smooth and consequently reduce thrust performance due to cavitation, trailing turbulence and frictional losses. Research carried out using computational fluid dynamics indicates that severely fouled propellers can result in a 19% loss in thrust efficiency (Song et al., 2020). Similar performance impacts have been observed in the power delivery performance of tidal turbines (Orme et al., 2001; Walker et al., 2014). Functionality can also be impeded on vessels through biofouling of niche areas.

According to the 2023 IMO Biofouling Guidelines, niche areas are a subset of the submerged surface areas on a ship that may be more susceptible to biofouling than the main hull, owing to structural complexity, different or variable hydrodynamic forces, susceptibility to AFC wear or damage, or inadequate or no protection by AFS (IMO, 2023). Due to their nature and location, niche areas are considered to foul more easily than the flat sides of a ship's hull and thus represent an enhanced opportunity for biofouling establishment and growth (Miller et al., 2018). These same effects also apply to smaller vessels used for recreational purposes.

The extent of colonization of marine species in sea chest niche areas has long been recognized as a factor in reducing a ship's operational efficiency. A sea chest is a watertight box recessed into the underwater area of the hull. It is fitted with an external protective grating on the side open to sea and with internal pipework suctions which supply seawater to onboard equipment such as machinery cooling systems and pumps (see Figure 2.5). When biofouling builds up in a sea chest or other internal seawater systems (Davidson et al., 2023), it can reduce the flow of water available in the ship for pumps and coolers, which may cause machinery to operate at higher than design temperatures with attendant risk of overheating and potential failure. In addition to this, fouled sea chests serving essential safety functions such as pumps may severely reduce emergency response capability for services such as firefighting.

Larger ships normally have two sets of main sea suctions: the lower suction used at sea to avoid cavitation and suction loss when the ship is rolling/pitching, and the higher suction used when the hull is near the sea bed, to avoid drawing in sediment.

As summarized in Section 2.4., in aquaculture for marine plant culture, biofouling can impede both the functionality of the culture facility though reducing light penetration and reducing algal growth; and for shellfish culture, it can also impede the function of the shellfish valve, reducing growth rates.

In maritime sectors such as offshore renewable energy, the current in electric cables causes the cables to heat up, which tends to be dissipated by the surrounding seawater. Biofouling on electric cables will create a physical barrier between the cables and the seawater, impeding the cables from cooling, potentially making them less effective up to the point of stopping working.

For all sectors, these impacts on functionality often lead to industry identifying best practices for their management. Even when identified as 'best practices', specific actions are less likely to directly influence regulatory standards in ways that would make the 'best practices' mandatory, unless the impacts could have serious and/or widespread consequences.

2.7 Ecological consequences

Direct and indirect ecological consequences of biofouling include providing a potential pathway for NIS, which will be addressed in the rest of this report. However, there are documented cases where other types of consequences have also occurred. These include:

Habitat alteration and engineering: Whether a species is native or not, its mere presence in biofouling assemblages can result in the alteration of habitats and ecosystems. The presence of artificial structures in the water provides additional habitat that would not have naturally occurred there. This increases the spatial extent of available substrata and thus the presence of biota that would not have occurred there naturally. As a result, this increased presence of biological communities can play a role in blue carbon sequestration through increased storage of carbon. Similarly, due to the presence of communities that may not have occurred there previously, one would expect changes in species diversity, by way of either an increase or a decrease. Further, by their mere presence, biofouling communities form part of the already occurring nutrient cycles in the system and therefore can play a role in taking up more nutrients from naturally occurring communities, but can also contribute nutrients into the system.

Changes in food web composition (shifts in trophic levels) or community functioning: Changes in the composition of food webs is necessarily linked to changes in nutrient cycling, to the extent that the cycling of energy and nutrients occurs within food webs. However, here the focus is on changes in trophic levels, where biofouling assemblages result in the presence of new predators or prey that previously were not occurring naturally in the environment. The new species can result in organisms recognizing a novel food source and altering firstly the number of organisms available at particular trophic levels; the new species could also contribute to other species experiencing a change in trophic levels, potentially altering the complexity of foodwebs.

Competition for space, light, plankton and nutrients: As with many of the other consequences, the presence of biofouling communities may have direct and indirect competitive influence in the environment. Biofouling communities can introduce novel pathogens or increase the extent of pathogens that can influence the ecological function of existing ecosystems. Biofouling organisms on aquaculture installations in particular may harbour pathogens that can infest the cultured stock as well as organisms from the surrounding ecosystem and can act as a refuge for disease. Examples include blue mussels that can harbour Vibrio bacteria detrimental to cod (Pietrak et al., 2012), or terebellid worms that are secondary hosts to blood flukes which infest bluefin tuna (Sugihara et al., 2015). In the case of aquaculture, this is particularly relevant where farmed shellfish and algae compete with biofouling organisms for settlement space on culture substrates, especially if the culture relies on the collection of natural spatfall. Filter feeding biofoulers may in addition deplete planktonic food sources in the direct vicinity of shellfish. Similarly, epiphytes may compete with seaweeds for nutrients, in addition to blocking light (reviewed in Bannister et al., 2019).

Increased population connectivity (stepping stones) for native and non-native species: Biofouling communities, made up of both native and NIS and being moved around by various pathways, may result in more pronounced ecological connectivity (Fernandez-Gonzalez and Sanchez-Jerez, 2014) and in some cases cause an increase in the distribution of particular species (Tsotsios et al., 2023). Populations of the same species that may not have had any connectivity previously may end up having some form of connectivity, thereby influencing gene flow of particular organisms (Lowe and Allendorf, 2010).

These consequences have not been influential in shipping industry practices or regulations in most vessel types, but have been considered in some of the other industrial sectors in this review. It is plausible that consequences such as the provision of new or altered habitat, serving as a reservoir for pathogens and even competition for nutrients, occurs with platforms involved in energy production and some types of sensors or other instruments, but these have received little study and have not yet given rise to a serious discussion about industry best practices in these sectors.

2.8 Economic consequences

These consequences all impose economic costs on uses of equipment and instruments and the generation of market products from aquaculture. For submersed instrumentation, biofouling is the single biggest factor affecting the operation, maintenance and data quality. There are direct costs associated with the maintenance/repair/replacement of instrumentation of all types. There are also indirect costs associated with reduced reliability of decision-making in cases when biofouling results in suboptimal and sometimes misleading performance of research instrumentation, or when mitigation measures for the biofouling alter the instrumentation calibration or performance. These direct and indirect costs have stimulated substantial investment in developing effective measures and strategies to combat biofouling of static structures involving instrumentation. Antifouling strategies also play a critical role in developing present and future aquatic sensor and sensor networks. Although progress in combating biofouling on instrumentation has been slow, many of the measures presented in Chapter 3 and Section 4.5 were developed or improved to address these areas of concern.

2.9 Safety and health

This section gives a brief overview of some of the inherent features of biofouling that can have a direct impact on basic safety and health issues both for humans and aquatic species.

2.9.1 Safety of personnel

Coastal shoreline structures such as docks, harbours and marinas may have numerous points of access and egress for personnel and transport units. These may include steps, ladders and slipways to provide a passageway between shore facilities and ships and boats. For aquaculture and some other coastal activities, walkways and transport routes to beaches and other resources may only be fully exposed at low tidal heights. As these access routes may span the intertidal zone, they can become readily colonized by biofouling algae and become extremely slippery due to the high quantities of slimy mucilage generated by the fouling flora to protect themselves from drying out when exposed to air. As a consequence of this, conditions underfoot and for vehicles can become treacherous when these access routes are not kept clear of biofouling and can cause multiple accidents and injuries.

Slipways represent the quintessential slippery slope. They are used to launch and recover trailer-borne craft and can

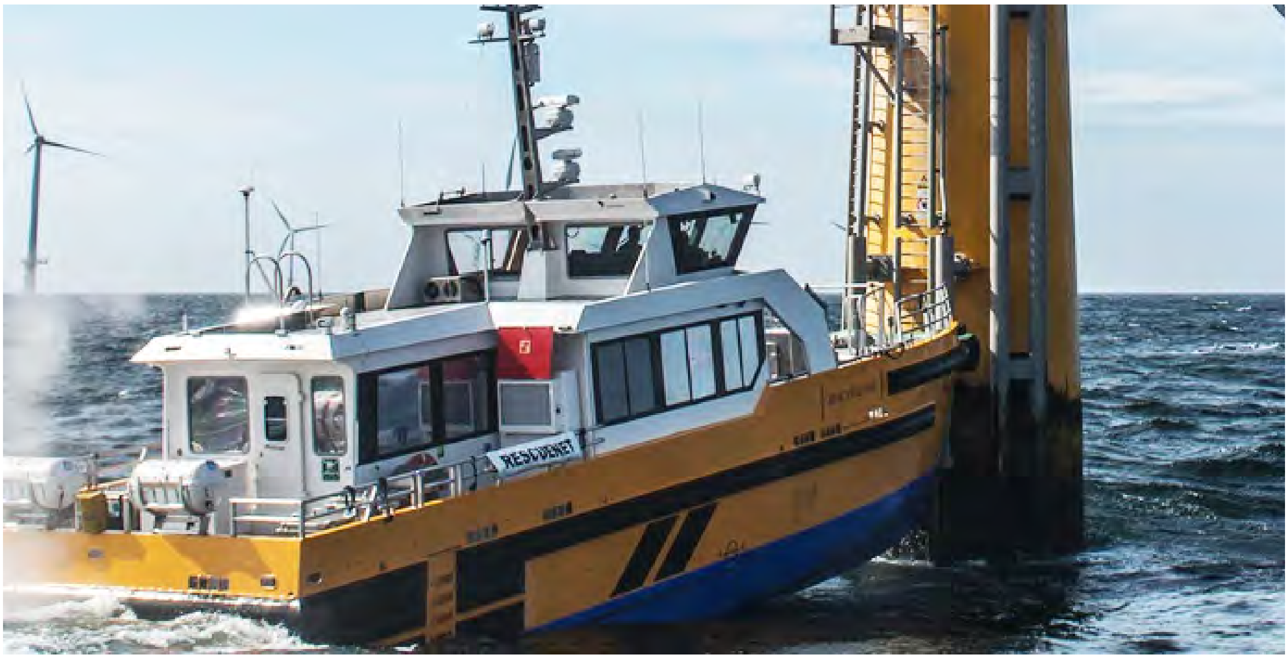


Figure 2.6 Windfarm service workboat and vertical access ladder. Note biofouling above the water line.
Source: Windcats.

present a serious risk of accident if not kept clear of fouling. Slipways are also used in smaller ferry operations where the risk to passengers and vehicles boarding and leaving the vessel can be critical if the level of biofouling on the slope is not controlled.

Where control of biofouling in such access points is undertaken, water jet blasting is a common method used to remove the algae, even though some damage may occur to concrete and wooden surfaces over the longer term. The use of chemical substances combined with manual scrubbing is also an alternative, although this can have unintended detrimental environmental effects if the chosen biocide is persistent and harmful to the local waters (Sections 3.2, 3.3). Local Environment Authority permission may be required to use such chemicals (UK Government, 2015).

The burgeoning offshore renewable energy market has also introduced some challenges in the form of providing and preserving safe means of access to offshore installations such as wind farm monopile towers. These structures require regular access for maintenance purposes and have fixed vertical ladders as shown in Figure 2.6 to provide access from the service workboat to the tower at all states of the tides.

As these vertical ladders are exposed to tidal variation and biofouling accretion, they can readily become slimy as a result of intertidal algae and present a grip hazard for the ascending service engineer (Klijnstra et al., 2017). Novel methods to provide biofouling prevention to such ladders have been researched, where a trial of an acoustic solution based on that outlined in Section 3.4 took place with a view to further development (Salimi et al., 2023).

2.9.2 Health of aquatic species and humans

Marine pathogens include microorganisms that can cause diseases in marine organisms such as fish, mammals, invertebrates and plants. They can be bacterial, viral, fungal, or parasitic in nature and are found in marine environments including oceans, estuaries and coastal waters. Marine pathogens can have significant impacts on the health and survival of marine organisms and can also affect the functioning of marine ecosystems. Harmful microalgae including pathogens can be found in the microbial biofilm associated with biofouling accretion both on ships' hulls and other marine structures (Drake et al., 2005; Revilla-Castellanos et al., 2015).

The harm caused to marine creatures by exposure to pathogens contained within biofouling is a well-known phenomenon in the aquaculture industry, with biofouling identified as a potential health risk to both cultured shellfish and finfish by providing a haven for pathogens that can cause various diseases (Bannister et al., 2019).

As an example of pathogen transfer from the water column to biofouling and then on to aquatic victims, research has indicated that the common mussel *Mytilus edulis,* frequently found in macrofouling, has the ability to uptake pathogens such as the bacteria *Vibrio anguillarum* and store concentrations of this bacteria at levels some two orders of magnitude above that of the surrounding water. These *vibrio*-laden mussels can then release high levels of the pathogen in their faecal pellets

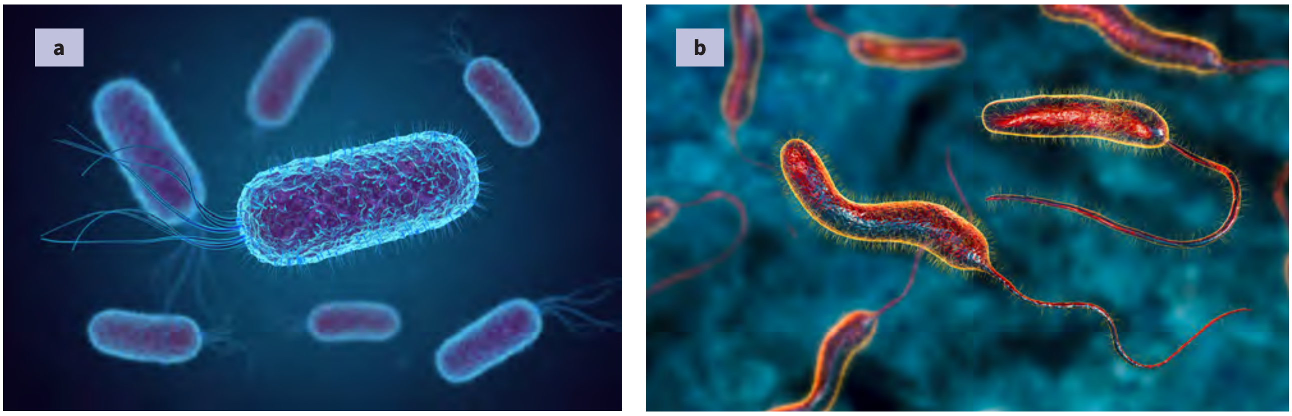


Figure 2.7 a) *Vibrio cholerae*, length 1.4 to 2.6 µm. *Source*: Kateryna Kon/Shutterstock; b) *Escherichia coli*, length 2 µm. *Source:* fusebulb/Shutterstock.

which, if up taken by fish, can cause mass mortality of certain species due to vibriosis haemorrhaging (Pietrak et al., 2012).

There are many types of pathogen-related diseases affecting aquatic species health. The World Organisation for Animal Health (originally founded as the OIE) has an Aquatic Animal Health Code which lists common infections of aquatic species and the pathogen responsible[5]. Many of the pathogens identified in the code can be associated with biofouling such as *Bonamia ostreae* in Chapter 11.3 of the code, and which can be found in both vessel and harbour fouling types.

Although the pathogens found in biofouling have a recorded history of infections in aquatic creatures, they can also have deleterious effects on humans. There have been occasions when serious infection has occurred as a result of manual handling or other exposure to biofouling. The Australian Institute of Health and Safety issued a safety warning after a worker contracted a life-threatening respiratory infection from the bacteria *Psychrobacter sanguinis.* The infection was reported to have been caused by the operative having been involved in cleaning biofouling from marine infrastructures including jetty pylons. The warning advice highlighted the potential for infection through nicks or cuts in the skin or by inhalation or ingestion (Government of Western Australia, 2020). It is noted that this harmful bacterium previously has been isolated from marine species and environments, including seaweed in macrofouling material (Bonwitt et al., 2018).

The International Convention for the Control and Management of Ships Ballast Water and Sediments entered into force in September 2017 (IMO, 2004) and includes a health standard set as a maximum allowable ballast water discharge constraint of indicator microbes. The microbial pathogens chosen as indicators are clinically significant to humans, as they can potentially cause life-threatening disease on an epidemic scale or have a severe adverse effect on health by causing a variety of infections, typically with accompanying extreme diarrhoea and vomiting.

The indicator pathogens and ballast water discharge limits are:

- Toxicogenic *Vibrio cholerae* (O1 and O139) with less than one colony-forming unit (cfu) per 100 ml or less than 1 cfu per 1 gram (wet weight) zooplankton samples (Figure 2.7.a)
- *Escherichia coli* less than 250 cfu per 100 ml (Figure 2.7.b)
- Intestinal enterococci less than 100 cfu per 100 ml

It has been known for many years that several bacterial pathogens found in the marine environment can produce biofilms (Huq et al., 2008). Further, it has been shown that marine biofilms on ships' hulls and in other areas such as harbours can form a reservoir for *Escherichia coli* and *Vibrio cholerae* (Shikuma and Hadfield, 2010). The threat of ballast water pathogens has been recognized for several years and the same suite of pathogens can be identified within the marine biofouling found on ships and other marine structures, resulting in a growing realization and increased scientific evidence that biofouling of vessels posed a pathogenic threat to humans. This feature of marine biofouling and the role of vessels in the carriage and distribution of such potentially harmful organisms to both the aquatic and human environment has been previously highlighted, along with the proposed need for further prevention management measures (Georgiades et al., 2021). This need has been reflected in the 2023 IMO Guidelines which include pathogens in the definition of 'biofouling' (IMO, 2023).

5 Available at: https://www.woah.org/en/what-we-do/standards/codes-and-manuals/

3. STRATEGIES AND APPROACHES USED TO ADDRESS/REDUCE BIOFOULING AND/OR RISKS OF BIOFOULING

The prevention and control of biofouling is a very difficult task which tends to further complicate the current scenario of climate change and increasing seawater temperatures (Vinagre et al., 2020; Delgado et al., 2021; Dobretsov et al., 2019). This chapter reviews the major strategies used to control, mitigate and prevent biofouling on surfaces exposed to marine environments. It presents the general characteristics of the major approaches used within each strategy. Because the effectiveness and appropriateness of each strategy may differ among industry sectors, the general properties and general strengths and limitations of each strategy are summarized here. The details of application of each strategy in individual industry sectors are presented with references in Chapter 4. For each strategy, this chapter summarizes the key strengths and enabling contexts for promoting their effectiveness, along with identified key weaknesses or concerns about their ancillary effects that may limit their use, within the overall context of deterring or reducing biofouling. Chapter 4 builds on this information, discussing implementation of these general strategies in the individual industry sectors.

Underlying regulations and guidance that are specific to strategies and approaches chosen in different industry sectors are examined in each relevant subsection below. Two global provisions of UNCLOS that are applicable to all sectors deserve to be recalled here. These are Articles 195 and 204 of UNCLOS, which apply to governments when devising response strategies to prevent, reduce or remove biofouling in order to decrease the risk of introduction of NIS. First, 'a bad cannot be traded for another bad', so national governments have the duty not to transform one type of pollution into another. Therefore, response strategies developed to reduce or de-risk the introduction of non-native species via biofouling must not create another source of pollution (UNCLOS Article 195). This is of particular relevance, for example, to antifouling and other coating systems used to prevent biofouling; these coatings must not be harmful to the marine environment. Second, national governments must also observe, measure, evaluate and analyse by recognized scientific methods the risks and effects to the marine environment of such interventions, if they permitted them or they are under their jurisdiction or control (UNCLOS Article 204). This is the case whether they are carried out within their national jurisdiction, under the control of national entities, or by their nationals. UNCLOS also includes a further obligation of surveillance in case of a risk of significant and harmful changes to the marine environment (UNCLOS Article 206).

3.1 Mechanical removal of biofouling

Physical/mechanical removal of accumulated biomass has been practised since the biofouling nuisance was first experienced by humans. Localized cleaning of components may be carried out by hand using scrapers and stiff brushes and larger areas of a substrate may require high pressure water jetting. The jetting forces water across a surface under pressure high enough to generate sufficient shear force to remove biofilms that do not adhere too tightly to the substrate (Figure 3.1) (Bannister et al., 2019). When the structures supporting the biofouling community are readily moveable, as in the case of some shellfish culture equipment, the need for physical scrubbing can be reduced by actions discussed in other sections of this chapter, depending on the type of culture equipment (e.g. Rolheiser et al., 2012; Cahill et al., 2021).

Mechanical biofouling removal techniques employed on structures still immersed in water is a methodology gaining recognition in certain industries, such as commercial shipping, as reviewed in Section 4.1. Divers using handheld equipment to polish propeller blades, as shown in Figure 3.2, has been a common practice for many years (4.1.1.4), as it maintains effectiveness of the rotating propeller by smoothing the surface roughness of each blade and thus reducing hydrodynamic cavitation to maintain the designed thrust per revolution.

In-water cleaning (IWC) of larger areas, such as a ship's hull, has become an increasingly applied approach to managing biofouling and can provide consequential fuel saving and emission reduction (Hopkins et al., 2010). This is as a result of the combination of evolving antifouling coating technologies coupled with the development of IWC systems (4.1.1.4).

The traditional removal of biofouling on ships and platforms through IWC has involved divers or remotely operated (ROV) cleaning units, which use scraping tools, brushes or water jets to remove macrofouling from submerged surfaces without capture of released debris (i.e. fouling organisms and coating material) (Jones, 1999; McClay et al., 2015; MPI, 2015). However, without the capture of debris, IWC can directly lead to discharges of NIS and harmful components of marine coating, including biocides and microplastics (Scianni and Georgiades 2019; Tamburri et al., 2020; Tamburri et al., 2022). IWC technologies are therefore rapidly developing to either (a) capture and process debris removed from cleaned surfaces, or (b) to conduct periodic proactive

Figure 3.1 Removing biofouling by high Pressure Water Jetting.
Source: Tawansak/Shutterstock.

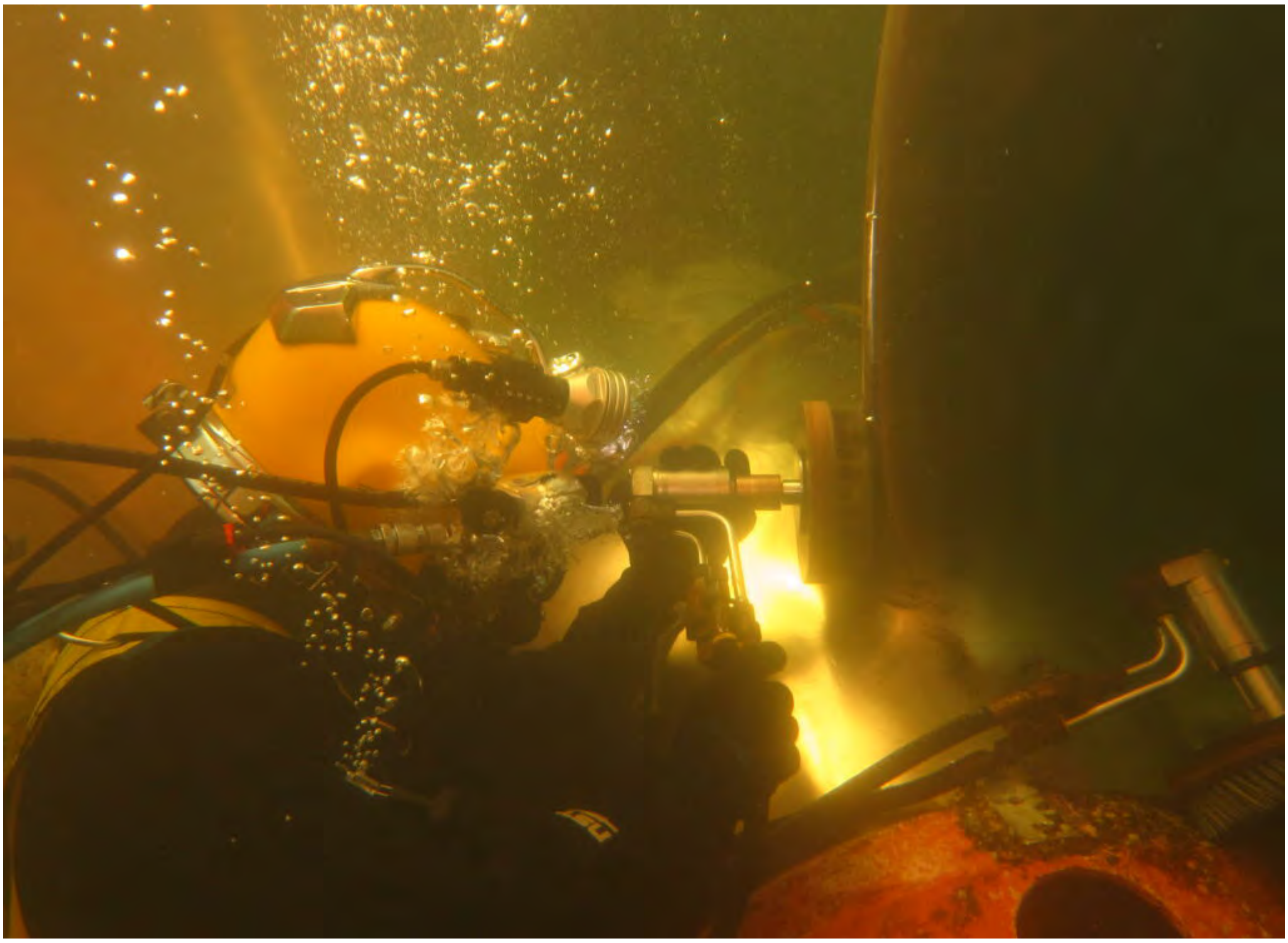


Figure 3.2 Diver undertaking propeller blade polishing in port.
Source: Hydrex.

IWC (i.e. reduction/removal of biofilms to prevent or inhibit/limit macrofouling growth) (Tribou and Swain, 2010; Scianni and Georgiades 2019; Tamburri et al., 2020). Proactive IWC is viewed as a relatively low risk for NIS introductions because it may ultimately minimize the translocation of macrofouling species (if any). However, while proactive IWC is typically less abrasive than macrofouling removal, substantial amounts of microscopic material (biological and chemical) of concern can be released into the environment unless a debris capture process is included. The frequency of needed IWC will depend greatly on many variables, including on location of operation, operational tolerances and environmental conditions (Atalah et al., 2016; Tamburri et al., 2020).

In aquaculture, autonomous brush-based technology that cleans pens constantly is starting to enter the market (Bloecher and Floerl, 2021). While tested successfully for hull cleaning (Swain et al., 2022), information about the efficacy of this technology in aquaculture is currently lacking. However, aquaculture facilities have tested methods to facilitate mechanical cleaning with immersion in freshwater and acetic acid, to loosen the attachments of the biofouling community and results have been promising (Jute and Dunphy, 2017; Rolheiser et al., 2012; Cahill et al., 2021).

Strengths and enabling conditions

IWC is gaining popularity in the biofouling management of larger surface areas such as that represented by ships' hulls. Its proponents in the shipping industry present it as a cost-effective way of minimizing the effect of hull drag created by the formation and accumulation of fouling organisms. There is also the possibility of avoiding more frequent visits to a dry dock to remove excessive fouling. When feasible, shore-based clearing, with the vessel temporarily removed from the water or beached, can eliminate or greatly reduce the release of organisms into the water, thus reducing risk of NIS transfer (Woods et al., 2012; Castro et al., 2020).

Mechanical methods may not involve the use of large quantities of toxic products with consequential environmental impacts, although hand cleaning may sometimes involve the low-scale use of proprietary cleaning agents which may contain toxic compounds (MPI, 2013).

In aquaculture, proactive cleaning may have the additional benefit of preventing the release of particles that could harm fish gills or transfer pathogens to the culture organisms (discussed in Bloecher and Floerl, 2021).

Constraints and limitations

The physical removal of biofouling is commonplace, but although the process may be effective, the final fate of the removed detritus from such cleaning requires consideration in applications (MPI, 2013; MPI, 2018; Paetzold and Davidson, 2010; Hopkins and Forrest, 2008; Tamburri et al., 2021). When such material is generated in a dry dock, it may be placed in an open container and left on the dockside for several days with the possibility of species leaching out and returning into the local waters. In a similar manner, when cleaned biofouling is removed from a component such as a seawater cooler or filter, it will often be brought back onto deck and jettisoned over the side of the ship or platform. There may be a case for treating the residue from a biofouling cleaning exercise as a controlled waste and handling it as such.

When physically removing biofouling organisms and communities, and particularly if biocides are being used as part of the process, human impacts must be considered. Suitable physical protection (masks, goggles, gloves) and/or air cleaning systems are needed if scrapers, brushes, jets or sand-blasting release dust, waste materials and debris to the air or exposed skin, risking contamination. In addition, in contexts such as aquaculture facilities the released organisms, waste and debris may affect the health and marketability of culture products (Willemsen, 2005; Bloecher and Floerl, 2021).

The goal of IWC is to reset surfaces to a more hydrodynamically smooth condition. However, it can also result in several unintended consequences, including:

(a) increased coating biocides and when present in the coatings, microplastics, discharged to ambient waters;
(b) increased risk of IAS introductions through the release of live biofouling organisms to local ecosystems; and
(c) possible damaged or diminished coating condition, resulting in reduced antifouling performance (Scianni and Georgiades, 2019; Tamburri et al., 2022).

There remains a lack of detailed evidence related to the full environmental consequences of different approaches to IWC of biofouling necessary for the assessment of potential risks associated with biological and chemical contaminants. This lack of evidence leaves substantial uncertainty and untested assumptions about current or future methods of cleaning (MPI, 2013).

Adverse environmental impacts from the release in the water column of (i) antifouling paint flakes of the surface coating being cleaned; and/or (ii) fouling organisms removed have been raised in discussions of the Marine Environmental Protection Committee (MEPC) of the IMO and those of the meetings of the State Parties to the London Convention and its Protocol (LC/LP) on the prevention of marine pollution by dumping of waste and other matter. These different regulatory bodies are competent in different but complementary aspects. Whereas the operational pollution from shipping falls is the competence of the IMO as the international body regulating shipping, the disposal of toxic material or removed fouling organisms in the water column falls within the regulatory mandate of the LC/LP.

Figure 3.3 Applying an antifouling paint to a hull in a dry dock.
Source: Lee Adamson.

Although an important milestone was reached in July 2023 with the adoption of revised IMO Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species, replacing the 2011 IMO Guidelines on this topic, guidance on IWC has been carved out for development in a separate guidance document on matters relating to IWC, with a target completion year of 2025 (IMO 2011, 2023). The 2023 IMO Guidelines acknowledge that IWC is a 'complex activity to manage appropriately and international standards for the management of IWC may continue to be developed and published in a stand-alone document to the Guidelines'. However, they also emphasize the risks related to IWC on antifouling coatings, including the release of harmful substances. Noting that cleaning is an important measure to remove biofouling from the hull and niche areas but that, when conducted in-water, it poses a risk of releasing IAS into the water, the general guidance provided for all cleaning of fouling organisms is to collect waste substances which are dislodged from the ship during the cleaning operation. The Guidelines also provide guidance for cleaning actions based on a fouling rating number with an overall aim to minimize the risk of transfer of IAS (IMO, 2023).

In parallel to these on-going developments at the IMO, under the auspices of the MEPC and its subcommittee on Pollution Prevention and Response (PPR), the LC/LP are also developing revised guidance on best management practices for the removal of antifouling coatings from ships, including TBT hull paints approved in 2009 (LC-LP.1/Circ.31 and AFS.3/Circ.3.) and revised in 2014 (LC-LP.1/Circ.31/Rev.1 and AFS.3/Circ.3/Rev.1). This guidance also includes the issue of organisms or coatings falling to the seabed from iIWC activities, which could potentially interfere with dredging and dredged material disposal operations that are regulated by the LC/LP. Further, following the 2021 amendments to the AFS Convention to introduce controls on cybutryne (MEPC.331(76)), this Guidance document was amended in 2023. The Revised Guidance on Best Management Practices for Removal of Antifouling Coatings from Ships is more generic than the previous version, which was focused on TBT removal (LC-LP.1/Circ.108).

3.2 Coating systems

This strategy includes several related methods for preventing or discouraging the colonization of a surface by biofouling organisms, and/or for prompting release if attachment has started. These include external sheathing with a variety of coatings, plates, sleeves and meshes.

Since the 1900s, the 'go to' solution to alleviate the effects of biofouling has been the application of optimized antifouling paint coatings, particularly for shipping and energy structures. Dedicated paint coatings as an antifouling system (AFS) remain the most applied biofouling prevention strategy for industries such as shipping. Paint manufacturers produce two basic types of coating:

- Biocidal – using controlled depletion polymers (CDP) or self-polishing copolymers (SPC)
- Non-biocidal – using a foul release method (FRC) or an (STC) coating of durable composites

It has been estimated that 90% of the shipping market uses approved biocides in some manner (Barnes, 2020), with the objective being the controlled release of toxic substances to kill or deter any biofouling organisms that attach themselves to the underwater areas of a ship.

An AFS usually consists of coatings such as paint or other surface treatments applied directly to a substrate such as the underwater surface area of ships (Figure 3.3) The surfaces are covered with a prophylactic coating generally with toxic properties (Lagerström et al., 2020), although some non-biocide coatings are used in appropriate circumstances (Lejars et al., 2012). Biocidal antifouling paints deliver a controlled and constant release of a toxic biocide from the paint matrix into the microscopic layer of water next to the substrate, thus effectively poisoning or making the surface unattractive to any organisms which try to settle and grow on the substrate.

The methods of delivery of permitted biocides from the paint coating to the water layer directly in contact with an immersed surface are designed to work in three possible ways:

Contact leaching coatings use high molecular weight binders that are insoluble in seawater, such as vinyl, acrylic and chlorinated rubber polymers. Thus, these are commonly called 'hard antifouling'. They can incorporate high quantities of toxic particles which are gradually released into the seawater. The biocide leaching rate reduces over the lifetime of the paint, while the paint itself remains durable and can be scrubbed or burnished periodically. However, renewal of the antifouling content will require removing the residual hard paint coating.

Erode in service (EiS) coatings are softer or ablative paints, commonly called 'soft antifouling'. In this methodology, the coating surface slowly erodes into the seawater, thus releasing the suspended biocide during the process. This means that the paint coating thickness will decline over the period of use, which can make for less surface preparation when renewing the coating. This paint type is variable among commercial products on the market and many may release microplastics to the sea as part of the erode-in-service.

Self-polishing coatings (SPC) are eroding/ablative coatings based on the use of acrylics or meth-acrylics which require water movement to slough microlayers from the paint surface and release the biocide in a controlled manner. They consequently require regular vessel or structure movement through the water to ensure that the biocide is released and to allow the paint surface to remain smooth over time. They are commonly referred to as self-polishing co-polymer types which will still erode, but over a particular designed period which is based on projected structure activity and geographical operating areas (e.g. expected speed of a vessel and which surfaces are exposed to or protected from movement). As with erode-in-service coatings, they may also release microplastics into the adjacent waters.

Non-biocidal hydrophobic coating materials have also been developed. They are based on non-toxic coatings and employ a physical strategy incorporating hydrophobic principles into paint structures to create a 'slippery' surface (Ciriminna et al., 2015). Larger biofouling organisms cannot adhere to these surfaces when they move through the water, thus ensuring that biofouling surface roughness cannot form. These coatings are referred to as 'foul release coatings' (FRC) and mainly use a silicone-based compound to create a slithery surface. Foul release coatings based upon silicones may also release many compounds, including toxic catalysts and often small silicone cycles – see Rittschof et al. (2022).

Another non-biocidal coating system is based on the use of surface treated composites (STC), where a hard, long lasting and durable coating based on vinyl ester and embedded glass fibre is applied to the substrate. This durable coating is designed to withstand the abrasive effects of a rigorous biofouling removal regime and consequently is aligned with the use of proactive in-water hull cleaning (Rompay, 2012).

For shipping, modern AFS paint coatings often use a tailored and vessel-specific substance coating, for a hull can be a complex blend of substances. Blending will be based on calculations carried out to take into account vessel speed, trading areas and other factors such as the expected time to be spent idle in port or at anchor. The coating strategy will normally be designed to have an efficacy interval of five years, representing the time between statutory dry-docking for a vessel.

Strengths and enabling conditions

Biocidal AFS coatings remain in popular use throughout industry and are effective in biofouling control when maintained regularly, by repairing damaged paint areas as they occur or by coating replacement at the end of the effective biocidal life. The coatings can be applied as part of a total protection system for carbon steel which incorporates both corrosion inhibitors and biofouling countermeasure ingredients. There is a range of coating types available which can be matched to operational circumstances, such as stationary structures found in the oil and gas industry, and mobile vehicles such as ships and other vessels. Once a coating is applied, it has a working life normally in the region of five years (Chambers et al., 2006) to coincide with dry-docking requirements and will require no external support in the manner of power supply or chemical replenishment. Coatings can be employed in large surface areas such as those found in tanker and bulk carrier ships. For the end user, coatings can be a cost-effective preventative measure compared to some of the other strategies outlined in this chapter.

Constraints and limitations

In the use of any coating antifouling treatments, there are many factors to consider. These include surface preparation and ease of application, anticipated stresses on the treated surfaces and durability of coating performance between scheduled evaluations and re-applications, and the many possible environmental and human consequences of the alternative treatments (Manov et al., 2004; Soroldoni et al., 2017). The expected duration of the protective coating relative to the expected life-span of fixed structures, such as offshore hydrocarbon platforms, is also a consideration (Coolen et al., 2020*a*) and additional coatings often combined with mechanical cleaning may be needed for platforms that are in place for several years (van der Stap et al., 2016; Almeida and Coolen, 2020).

Antifouling system paint coatings remain largely biocidal-based, with copper being the predominant toxic additive. The use of such noxious substances has been under growing scrutiny due to the rising levels of copper accumulating in the oceans and coastal regions as a result of excessive leaching of copper from the paint binder (Lagerström et al., 2020). It has also been noted that the effectiveness of toxic-based coatings will deteriorate over time, thus also introducing the potential release of microplastics (Tamburri at al., 2022). The use of non-toxic foul release coatings is now gaining traction as part of a proactive biofouling management scheme incorporating regular proactive in-water hull cleaning with capture, consistent with the BIMCO published industry standard (BIMCO 2021*b*).

Foul release coatings require a regular velocity of passing water to wash away algae or fauna attempting to attach themselves to the substrate. Antifouling paints are frequently based on self-cleaning products that slowly dissolve in water, providing an unstable substrate for fouling organisms (Kiil et al., 2001). This is most effective with fast-moving vessels and thus has limited effectiveness on the slow-moving mobile or stationary substrates such as oil and gas platforms (Ferreira et al., 2006). Also, the efficacy of antifouling coatings is expected to be reduced in high-current speeds, where greater shear stress and increased flow may accelerate the dissolution of antifoulant compounds (Kiil et al., 2002) and coatings may be impacted by sediment abrasion (Walker et al., 2014).

The effectiveness of many types of chemical coatings can be synergistically amplified by coatings that include booster biocides, solvents and binders that can have additional synergistic toxic effects (Muller-Karanassos et al., 2020). Although the boosters may be increasing effectiveness for deterring biofouling, antifouling paint particles are regarded as continuous and localized sources of metals, microplastics/polymers and pigments to the marine environment (Soroldoni et al., 2017; Dibke et al., 2021). It has been confirmed that antifouling paint particles can easily be taken up by biota and induce toxicity (Amara et al., 2018; Muller-Karanassos et al., 2020).

Large-scale application of antifoulants in aquaculture may also harm human health via consumption of farmed fish and seafood (Guardiola et al., 2012) and effectiveness varies with local conditions of the aquaculture facility – currents, depth, etc. (Cardia and Lovatelli, 2015; Swain and Shinjo, 2014). In addition, they may also carry the risk of contamination of farmed stock and environment pollution and thus may be subject to additional regulation for such uses.

The AFS used in shipping are regulated by the 2001 IMO Convention on the Control of Harmful Antifouling Systems on Ships (the AFS Convention), which prohibits the use of harmful organotins in antifouling paints used on ships (especially the organotin tributyltin (TBT)) and establishes a mechanism to prevent the potential future use of other harmful substances in antifouling systems (IMO, 2001). In effect, this applies to any vessel of any type whatsoever operating in the marine environment, including commercial vessels as well as fishing vessels, recreational craft and offshore installations, whether fixed or floating, provided that they fly the flag of a state party to the Convention, operate under the authority of a state party (e.g. offshore platforms within 200 nautical miles of the coast of a state party) or enter the port of a state party. The AFS Convention has been adopted by 95 States as of 19 April 2023. It was amended in 2021 to include controls on the biocide cybutryne. Other biocides or AFS found to be harmful to the marine environment and falling within the scope of the AFS Convention, can be similarly added in the future. IMO guidance is routinely taken into consideration by the diverse authorities regulating other sectors that may also use chemical coating systems. To ensure continued performance of the AFS, the 2023 IMO Guidelines also recommend that details for performance monitoring of the AFS be included in the ship-specific ADS (BFMP) and be based on recommendations from the manufacturer of the AFS (IMO, 2023). Necessary measures to ensure that the AFS remains effective over the specified docking interval, plus any recommendations on how to return the AFS to optimal performance, are recommended for inclusion in the BFMP.

3.3 Non-coating chemical treatments

Alternatives to using coatings include a range of methods, each with different characteristics and contexts for use. The application of chemical treatments can include:

- direct chemical dosing of stored chemicals;
- electrolytic systems; and
- electrochlorination systems.

These methods are frequently used to deter development of biofouling communities in places that are hard to access, such as essential instruments and water-cooling systems for industries such as power generation, water treatment works and shipping. Chemical treatments are often used because they can be less expensive than other modes (Costa et al., 2021).

Direct chemical application involves the use of proprietary brands of biocide to effectively kill any assemblages of biofouling within contained structures. The chemicals involved can use oxidizing agents such as chlorine, which can kill a broad spectrum of species by attacking an organism's cellular integrity, or can be non-oxidizing in the form of quaternary ammonium compounds (QACs), which target specific species and disrupt an organism's metabolism (Growcott et al., 2016).

For chemicals to be fully effective, the contact time and concentration level of the applied biocide are important factors and may require several injection points in a structural network, such as a cooling water system or treatment plant. Biobullets, which are a technology using small micron-sized balls containing a biocide, have been used successfully to deliver biocides in such contexts and industries. These minute balls can overcome the issue of shell closing by bivalves when they detect disinfecting substances in the surrounding water and are ingested by bivalves to deliver a fatal dose of biocide.[6]

As an electrolytic system, it uses generation and application of toxic copper ions via electrolysis as a method of biofouling control. It is a method commonly employed to provide biofouling prevention to specific components such as heat exchangers and filters. This electrolytic technique involves the placement of electrical anodes upstream in an area of water flow, such as within a water treatment pipeline or a ship's sea chest. A typical anode system will employ copper ions for biofouling control and aluminium ions for corrosion control. Figure 3.4 shows the arrangement for such a biofouling growth prevention system.

When a direct current is passed through the anodes, copper ions are produced as a biocide to be carried in the water flow to control biofouling in ancillary equipment. The second anode is used to prevent corrosion of the metal surface. The iron anodes help in preventing layers of oxide films of the metals from breaking down by the corrosive agents (primarily sulphur) of seawater. This system also gives protection to valves, condensers, engine cooling systems and ancillary equipment.

The third method of chemical treatment again involves electrochlorination, where the biocide sodium hypochlorite is produced by a separate electrolyser unit and is then injected as a solution into a pipeline or sea chest in a similar manner to chemical dosing. The electrolyser unit can be a compact unit or larger, depending on required output. The unit is fed salt water, either from a side stream from a seawater coolant water flow or a separate tank of brine solution. A titanium cathode and a platinum anode are employed to produce chlorine, which then forms sodium hypochlorite in the water stream, to be fed into the relevant injection points in the protected system.

Strengths and enabling conditions

Chemicals are commonly used to control biofouling in a variety of industries, as they provide a flexible and low-cost solution. Oxidizing chemicals such as chlorine and chlorine dioxide can cause mortality in a wide variety of biofouling organisms. Such chemicals are readily available and can be kept in storage tanks to provide a continual supply of biocide at a particular site.

The concentration of the delivered biocidal chemical is a vital component in the effectiveness of this methodology. If it is possible to seal an area of application physically, such as a length of pipe or cavity-containing coolers, then flooding the area with a concentrated biocidal agent and controlling the effective contact time may produce more effective results than injecting a chemical into a water flow (Piola and Grandison, 2013).

Non-oxidizing chemicals such as QACs are used as biocides in the removal of biofouling from industrial plants and have the advantage of inhibiting the corrosion of steel (Meakins, 1963).

Chemicals may have an advantage in the treatment of inaccessible niche areas of biofouling, as they may be applied by hand or spray techniques, taking into consideration all the safety measures required in handling highly toxic substances.

6 See http://biobullets.com/

Constraints and limitations

Any use of stored biocides such as liquid chemicals will require extra vigilance in the handling and application of the substance, along with care in the removal and disposal of resultant detritus.

When using a system which injects a liquid chemical into a water stream, the rate of flow and final concentration applied may be difficult to control, with the result that a higher dose than that required may be applied with a potential of resultant overcarry to the local environment (Rajagopal, 2012).

Some of the hardest to remove shelled animals, such as mussels and barnacles, have the ability to detect harmful substances suspended in a water body and can effectively close off their shells to prevent the uptake of biocides, which means that the application of a biocide in the water may not be wholly effective (Rajagopal, 2012). The use of micron-sized balls containing a biocide can offer a potential solution to this.

Electrolysis systems can be expensive to install and require a power source to keep them active. The anodes require replacing at regular intervals. Their operation provides a steady stream of toxic copper ions, which may be a concern in that these may be released into the marine environment.

3.4 Acoustic measures

Acoustic measures have been proposed as a non-invasive and environmentally friendly method for preventing marine biofouling. This approach involves emitting sound waves that can disrupt the attachment of fouling organisms to submerged surfaces, reducing the need for traditional anti-fouling coatings.

Acoustic measures fall into two basic categories:

- Ultrasonic and audible range devices
- Acoustic sparkers

3.4.1 Ultrasonic waves (non-inertial cavitation)

Acoustic antifouling devices operating in the ultrasound frequency range greater than 20 kHz are commonly used in various industries as a localized and highly effective cleaning method for items ranging from foodstuffs to medical instruments and large metallic castings. Ultrasound is particularly effective for cleaning because it is capable of dislodging and removing surface contamination in the form of inorganic dirt or microbiological material through the shock waves and jet formation that accompany acoustic cavitation bubble collapse. This type of cleansing can be used for both small and large items and can penetrate deep into crevices and cavities in the surface of an object (Mason, 2016).

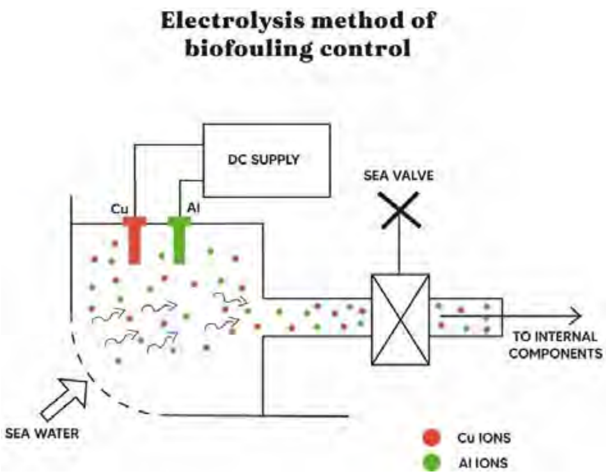


Figure 3.4 Sea chest arrangement for electrolytic biofouling control system.
Source: H. Eustice.

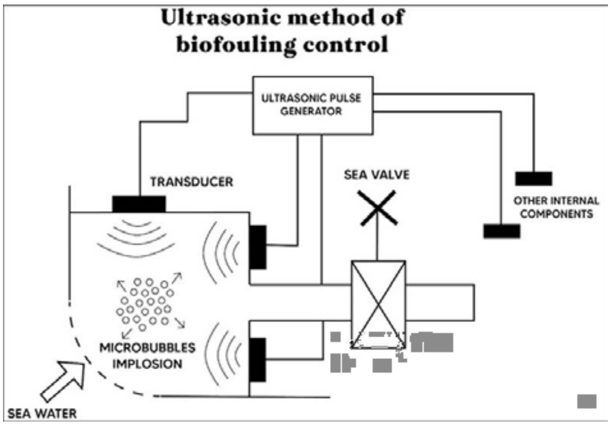


Figure 3.5 Ultrasonic biofouling control.
Source: H. Eustice.

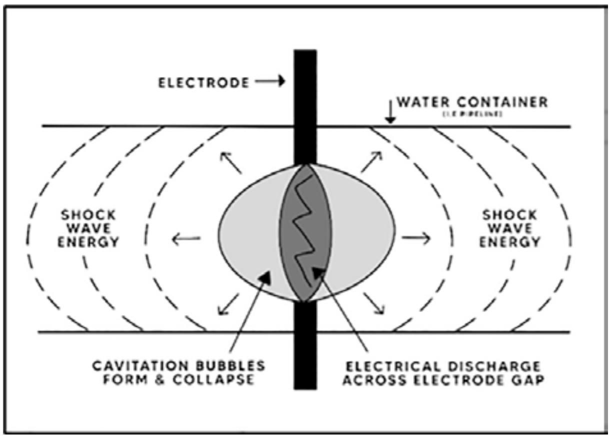


Figure 3.6 Acoustic sparker transducer in a water filled pipeline.
Source: H. Eustice.

There have been many studies over recent years considering the practical use of ultrasonic sound in the prevention and control of marine biofouling (Legg et al., 2015; Park and Lee, 2017). The devices currently available on the marketplace for marine and freshwater biofouling prevention are mainly made up of transducers attached to a substrate such as the plating of the underwater surface area of vessels. A frequency generator and power amplifier send oscillating electrical signals to the transducer usually at less than 30 Hz, which in turn produce local vibration of the plating at the set frequency. If the amplitude of the alternating sound pressure created at the plate surface is higher than the cavitation threshold then microbubbles will form in the water near the plate (Cong and Qu, 2021).

Non-inertial cavitation is a terminology used by some manufacturers of marine biofouling prevention equipment to describe how the microbubbles created by a pattern of increasing and decreasing pressure created at the substrate surface will locally implode and create shock wave energy. These shock waves disrupt the interactions between foulants and the substrate, detach the fouling film from the surface and prevent the accumulation of microscopic particles at the substrate/water interface (Aktij et al., 2020; Han and Qu, 2021).

Figure 3.5 represents a typical arrangement for an ultrasonic biofouling deterrent system for a sea chest in a ship. Such a system may employ an array of transducers, as the amplitude of the ultrasonic waves may decrease with distance from the individual transducers.

Studies have shown that such ultrasonic devices can significantly reduce biofouling settlement (Legg 2015). This was confirmed by sea trial verifications carried out over a four-month period on the shell plating of a large drill-ship (Park and Lee, 2017).

Studies have also indicated that ultrasound frequencies of around 23 kHz may be the optimum to deter the settlement of organisms such as barnacle cyprids. (Guo et al., 2011).

3.4.2 Audible frequency range biofouling deterrent

Studies have been carried out into the potential use of biofouling control devices operating within the lower end of the human audible frequency range of 20 Hz to 20 kHz.

Using a low frequency of 30 Hz applied to plating substrates, it has been determined that barnacle settlement onto the surface of the vibrated plates can be inhibited and that frequencies of 15 and 40 Hz could reduce the metamorphosis of younger developing barnacle cyprids (Branscomb and Rittschof, 1984). The results, however, did not indicate that such frequencies would be effective as an all-round biofouling prevention control.

Studies that considered frequencies between 70 to 100 Hz concluded that such frequencies had little or no effect on barnacle settlement, whereas frequencies greater than 260 Hz demonstrated some reduced barnacle settlement. In these studies, it was also concluded that the velocity amplitude of the generated signal was a key influence in inhibiting settlement. The studies also showed that other fouling organisms such as tubeworms, ascidians and bryozoans and algae did not appear to be affected by the excitation applied to the substrate (Choi et al., 2013).

These studies indicate that low frequency sound may be useful if applied to target a particular species such as barnacles, but may not be particularly suitable as a general control mechanism for a wider range of fouling organisms.

3.4.3 Acoustic sparkers

Acoustic sparkers (sometimes referred to as acoustic pulsers) work by emitting short, high-intensity pulses of sound that disrupt the attachment and growth of biofilm, the initial layer of organisms that forms on a surface. Studies have shown that pressure pulses from sparkers can eradicate existing Zebra mussels (*Dreissena polymorpha*) and stop the further settlement of larval stages (Schaefer et al., 2010).

Such devices consist of a high-voltage power supply, capacitors and a transducer containing electrodes spaced apart to create an electrical potential gap (Figure 3.6). When a high voltage is passed to the electrodes, a high energy spark is created across the electrodes in a similar manner to that of an automotive spark plug.

The electrodes are fed from a capacitor charged to a high voltage (5–10 kV), which is then applied to the electrode gap of the transducer. The high voltage discharges itself as a spark across the electrode gap. As the high-energy spark is in contact with the contained water, it vaporizes a small volume of the water to create a high-pressure gas cavity bubble that expands as the electrical current passes across the gap and then suddenly collapses when the spark discharge is completed. When the cavity bubble suddenly collapses, it produces a high-energy acoustic shock wave (Schaefer 2002). This wave travels through the surrounding water, having deleterious effects on organisms such as mussels until the wave attenuates.

This methodology has been tested for industrial processes such as those requiring cooling water, where extreme levels of biofouling in the water inlet pipes of cooling water supply systems can cause reduced flow of coolant and consequent reductions in process efficiency. Although chemicals such as chlorine and other oxidizers may be used to exterminate these pests, the need to seek non-toxic solutions has prompted exploration of acoustic sparkers, similar to those used in seismic surveys (Randal, 1999).

Strengths and enabling conditions
Acoustic measures do not involve the use of toxic chemicals that are typically used in traditional antifouling coatings and thus have greater environmental acceptability.

By preventing the attachment of fouling organisms, acoustic measures can reduce the need for maintenance and cleaning of submerged surfaces. This can lead to cost savings for industries such as water treatment and shipping. Low-frequency sound may also improve the effectiveness of antifouling coatings by increasing the release of biocides from the coatings by disturbing the boundary layer.

Unlike traditional antifouling coatings, acoustic measures often do not involve the physical application of the remedy across the whole of the submerged surfaces. Transducers for acoustic measures may be a simple bolt-on solution in some cases.

For niche areas where antifouling paint coatings are difficult to maintain, acoustic measures may be able to provide biofouling control. This can also be beneficial for sensitive surfaces or for surfaces that cannot be coated, such as instrument sampling points.

Acoustic measures can be selective in targeting specific fouling organisms, such as barnacles or algae, which can be beneficial for reducing the impact of specific fouling organisms on submerged surfaces.

Constraints and limitations
Acoustic measures may not be effective in all environments or against all types of fouling organisms. The effectiveness of acoustic measures can also be affected by factors such as the frequency, intensity and duration of the waves emitted. They also require a continuous electrical power source which may not be available on smaller craft.

Ultrasonic and high-frequency measures may also have limitations with respect to structural damage to the hulls or exposed surfaces, when the surfaces are vulnerable to vibrations from the direct high frequencies or their harmonics. On the other hand, low frequencies have harmonics which result in interference which can reduce effectiveness and there are places where low-frequency sound is not effective. Low frequency is also dramatically impacted by structural elements of hulls and exterior surfaces of structures.

In addition, the initial cost of installing acoustic measures can be higher than traditional antifouling coatings, which can be a barrier to adoption for some industries.

Acoustic measures are currently employed in specific areas such as a ship's sea chest or cooling systems and may be challenged in supplying effective biofouling prevention measures in larger areas such as ships' hulls.

The use of acoustic measures can potentially cause noise pollution that may impact marine life in the surrounding area. This concern needs to be considered in the development and implementation of acoustic measures to prevent and control biofouling. Some acoustic devices used to control biofouling organisms operate within the noise exposure criteria for marine mammals. Audiogram data for a range of marine mammals, such as the common dolphin and pilot whales, document acoustic sensitivity in the region of 5–150 kHz (Erbe et al., 2016). This may allow them to receive the acoustic output of some biofouling devices. Such sensitivity may be relevant to the growing concern over the potential impacts of ocean noise on the overall well-being of marine species, including:

- temporary or permanent hearing loss;
- stress responses;
- forcing animals to move from their preferred habitat or divert from their migratory path;
- disruption of feeding, breeding/spawning, nursing and communication behaviours.

The National Oceanic and Atmospheric Administration in the United States has identified knowledge gaps in these areas and has produced recommendations for future research (NOAA, 2018).

3.5 Thermal treatments

Thermal treatment is used extensively as a biofouling treatment in industrial water cooling systems (Rajagopal, 2012).

Hot water treatments involve the application of heated water to submerged surfaces to kill or deter marine organisms and can be applied using a variety of methods, including immersion, spray and circulation. The effectiveness of hot water treatments depends on several factors, including the temperature of the water, the duration of the treatment and the species of marine organisms present . Generally, higher temperatures and longer treatment times result in more effective biofouling control; however, the use of high temperatures can also damage some types of submerged structures, such as those made of composites. Therefore, the selection of the appropriate temperature and treatment time must be considered carefully for each specific application.

Steam treatments involve the application of high-pressure steam to submerged surfaces to kill or deter marine organisms. Steam treatments are often used in conjunction with hot water treatments to increase their effectiveness. Steam treatments can be applied using a variety of methods, including immersion, spray and circulation. The effectiveness of steam treatments depends on several factors, including the temperature and pressure of the steam, the duration of the treatment and the species of marine organisms present. Generally, higher temperatures and pressures and longer treatment times result in more effective biofouling control.

In shellfish culture, thermal treatment may be combined with acid immersion to improve the efficacy of either treatment alone (Sievers et al., 2019), whereas thermal treatment tested in finfish culture showed only limited effects and greater technical difficulties (Guenther et al., 2011).

Thermal treatments have been demonstrated to be effective for controlling marine biofouling, with several factors affecting results. For example, Lai et al. (2017) tested the efficacy of hot water treatments for controlling biofouling on a ship's hull. The researchers found that a treatment temperature of 60 °C for 20 minutes was effective in controlling biofouling, whereas a treatment temperature of 50 °C for 20 minutes was less effective.

Tests on the efficacy of heated water for the treatment and remediation of organisms found in sea chests also have shown the potential of this technology (Piola and Hopkins, 2012). There are some systems that employ a thermal antifouling system for use with box coolers,[7] but larger scale applications for ships' seawater cooling systems are yet to be fully developed.

Strengths and enabling conditions

When mortality of adjacent marine life is not a concern, thermal treatments such as hot water, steam and ultrasound are generally considered cost-effective compared to other biofouling control methods such as antifouling coatings and biocides. These treatments do not require the use of expensive chemicals or equipment and they can be easily applied to large areas.

Thermal treatments are also considered environmentally friendly because they do not introduce harmful chemicals or pollutants into the marine environment. This makes them an attractive method for controlling biofouling on aquaculture equipment and other marine structures where the release of pollutants could have a significant impact on marine life (see Section 4.2.3).

Thermal treatments have been shown to be effective in controlling a wide range of marine organisms, including bacteria, algae and larger organisms such as barnacles and mussels. The effectiveness of these treatments is largely dependent on the temperature and duration of the treatment.

Constraints and limitations

Thermal treatments require a significant amount of energy to heat the water or other treatment medium to the required temperature. This can be a significant disadvantage, especially when large areas such as a ship's hull need to be treated and the energy consumption is high.

Thermal treatments are most effective when they are applied directly to the surface of the organism or biofilm and may not be effective for organisms that are embedded within the surface, such as some types of barnacles, or for biofilms that are present on the inside of pipes or other structures.

Prolonged exposure to high temperatures created by some thermal treatments can potentially damage the surfaces being treated, particularly if the material or non-biofouling organisms are sensitive to heat. This can lead to reduced effectiveness of the treatment and the need for repair or replacement of the treated surfaces.

Thermal treatments may have unintended effects on non-target organisms in the surrounding environment, particularly if the waste water and detritus from the treatment medium is discharged back into the ocean. This may be particularly problematic for sensitive marine ecosystems.

3.6 Light treatment

Light treatments have been shown to be effective in preventing marine biofouling by disrupting the attachment and settlement of some types of fouling organisms. Although light treatment avoids the use of toxic chemicals, shorter wavelengths are increasingly powerful and may have environmental consequences. UV-C, for example, may damage DNA and causes photochemical reactions in proteins and polymers that make up coatings. The DNA impacts may occur with either animals or plants in the water between the light generator and the target surface, with potential harm increasing near the source of the UV light.

UV light, which has frequently been used for some medical sterilization and the treatment of harmful aquatic organisms and pathogens in drinking water and ballast water management, is an emerging antifouling method. UV light can reach various surfaces with different characteristics (Friedman et al., 2016), even in structures with irregular shapes (Kolappan and Satheesh 2011; Kolappan et al., 2016). Ultraviolet irradiation techniques use wavelengths of the ultraviolet spectrum (100–400 nm) and take advantage of the effects these wavelengths have on the DNA of organisms. Research in the medical field has shown these wavelengths are effective because at the

7 See https://karasmarine.com/index.php/2020/01/01/heat-nord/

cellular level ultraviolet light is absorbed by the nucleic acids and lead to the formation of lethal products (Peak et al., 1984).

The irradiation of surfaces by UV light has been investigated as a possible method to prevent biofouling in filtration membranes, marine sensors, industrial cooling systems and the disinfection of wastewater in treatment plants (Delgado et al., 2021; MacKenzie et al., 2019). This is often undertaken in combination with ultrasonic measures. Combined with the cavitation phenomenon developed by high-intensity ultrasound, the combined effect of sound and vibration was found to destroy Zebra mussel (*Dreissena polymorpha*) larvae and waterborne sound prevented juvenile and adult mussels from settling and translocating onto exposed surfaces, implying potential for more widespread use to combat biofouling from developing (Donskoy and Bruno, 1996).

In particular, UV-C light (200–280 nm) is promising because it is usually filtered out by the ozone layer and thus biofouling organisms have not developed resistance against it (Braga et al., 2020; MacKenzie et al., 2019; Ryan et al., 2020). In addition UV-C may produce by-products with disinfection properties that further improve effectiveness at reducing biofouling. Most biofouling organisms that have been tested have been shown to be susceptible to UV-C irradiation, with a decrease in sensitivity from calcifying organisms (except mussels) to soft fouling organisms and biofilms (Braga et al., 2020; MacKenzie et al., 2019). Efficacy is dose- and duration-dependent and varies among biofouling organisms (Braga et al., 2020; Hunsucker et al., 2019; MacKenzie et al., 2019; Ryan et al., 2020). Although constant exposure prevents all biofouling, very similar results may be achieved with intermittent exposure (MacKenzie et al., 2019; Ryan et al., 2020) and if combined with antifouling coatings, the duration of irradiation may be reduced further (Hunsucker et al., 2019).

Coating surfaces with photocatalytic materials which inhibits algal growth (Ochiai et al., 2010), such as titanium dioxide (TiO_2) and tungsten trioxide (WO_3), has been widely used for hydrolysis-induced self-cleaning surfaces owing to their favourable physical and chemical properties. They have also been found to show photocatalytic and super-hydrophilic photoinduced properties when used with UV irradiation, making them effective in combating marine fouling (Banerjee et al., 2015). A study investigating the use of a photocatalytic coating containing silicone nanoparticles for preventing the attachment and growth of fouling organisms on ship hulls concluded that the use of such substances could be developed within foul-release coatings which were enhanced when exposed to UV and natural light (Selim et al., 2016).

Another possible solution still in the experimental phase is laser irradiation as a means of preventing biofouling by barnacles and diatoms (Whelan and Regan, 2006). Pulsed laser irradiation was found to cause damage to two different species of diatoms. A study demonstrated that, when exposed to low-power laser irradiation for 2 and 300 seconds, *Skeletonema costatum* and *Chaetoceros gracilis* showed mortalities of between 53% and 98%, respectively, with mortality increasing with increasing duration of the laser irradiation (Nandakumar et al., 2003)

The effect of blue (448 nm) and infrared (1016 nm) laser radiation as a tool to provide a contact-free method of removing biofouling from both FRC (foul release) and SPC (self-polishing) antifouling coatings has been proposed as an underwater solution to the removal of existing fouling from paint surfaces with minimal damage to the coating structure (Zimbelmann et al., 2022).

In a similar manner, studies have shown that UV light may be used to the same effect as laser (Hunsucker et al., 2019). The findings from these studies support a conclusion that intermittent UV light exposure may work synergistically with coatings to improve the performance of the coating system over time.

Strengths and enabling conditions

Unlike more traditional antifouling methods, light treatment does not involve the use of toxic chemicals or metals, which can harm marine life and the environment. Thus, light treatment can be considered to be an environmentally friendly approach because, other than impacting organisms and water chemistry in the water between the light and the surface, it does not generate any harmful by-products and the energy used to power the light source can come from renewable sources such as solar or wind power.

In contrast to chemical treatment technologies which can lead to the development of resistance in fouling organisms over time (e.g. Cloete et al., 1998), light treatment does not appear to present this issue.

Light treatments can be less expensive than traditional antifouling methods over the long term, as they require less maintenance and do not require the application of chemicals or coatings.

Studies have shown that both UV and laser light treatments may have a use in-water cleaning systems, when used in conjunction with conventional paint coatings.

Constraints and limitations

One of the main limitations of light treatment is the limited penetration of light through water, which can reduce the effectiveness of the treatment on surfaces that are submerged or located in areas with low light levels. This can limit the practical applications of this technology, especially in waters with higher turbidity levels.

Light treatment is most effective in preventing the attachment and growth of most fouling organisms, but often has lower effectiveness on existing biofilms. This means that surfaces that have already been fouled may require additional cleaning or treatment before light treatment can be applied.

Light treatments require a high amount of energy to power the light source, which can make them impractical for some applications, especially those that require continuous operation.

Light treatments may require regular maintenance, such as cleaning the light source and monitoring its performance, to ensure that the treatment is effective over time.

Light treatments also can pose safety risks to marine life if not used properly. UV light may cause damage to the DNA of untargeted marine organisms due to direct exposure or light scatter. UV light and lasers can also be harmful to human health and must be applied taking measures to protect the workers applying the treatments.

3.7 Floating boat lifting devices and other methods of air exposure

In addition to treatments of surfaces with antifouling coatings, sound or energy sources, biofouling can be prevented through exposing surfaces to air. For vessels and instruments, this can be achieved by raising them out of the water, using manufactured lifting systems, when not in use (Wezenbeek et al., 2018). This is particularly useful for recreational craft, as it prevents direct contact with the water, thereby ensuring that no biofouling occurs (Figure 3.7). Removing boats and other structures from the water also reduces the cost of long-term maintenance with regard to manual cleaning of the vessel or structures and decreases the frequency of application of antifouling coatings (Peters et al., 2017). Although the vessel or structure itself will not be subjected to biofouling, the floatation system itself will be fouled and will require periodic cleaning, although this is unlikely to pose a risk of transfer of NIS, because the berthing system will not leave the site. This does not, however, mean that it cannot act as a source of NIS, much like the fouled marina infrastructure (Peters et al., 2014, 2017; Ulman et al., 2017; Miralles et al., 2021).

Figure 3.7 Example of an air berthing system.
Source: Agnese Marchini.

In net-pen aquaculture, regular air drying can be used to kill biofouling on nets, e.g. through lifting the upper part of the net out of the water. In addition, there are net constructions that allow the rotation of the net so that one part is always air-exposed. In seaweed and shellfish culture, it can be used on the culture organisms themselves. High tolerance to desiccation, especially in cultures of intertidal organisms, such as intertidal bivalves, can be exploited to reduce epibiotic growth (reviewed in Bannister et al., 2019).

Strengths and enabling conditions

A strength of air exposure is that vessels will not accumulate any biofouling at all. This has positive implications both for the spread of NIS as well as for the maintenance of vessels. From an environmental perspective, the absence of biofouling on the hulls and niche areas of vessels means that no species will be transferred. From a socio-economic perspective, yacht owners will not have to maintain their vessels frequently, as there would be substantial reductions in the number of times that the vessels need to be cleaned of fouling material with paint applications. The lifting device itself may need to be cleaned; however, the surface area to be cleaned will be less than the surface area of a submerged yacht that would have had to be cleaned.

In aquaculture, air exposure can be a low-cost method that has no negative impact on the edible product or the environment at large.

Weaknesses and limitations

There are few weaknesses and limitations to air exposure. One weakness would be the consideration of the initial cost to purchase the system and the initial installation. However, this is a minor consideration. Another disadvantage of this system may be that its use may be restricted to vessels and structures that spend substantial periods of time not in use and are relatively small, so they can be easily manoeuvred on and off the system. It should be noted that many of these systems are adapted to allow vessels to drive onto the structure.

In aquaculture, one challenge is that although drying may kill biofouling organisms attached to nets or culture organisms, it may not be enough to detach them and may thus provide attractive substrate for other settling organisms (IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships, 2022).

3.8 In-water physical encapsulation

There are no marine growth prevention systems for large vessels that are fully effective under all possible conditions, making periodic in-water active cleaning of large vessels and structures almost essential. Even the most advanced antifouling coatings have limitations, such that physical maintenance of ship-immersed surfaces will be needed at some point during the typical five-year coating service life. When fouling on vessels and other structures is managed during cleaning in-water as well as in dry-dock conditions, there could be several steps leading to loss of effluents discharged while washing the biofouling, depending on the specific cleaning method used. Special attention to particular parts of a vessel or structure may be highly efficient, such as bagging propellers of ships.

A complementary or alternative approach to the manual removal of biofouling material is the use of in-water encapsulation as a management tool for biofouling (Coutts et al., 2010*a*; Roche et al., 2015; Atalah et al., 2016). These systems make use of either buoyant under-hull covers that need to be wrapped around the vessels or structures (Keanly and Robinson, 2020), or alternatively, use of a 'decontamination berth' which a vessel or structure can enter, be cleaned and then leave (Roche et al., 2015). It is necessary to ensure that the submerged parts are well enclosed, thereby creating a barrier between the vessel hull, or other structure and the water.

Even without direct cleaning and active removal of biofouling organisms from surfaces, the encapsulation process may result in an environment that is devoid of light, oxygen and food for biota and produce increasing temperatures and, thereby, could generate an inhospitable environment for the biofouling organisms present (Atalah et al., 2016; Keanly and Robinson, 2020). This approach to biofouling removal or management does not require the use of chemicals or toxins during the encapsulation, but death and decomposition of organisms themselves creates a naturally toxic environment. Depending on the material being used for the encapsulation, biocides can be added to exacerbate the process (Morrisey et al., 2016). A more environmentally sensitive approach involves the addition of freshwater, although this method is likely to take longer to reduce and remove the biofouling (IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships, 2022.).

Strengths and enabling conditions
A strength of this approach is that vessels do not have to be removed from the water and could therefore be treated or anti-fouled *in situ*. Further, there is no need for the manual removal of biofouling with scrapers and brushes, which often damage the antifouling paint. Instead, chemicals can be used within the encapsulation system to accelerate the antifouling process (Roche et al., 2015).

Weaknesses and limitations
The use of this method takes a longer period of time compared to manual removal of biofouling, depending on the extent of the biofouling (e.g. five days for encapsulation vs one day for manual removal) (Atalah et al 2016; Keanly and Robinson, 2020). In addition, it is challenging and often expensive to wrap boats underwater and the process would ideally require more than one trained individual to cover the submerged section of the vessels. Further, without access to an encapsulation berth, it becomes logistically challenging to make use of this technique.

3.9 Biological control

Biological control and eradication have been suggested as a possible approach for biofouling management. This is the practice of using natural predators or parasites to remove biofouling from cultured species or associated infrastructure. For finfish culture (Bannister et al., 2019), there have been trials to remove biofouling from nets using, for example, spider crabs or wrasse (Kvenseth, 1996; Zeinert et al., 2021). Similarly, although grazers such as isopods can control the presence of epiphytes on cultured seaweeds (e.g. Smit et al., 2003), this is not standard practice. In contrast, fish, crabs, periwinkles and sea urchins have been shown to be able to remove biofouling from the mesh of culture bags as well as the shells of cultured shellfish. This can have positive effects on growth and survival of the target organisms, although the practice is not widespread commercially (Li et al., 2018; Sievers et al., 2017; Sterling et al., 2016; Zhanhui et al., 2014).

Strengths and enabling conditions
Biological control involves the use of natural enemies or competitors to control the population of an NIS . Therefore, it has the potential to reduce the environmental impact of biofouling prevention methods. For example, the use of probiotics or natural competitors does not involve the use of toxic chemicals that can harm marine organisms.

When appropriate control species are available, biological control can be more cost-effective than traditional methods of biofouling prevention, such as chemical coatings or mechanical cleaning. Once established, natural competitors or probiotics may provide long-term protection against biofouling without the need for regular maintenance. For example, the use of natural competitors can prevent the establishment of fouling organisms by creating a competitive environment that is unfavourable to fouling organisms.

Biological control may minimize the impact on non-target species or the edible product in aquaculture, as opposed to biocidal antifouling solutions. Biological control can be integrated with other methods of biofouling prevention, such as chemical coatings or ultrasonic systems. This can provide a comprehensive solution to biofouling that is more effective than any single method (Sievers et al., 2017). The co-culture of economically relevant species may provide additional income to an aquaculture business (Zeinert et al., 2021).

Weaknesses and limitations

This approach is for the most part tailored for particular applications and would require an in-depth understanding of the system in which it is to be applied to achieve an appropriate degree of biological control. To avoid introducing new possible invasive species as part of the control strategy, compatible native species must be selected and acquisition of adequate supply of the control species can be challenging.

Even when effective control species are found, challenges arising include the control of the grazer population – regarding both the containment of organisms on site (Comeau et al., 2012) and, in the case of seaweeds, balancing population size so that epiphytes are controlled without a food shortage that encourages predation on the cultured plant (Smit et al., 2003). In addition, as co-cultured organisms may be hosts to pathogens, this may also increase the risk of disease for the cultured species.

Biological control using competitors to the fouling taxa may not be effective against all types of fouling organisms, e.g. those fouling organisms that may have developed resistance to natural competitors or probiotics. It is also dependent on environmental conditions, such as temperature, salinity and nutrient availability, such that it may not provide complete control over biofouling in all environments.

Biological control involves the introduction of living organisms into the marine environment, which can have unintended consequences. For example, the introduction of natural competitors or probiotics may have unplanned or unexpected effects on other marine organisms, including non-target species.

At the international level, working groups established under the auspices of the CBD have examined the use of biological control of established IAS and published technical documents for policy-makers. CBD COP13 recognized biological control as a potentially effective measure to manage already established IAS but highlighted the direct and indirect risks that the use of biological control agents can create to non-target organisms and ecosystems. They also added that these risks should be addressed by applying the precautionary approach, appropriate procedures including a comprehensive risk analysis and contingency planning. Pending the development and adoption of guidance documents on the use of biological control agents, risk assessment and risk management standards, it also encouraged considering using native species where possible as a biological control agent (CBD COP13 Decision XIII/13 para.12-16). Developments are therefore expected in the coming years. At the national level, the use of biological control for biofouling prevention may require regulatory approval, which can be time-consuming and costly. In addition, there may be concerns about the safety and effectiveness of these methods.

3.10 Emerging treatments

Traditional methods of biofouling prevention, such as chemical coatings and mechanical cleaning, have limitations and drawbacks. There are some emerging technologies which seek to control marine biofouling by adopting unique approaches which address some of the shortcomings of existing methods. These include:

3.10.1 Biomimetics

In recent years, biomimetic approaches have been employed in the development of new methods for the control of marine biofouling. Biomimetics is a field of study that involves the imitation of biological systems and processes to develop innovative technologies and materials. By mimicking the natural strategies that marine organisms use to prevent fouling, biomimetic concepts aim to provide new concepts for environmentally sustainable long-term protection against biofouling.

Examples of biomimetic approaches include efforts to mimic the natural anti-adhesive properties of certain marine organisms, such as barnacles and mussels. These organisms use specialized proteins and other substances to prevent the attachment of other organisms to their surfaces. For example, researchers have developed coatings that mimic the surface properties of shark skin, which has been found to reduce the attachment of bacteria and algae to surfaces (Wen et al., 2014). This approach has been successful in reducing the growth of fouling organisms on ship hulls and other marine structures, as well as in medical applications such as preventing bacterial colonization of medical implants (Sarmento et al., 2021).

Another approach is to use natural substances found in marine organisms to create environmentally friendly antifouling paints. For example, some marine algae produce compounds that are toxic to other marine organisms and can prevent their attachment to surfaces. Researchers have isolated and synthesized these compounds to create antifouling paints that are non-toxic and effective in preventing the growth of fouling organisms (Chambers et al., 2006). Additionally, some marine bacteria produce compounds that can inhibit the attachment of other bacteria, which can be used in the development of environmentally friendly antifouling coatings (Mitra et al., 2021).

Biomimetics has also been used to develop innovative technologies for preventing marine antifouling. For example, researchers have developed a system that mimics the natural movement of seaweed to prevent the attachment of fouling organisms. The system uses a flexible polymer material that moves in response to the motion of the water, preventing the attachment of organisms by creating a constantly moving surface (Wang et al., 2020).

The research field is developing rapidly, with new approaches combining different material properties to achieve multi-functional surfaces. For example, the Harvard-patented Slippery Liquid Infused Porous Surfaces (SLIPS) technology combines hydrophobic material with a microstructured porous material infused with lubricants (Deng et al., 2020). Biomimetics shows promise in providing inspiration for sustainable approaches to managing antifouling.

3.10.2 Air bubbles

The concept of using air bubbles to prevent marine biofouling is based on the observation that many marine organisms require a solid surface and are unable to attach to surfaces that are covered in air or gas bubbles. Therefore, by introducing a layer of air or gas bubbles on the surface of a marine structure, it may be possible to prevent the attachment of biofouling organisms.

Two main mechanisms have been identified in the efficacy of continuous air bubble streams as a control for biofouling, these being the disruption of any macroscopic biofouling settlement because of the bubble stream passage and the scouring of any recently settled larvae through shear stress at the substrate surface (Hopkins et al., 2021).

There are several methods for creating air bubbles on marine surfaces. One common method is to use a perforated tube or diffuser to release a stream of air bubbles into the water. Another method is to use a specialized coating or material that contains microstructures that trap air and create a layer of air bubbles on the surface.

Several studies have investigated the effectiveness of air bubbles as a control mechanism for marine biofouling.

The practical use of continuous bubble streams to control biofouling on marina pontoons was evaluated by a study which indicated that such a system had the possibility to keep the undersides of pontoons free of biofouling but that the practical application at full scale was not currently a viable proposition (Hopkins et al., 2023).

The use of air bubble curtains has also been suggested as a remedy to reduce the formation of fouling on the hulls of ships which experience long periods of inactivity, such as those which have been placed in long-term lay-up (Scardino et al., 2009).

Some researchers have also investigated the use of superhydrophobic surfaces that repel water and create a layer of bubbles on the substrate surface. (Hwang et al., 2018).

The use of air bubbles to control biofouling has proven to be an effective small-scale technique when applied to hard substrates found in the marine environment and can be an environmentally acceptable means to prevent biofouling (Bullard et al., 2010).

Although the use of air bubbles to prevent marine biofouling has shown promise as a non-toxic biofouling prevention solution, there are limitations to this approach at a larger scale. This is due to the number and size of bubble diffusers required to maintain an effective surface coverage. There are also the energy costs involved in the provision of operational machinery to supply a suitable and sufficient supply of compressed air on a 24/7 basis.

For an application to shipping, there also remains the operational challenge of maintaining a consistent layer of air bubbles on a dynamic marine structure, such as the whole of a ship's immersed hull.

It is noted that the use of micro air bubbles to reduce the frictional drag resistance has long been an identified potential means to reduce ships' fuel costs and consequent GHG emissions (Hashim et al., 2015). The technology to apply this phenomenon to the underside of a ship's hull is now available and air lubrication systems are currently being fitted to vessels as an effective efficiency measure. The overall secondary effect on bottom fouling reduction as a result of air lubrication is yet to be practically assessed and may prove to be advantageous and applicable to other areas of the immersed hull.

3.10.3 Electric field technology

One of the emerging methods used to control biofouling is electric field technology. This technology utilizes electric fields to prevent the attachment and growth of marine organisms on submerged surfaces.

Electric field technology works by creating an electric field around the submerged structure, which creates a repelling force that prevents the initial attachment of microorganisms and the settlement of larger organisms. The electric field can be generated using either direct current (DC) or alternating current (AC) power sources. In DC electric field systems, the anode is positively charged and the cathode is negatively charged. In AC electric field systems, the polarity of the electrodes is reversed periodically.

Some studies have investigated the effectiveness of electric field technology as a control mechanism for marine biofouling. A study by Long et al. (2021) demonstrated that the application of an alternating low-intensity electric field generated by a nanogenerator using local wave action could prevent initial microbe adhesion and consequent biofilm formation on a substrate immersed in both freshwater and seawater environments.

Further to this, Blenkinsopp et al. (1992) concluded that the bactericidal agents used to control biofilms in industrial pipelines may have an enhanced eradication effect if a low-strength electric field was applied to the water passing through the pipeline structure.

The effect of electromagnetic fields (EMFs) on biofouling in heat exchange systems using seawater was examined by Trueba et al. (2015) with the conclusion that the application of such EMFs could accelerate the formation of calcium carbonate which weakened the growth of biofilm and reduced its adhesion capability.

The use of electric field technology has several potential advantages over other methods of biofouling control. It is non-toxic and does not require the use of chemicals or biocides that can have harmful effects on the environment. Additionally, it can be retrofitted onto existing underwater structures and is not affected by water temperature or salinity. However, as a developing technology, studies have not yet established whether the technologies release toxic metal ions and other short-lived reducing or oxidative compounds into the environment.

The effectiveness of electric field technology as a control mechanism for marine biofouling is influenced by several factors, including the strength and frequency of the electric field, the distance between the electrodes and the type of substrate. In general, higher field strengths and frequencies are more effective in preventing the attachment and settlement of marine organisms. Additionally, the distance between the electrodes should be optimized for the specific application, as too much distance can reduce the effectiveness of the system. The type of substrate can also influence the effectiveness of electric field technology, as the electrical conductivity and surface charge of the substrate can affect the distribution of the electric field.

The application of electric field technology for biofouling control is not without its limitations, however.

One of the major challenges is the maintenance of the system, as the electrodes can become fouled with marine growth and require frequent cleaning. Additionally, the effectiveness of the system can be reduced in areas of low flow, where the electric field is less effective in preventing attachment and settlement.

In conclusion, electric field technology is potentially an effective and environmentally friendly method for the control of marine biofouling. The technology has been shown to reduce the growth of biofilms and the abundance of fouling organisms on submerged surfaces. However, the effectiveness of the system is influenced by several factors which need to be overcome when such a system is to be applied in a practical manner.

3.11 Monitoring of biofouling

Effective monitoring and managing marine biofouling is important for maintaining the safety and sustainability of marine ecosystems and human activities. As highlighted in the opening of Chapter 3, where activities create a risk of pollution of the marine environment, including the introduction of NIS, these risks must be observed, measured, evaluated and analysed by recognized scientific methods (UNCLOS Article 204). Where a risk of significant and harmful change of the marine environment has been identified (e.g. the introduction of a known invasive species), impacts must also be assessed and the results published (UNCLOS Article 206). These provisions are applicable to all the pathways reviewed in this report, whichever part of the marine environment the introduction may occur in. However, the extent of the monitoring obligation and the methodology used to carry out monitoring vary among domestic regulations of various countries.

For the monitoring of biofouling on commercial shipping vessels, fisheries vessels, recreational craft and offshore platforms, the 2023 IMO Guidelines recommend the maintenance of a biofouling management plan (BFMP) and a biofouling record book (BFRB) (IMO, 2023). The BFMP is based on the ship-specific biofouling risk profile and the monitoring of risk parameters. Elements that are most relevant to biofouling monitoring and are expected to be included in the BFMP include an inspection schedule, a description of the monitoring on biofouling risk parameters and a ship-specific contingency action plan based on specific triggers from monitoring of biofouling parameters (e.g. areas of particular biofouling accumulation). The BFRB is to include details of cleaning and inspections and their results, together with details on the AFS installed.

Routine surveillance should be augmented with specific inspections to address any situation of elevated risk, and all monitoring needs to follow tested protocols and standards appropriate for the context to be effective and reliable.

There are various methods used to monitor marine biofouling, which can be broadly categorized into three monitoring types: physical, chemical and biological.

3.11.1 Physical monitoring

Physical monitoring involves the direct observation and measurement of biofouling on submerged surfaces. This method can be conducted visually, either by human observation or through the use of remote cameras or ROVs. Other physical methods include measuring the thickness or weight of biofouling on a surface, using acoustic sensors to detect the presence of fouling organisms and using texture analysis to quantify the roughness of surfaces. Physical monitoring is useful for tracking changes in biofouling over time and identifying areas where biofouling is particularly severe. This method, however, is limited in its ability to identify specific types of fouling organisms and can be labour-intensive and time-consuming.

3.11.2 Chemical monitoring

Chemical monitoring involves the analysis of water samples for the presence of fouling organisms or their by-products. This method can be conducted using a variety of techniques, including microscopy, DNA and eDNA analysis and immuno-assays. Chemical monitoring can be used to identify specific types of fouling organisms, even if they are not visible on the surface. Additionally, chemical and biochemical monitoring can provide information about the abundance and distribution of fouling organisms in the surrounding water. This method, however, may not be sensitive enough to detect low levels of fouling organisms, is expensive and may be affected by interference from other substances in the water.

3.11.3 Biological monitoring

Biological monitoring involves the use of living organisms as indicators of biofouling. This method can be conducted using a variety of organisms, including mussels, oysters and sea urchins, which are known to accumulate fouling organisms on their surfaces. By measuring the abundance and diversity of fouling organisms on these indicator species, researchers can gain insight into the overall level of biofouling in the surrounding environment. Biological monitoring can be a useful tool for detecting early signs of biofouling and for monitoring changes in the composition of fouling communities over time. However, this method may be affected by environmental factors that can impact the behaviour and survival of indicator species.

In addition to methods based on indicator species, researchers may also use a combination of different monitoring techniques to gain a more comprehensive understanding of biofouling. For example, researchers may use physical monitoring to identify areas of heavy fouling and then use chemical or biological monitoring to gain more detailed information about the types of organisms present. Additionally, researchers may use multiple methods of monitoring over time to track changes in biofouling patterns.

By using a combination of physical, chemical and biological monitoring techniques, researchers can gain insight into the abundance, distribution and composition of fouling communities and use this information to inform management strategies.

3.12 Global and regional databases

Online datasets of aquatic NIS are of paramount importance for the success of management actions, for several reasons:

(i) Information on introductions, including pathways and impacts of aquatic NIS, is scattered in the scientific literature and difficult to access for managers.

(ii) Many aquatic NIS are poorly known and not perceived as ‘alien’ to an environment, especially when belonging to small-sized, ‘unpopular’ taxonomic groups, hence it is necessary to have an easily consultable inventory of species to be targeted.

(iii) Information on NIS occurring in neighbouring regions is crucial for risk assessment and prevention (Katsanevakis et al., 2016; Olenin et al., 2014; Marchini et al., 2015; Costello et al., 2021).

In the past two decades, several online NIS databases have been developed at national, regional and global level, representing admirable efforts to gather large amounts of information and disseminate it to the scientific community and to the public. The proliferation of initiatives – led either by national or supranational authorities, or scientific institutions of different specializations, and mostly maintained on a voluntary basis by scientific experts – has significantly contributed to improving awareness on the problem, but also has generated some confusion. Different databases rely on different data formats, timeframes and levels of comprehensiveness and have been developed mainly in English. In addition, scientific names of organisms may be revised, particularly as new taxonomic methods are more widely applied and changes to species’ names and classifications may introduce inconsistencies within and among databases. As such, information obtained from the different inventories can be difficult to collate and the criteria behind the records are not always made explicit and may even be controversial. Furthermore, online inventories, even those delivered by scientific institutions, are not subjected to peer reviews (Rocha et al., 2013; Marchini et al., 2015).

Table 3.1 reports an analytical comparison of databases, highlighting similarities and differences in coverage, data format and openness (represented by format of data export). A major problem faced in the maintenance of these databases is ensuring the continuous updating of information, which is extremely important in a highly dynamic context such as aquatic bioinvasions (Olenin et al., 2014).

An ideal database should be based on agreed-upon definitions, standardized data and scientifically validated criteria (McGeoch et al, 2012; Marchini et al., 2015); be as comprehensive and open as possible in many languages, include geo-referenced data; provide details for species identification, information on pathways and impacts; and report the full data editing history, in order to provide transparent information on the update status of the information displayed.

Table 3.1. Overview of some existing global, regional and national NIS databases, including biofouling taxa.*

Full name	Acronym	Geographical reach	Habitats	Geographical information format	Pathway information format	Species ID information	Updates transparency	Exportable data format	Technical maintenance	Scientific maintenance	Notes
CABi Invasive Species Compendium		Global	Terrestrial, Aquatic	Country, Large Marine Ecosystem, Locality (not georeferenced)	Own classification system	Yes	Yes	Yes	CABI	CABI	
Global Register of Introduced and Invasive Species	GRIIS	Global	Terrestrial, Aquatic	Country	No	No	No	No	IUCN	Invasive Species Specialist Group	Country-level information
Global Invasive Species Database	GISD	Global	Terrestrial, Aquatic	Country	No	No	No	No	IUCN	Invasive Species Specialist Group	Species-level information
World Register of introduced Marine Species	WRiMS	Global	Marine	Country, Marine region	No	No	Yes	Yes	Flanders Marine Institute - VLIZ (Belgium)	Editorial board (taxonomic / regional experts)	
Information system on aquatic non-indigenous and cryptogenic species	AquaNIS	Global (only partial coverage)	Aquatic	Country, Large Marine Ecosystem, Locality (not georeferenced)	Own classification system	No	Yes	Yes	Klaipeda University (Lithuania)	Editorial board (national experts, members of ICES and PICES working groups)	
European Alien Species Information Network	EASIN	Global (Europe)	Terrestrial, Aquatic	Country, Marine region, Locality (georeferenced)	CBD classification	No	No	No	European Commission's Joint Research Centre	Dedicated staff + Editorial board (taxonomic experts)	
Great Lakes Aquatic Nonindigenous Species Info. System	GLANSIS	Regional (Great Lakes region)	Freshwater	GPS coordinates	Narrative	Yes	Yes	Yes	NOAA - Great Lakes Environmental Research Laboratory (USA)	NOAA - Great Lakes Environmental Research Laboratory (USA)	
European Network on Invasive Alien Species	NOBANIS	Regional (North and Central Europe)	Terrestrial, Aquatic	Narrative	Narrative	Yes	N/A	N/A	Nordic Council of Ministers	Consulted regional experts	Species factsheet in PDF format
Marine Mediterranean Invasive Alien Species	MAMIAS	Regional (Mediterranean)	Marine	N/A	N/A	N/A	N/A	N/A	SPA/RAC: Specially Protected Areas Regional Activity Centre of UNEP/MAP – Barcelona Convention	N/A	Temporarily unavailable
National Estuarine and Marine Exotic Species Info. System	NEMESIS	National (USA), but also shows global records	Marine	GPS coordinates	Narrative	Yes	N/A	N/A	Smithsonian Env'tal Research Center (USA)	Smithsonian Environmental Research Center (USA)	Species-level information
Sistema Nacional de Información sobre Especies Exóticas Invasoras	SNIEEI	National (Argentina)	Terrestrial, Aquatic	No	No	No	No	No	Ministry of Environment and Sustainable Development	Consulted taxonomic experts	Species list in PDF format. Available in English, Spanish and Portuguese

* Information updated to the time of websites visit, February 2023.

4. BIOFOULING SOURCES

4.1 Vessels

This section considers biofouling from vessels, categorized as follows:

(i) Vessels engaged in shipping:
Ships or other floating transport or storage vehicles, including both commercial and naval ships. This also includes special purpose craft and other marine transport units, such as barges and inland waterway craft plying between different bioregions.

(ii) Vessels engaged in fishing:
Any vessel fishing with nets, lines, pots or trawls for the purpose of commercial gain or subsistence.

(iii) Recreational craft:
A vessel less than 24 m undertaking sport or leisure activities without commercial gain. This includes trailored craft.

(iv) Other vessels:
Any vessels both under and above 24 m in length, other than specified above, engaged in activities which may give rise to a biofouling security threat.

Fixed and floating offshore structures, such as those used for offshore energy operations (e.g. oil and gas) and ocean renewables energy generation, are considered in Sections 4.3, 4.4 and 4.5 below.

4.1.1 Shipping

4.1.1.1 Background

Although factors such as climate change may be identified as having some impact on species distribution due to, for example, alterations to ocean chemistry and temperature (Mainka and Howard 2010; Vaz-Pinto et al., 2014), the increasing number of global marine biological invasions is intrinsically linked to international shipping operations. These activities provide two main pathways for the potential spread of NIS, namely the carriage and discharge of organisms in ballast water and the presence of biofouling on the immersed areas of a ship's hull and fittings (Hewitt et al., 2009, 2010). Both these mechanisms have the potential to introduce unwanted species into new environments where they may multiply and flourish to the detriment of the local environment and native marine species (Karim, 2015; ICES, 2019*a*).

The carriage and discharge of ballast water by ships has long been recognized as a major source of marine NIS transfer with both ocean and coastal shipping having the potential to act as perfect supply chains of unwanted organisms into local receiving waters (GEF-UNDP-IMO, 2017).

Biofouling on ships has also been recognized as one of the major invasion pathways (Bailey et al., 2020), but for some time it was considered to have been managed effectively by the use of antifouling systems such as paint coatings. Nevertheless, it was recognized that as biofouling can readily form on the immersed areas of a ship's hull, it is a clear potential source of IAS (Bouyssou and Madjidian, 2014). There has also been some research that would suggest that the extent of this biofouling pathway for IAS introduction may be equivalent to or even greater than that of ballast water (Drake and Lodge, 2007).

4.1.1.2 Shipping-specific biofouling information

Given the vast number of species that can be potentially found in shipping, and biofouling coupled with the large number of vessels available to transit between bioregions (in excess of 200,000: Sea-web™ Ships, 2022), the prospect of a species being carried from one area to another represents a substantial biosecurity risk when events such as detachment or spawning occur (Minchin and Golasch, 2003). If the arriving species can withstand the environmental conditions at their new location, they may survive and flourish to the detriment of the indigenous species and overall local ecology.

Table 4.1 gives examples of IAS associated with the fouling of ships' hulls.

Table 4.1 Common hull fouling invasive species*

Name	Native to	Introduced to	Impact
Asian paddle crab Charybdis japonica	Ranges from North-west Pacific (China, Japan) to the East Asian seas (Thailand, Malaysia)	New Zealand; detected but not established in Australia	May carry the White Spot syndrome virus which can affect crustacean mariculture Can affect biodiversity through predation or altering trophic levels
Colonial tunicate Didemnum vexillum	North-east Pacific	North-east and north-west Atlantic	Aggressive invader Can reproduce sexually or asexually Fragments can survive, reproduce and thrive Outcompetes for habitat and simply grows over or smothers existing species
North Pacific seastar Asterias amurensis	North-west Pacific	North-east Pacific, Southern Australia	Voracious carnivorous feeder Prolific breeder able to quickly establish large populations in new areas Consumes local fish egg masses. Impacts mollusc aquaculture and wild fisheries
Asian Green mussel Perna viridis	Persian Gulf to Philippines. Throughout the East-Asian seas to eastern China	The Caribbean, South Atlantic, South Pacific; detected but not established in Australia	Tolerates wide fluctuations of temperature and salinity and reaches high densities Fouls hydrotechnical constructions, ships and aquaculture infrastructure
Black Striped Mussel Mytilopsis sallei	North-west Atlantic, the Caribbean and South Atlantic	India, East-Asian seas (Malaya, Singapore) South Pacific, North North-west Pacific (Japan, Thailand, Hong Kong). Was detected in Darwin, Australia but eradicated	Tolerates wide fluctuations of temperature and salinity. Highly fecund, grows and matures rapidly Can form dense aggregations to the exclusion of other species. The fouling of hydrotechnical constructions, ships and aquaculture infrastructure with this species causes corrosion, technical problems and loss of efficiency
Wakame seaweed Undaria pinnatifida	North-west Pacific	Mediterranean, North-east Atlantic, South-west Atlantic, North-east Pacific, South-east Australia, New Zealand	This species can rapidly colonize temperate regions; it can colonize any hard surface and is therefore able to foul hydrotechnical constructions, ships and aquaculture infrastructure Able to affect biodiversity, change community structures and alter trophic levels

* Illustrative only, as there are many other taxa involved in NIS invasions. *Source:* IMO.

Table 4.2 Wetted surface areas by ship type

	Approximate WSA in m²									
Ship Type/GT	**<2,500**	**2,500**	**5,000**	**7,500**	**10,000**	**25,000**	**50,000**	**100,000**	**150,000**	**>150,000**
LNG/LPG Tanker	550	1,400	2,300	2,700	3,600	6,000	6,500	9,100	15,400	20,000
Bulk carriers	950	1,500	2,300	2,700	3,400	6,500	9,700	16,500	22,000	27,000
Tankers	140	1,300	2,400	2,900	3,900	6,800	9,600	16,400	21,000	22,000
Container ships	400	1,800	2,300	2,900	3,600	6,500	8,700	14,000	17,000	20,500
Passenger/Cruise ships	140	950	1,800	2,300	2,600	3,600	6,100	10,000	12,000	16,400
General cargo ships	250	1,600	2,100	2,300	3,100	5,600	8,000	9,000		
Fishing vessels/trawlers	150	1,400	1,900	2,400	3,800					
Tugs	60	1,250	1,800	2,400						

Source: BIMCO, 2021*a*.

4.1.1.3 Shipping as a carrier and source of invasive species

Shipping represents an ideal platform to accumulate and distribute NIS from one bioregion to another. The immersed surfaces of ships (hull and niche areas) provide hard substrates which are ideal for the formation of biofilm and the progressive biofouling cycle.

According to the IMO 2023 Guidelines (IMO, 2023), the biofouling pressure on a specific ship is influenced by a range of factors including:

- design and construction of the ship's hull and niche areas;
- operating profile of the ship; and
- maintenance history.

When considering the design of a vessel, there are certain features of the underwater areas of ships that reflect the overall potential of biofouling accretion with consequent invasion risk. These features relate primarily to the detail of the underwater parts of a ship where biofouling can occur. It includes the physical form and size of the submerged surfaces, including the nature and location of appendages and recesses along its length. The total surface area is termed the total wetted surface area (WSA) as expressed in m^2. The WSA will vary by ship type and individual construction.

The WSA available for potential fouling on a ship can be considered as having two main components, namely the hull and niche areas, which are identified as recesses and protrusions in the underwater arrangements where fouling can attach and grow in addition to the main hull surfaces.

4.1.1.4 The ship's hull – NIS risk

As a ship's potential for the accretion and spread of biofouling NIS is dependent on its WSA, it is useful to consider the different underwater hull forms that vessels have. The consideration takes into account the ship design type and how the operating immersion depth (termed 'draft') dictates the size of the WSA and consequent NIS risk.

The hull is the main body or frame of the ship. A ship's hull form is decided upon at the design stage as it determines many of the ship's attributes, such as load carrying capacity and desired speed (Tupper, 2013). Vessels requiring faster speeds will have finer lines and thus a smaller WSA, as shown in Figure 4.1, when compared to those designed to carry maximum cargo at lower speeds, as in Figure 4.2.

The immersed sections of a ship's hull consist of a mixture of flat and contoured plating along the sides and on the bottom of the ship with the addition of structures such as a bulbous bow and transom. The hull represents the largest constituent of the immersed WSA. The expanse of comparatively large area and flat substrate that the hull presents to the local environment means that the hull has the potential to be readily colonized by fouling organisms, as shown in Figure 4.3.

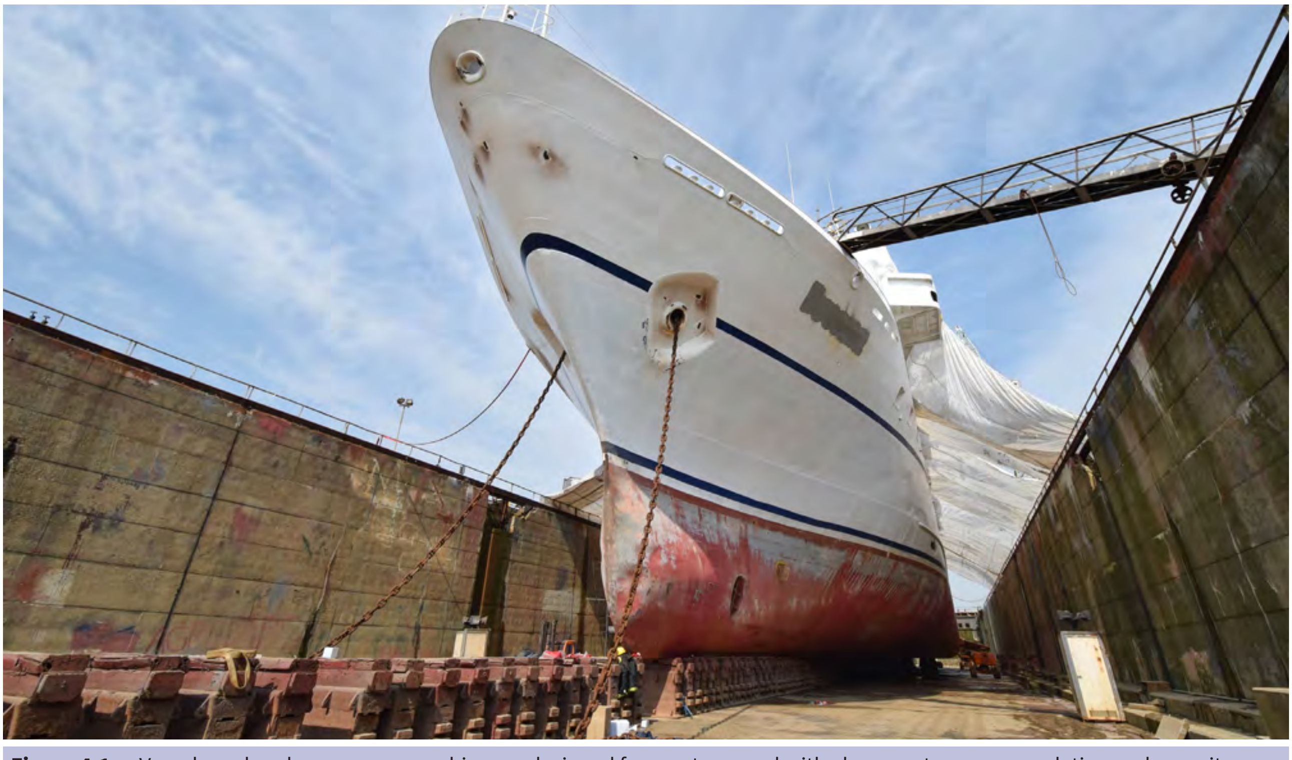


Figure 4.1 Vessels such as large passenger ships are designed for greater speed with above-water accommodation and amenity spaces and thus have a comparatively shallow operating draft when loaded and a small WSA.
Source: SebastiaanPeeters/Shutterstock.

Figure 4.2 Large tanker hull designed for maximum cargo volume at slower speed have greater operating draft and considerably larger WSA when fully loaded.
Source: Nightman1965/Shutterstock.

There has been some work carried out to try and assess the global scale of the biosecurity risk introduced by commercial ship-mediated biofouling transfers based on WSA appraisal (Moser et al., 2016).

These studies endeavoured to produce a figure to represent the total WSA of the world shipping fleet (including those vessels <100 tonnes), along with a breakdown of wetted area by ship type. These investigations were carried out to assist with mathematical modelling to try and quantify the world-wide extent of ship biofouling and the attendant biosecurity risk. A conservative global WSA figure of 325 x 10^6 m^2 was derived which, when placed into perspective, equates to the surface area of the United States Virgin Islands (Britannica, 2020). Given that the world fleet was forecast to grow at some 6.4% between 2021 and 2026, the latent risk of marine NIS invasions as a result of biofouling transfers has the preconditions to rise.

Apart from the design and WSA of a vessel, speed may have a direct effect on its ability to provide an effective host environment for biofouling species. Studies have been carried out to quantify the survival rate of biofouling organisms at different hull locations on vessels undertaking voyages at different speeds and then considering organism survival rates post voyage (Coutts et al., 2010*a*). The results of these investigations suggested that concentrations of hull-borne biofouling organism were markedly reduced on faster vessels relative to slower craft. This was attributed to morphological characteristics such as the adhesion capability of different biofouling species. This indicated that faster vessels have a lower risk of transporting and depositing potential invasive species between marine ecoregions.

4.1.1.5 Niche areas – NIS risk

The 2023 IMO Biofouling Guidelines define niche areas as 'a subset of the submerged surface areas on a ship that may be more susceptible to biofouling than the main hull owing to structural complexity, different or variable hydrodynamic forces, susceptibility to AFC wear or damage, or inadequate or no protection by AFS'.

Common niche areas include:

- Seawater chests and gratings
- Seawater inlet pipes, valves, strainers and internal cooling systems
- Keel and box coolers
- Manoeuvring thrusters and thruster tunnels
- Stabilizer fins and boxes
- Propellers, shafts and struts
- Bilge keels
- Rudders, hinges and stocks
- Anchors and cables including chain lockers
- Dry-docking support blocks
- Cathodic protection anodes

Some of these are identified in Figure 4.4.

Figure 4.3 Underside of a ship's hull showing extensive fouling.
Source: David Smith.

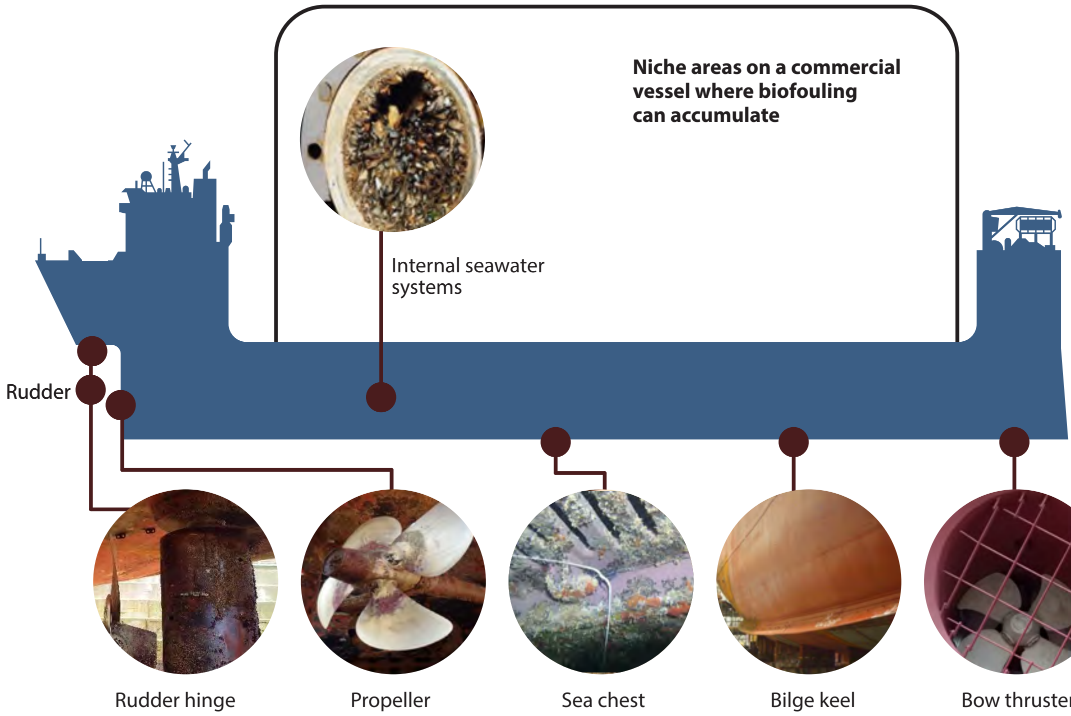


Figure 4.4 Niche areas on commercial vessels.
Source: After MPI, 2018.

Due to their nature and location, niche areas are considered to foul more easily than the flat sides of a ship's hull and thus represent an elevated invasion risk in terms of biosecurity (Miller et al., 2018). To quantify the ratio of hull-to-niche area WSA, a study was carried out which estimated that 10% of the total global WSA consisted of niche areas (Moser et al., 2017). A highlighted example of the risks posed by niche areas considered the arrangements on a vessel to use a seawater heat transfer system as the cooling provision for on board machinery and other services. A dataset obtained from a 249-ship sample showed that 95% of the vessels have animal biofouling organisms in their niche areas, whereas only 44% of them had unacceptable levels of hard biofouling (>10%) on the hulls (Hoffmann, 2021).

For a ship operator, hull and propeller fouling create drag and loss of overall ship performance with attendant increase in fuel costs. Consequently, the emphasis has traditionally been on keeping these main areas as clear of fouling as possible, with an emphasis on the immersed vertical sides and flat bottom of a ship (Davidson et al., 2016). This sometimes resulted in some niche areas receiving little or no biofouling control. As legislation develops to enhance the biosecurity of a vessel, the importance of these areas is being realized and considered when developing a ship's biofouling management plan and record book in accordance with the 2023 IMO Guidelines (IMO, 2023). Annex II gives additional detail on common niche areas found in ships.

4.1.1.6 Regulations and guidance

The tenth session of the PPR sub-committee of the IMO approved Revised Guidelines for the Control and Management of Ships' Biofouling to Minimise the Transfer of Invasive Aquatic Species on 28 April 2023, following a request in 2018, by the MEPC, to revise the 2011 IMO Guidelines (IMO, 2011). These 2023 IMO Guidelines represent a new milestone towards reducing the transfer of NIS by ships. despite their voluntary nature. Although the non-mandatory nature of these new guidelines may, again, translate into limited compliance, the text was developed to respond to the urgency of addressing threats from biofouling from shipping, while recognizing the challenges faced by the shipping industry in changing practices. Due to the complexity of predicting the risks for introducing invasive species through ships and the difficulty in identifying ships that may carry high-risk organisms, the approach taken is to minimize the accumulation of biofouling. This approach in the 2011 IMO Guidelines is reiterated in the 2023 IMO Guidelines (IMO, 2023).

The 2023 IMO Guidelines provide recommended biofouling management practices for ship design and construction and via the use of AFS for all types of submerged or otherwise wetted surface areas of ships, including hull and niches, or ships using coatings or surfaces that are not used to control or prevent attachment or organisms. The Guidelines also recommend the monitoring of risk parameters to identify potential higher risk for biofouling and inform selection of the most appropriate and adequate management, such as the type of recommended cleaning, including IWC with capture, as well as regular inspections.

PPR 10 also agreed to develop new guidance on IWC at subsequent sessions, with a target date of 2025. In the meantime, due to the increase in the use of IWC technology, several groups are developing standards and approaches for testing and conducting safe and effective IWC (e.g. the Alliance for Coastal Technologies/Maritime Environmental Resource Center, BIMCO/ICS and ISO). These efforts are designed to help increase the quality and safety of IWC and ensure biofouling cleaning is carried out in an efficient and environmentally sustainable way.

With respect to antifouling systems, there are a number of IMO regulations and guidelines, in particular:

- 2001 IMO Convention on the Control of Harmful Antifouling Systems on Ships (IMO, 2001)
- Guidelines for Survey and Certification of Antifouling Systems on Ships, adopted by resolution MEPC.102(48), superseded by resolution MEPC.195(61)
- Guidelines for Brief Sampling of Antifouling Systems on Ships, adopted by resolution MEPC.104(49)
- Guidelines for Inspection of Antifouling Systems on Ships, adopted by resolution MEPC.105(49), superseded by resolution MEPC.208(62)
- Guidance on Best Management Practices for Removal of Antifouling Coatings from Ships, including TBT Hull Paints, as revised in 2023 (LC-LP.1/Circ.108)

(see also Section 3.2 above on coating systems).

4.1.1.7 Conclusion – Key findings, gaps and recommendations

4.1.1.7.1 Key findings and biofouling prevention

The potential of shipping to act as a pathway for the transfer and introduction of NIS from one bioregion to another through biofouling is a well-documented risk (Davidson et al., 2016). This hazard posed by a vessel's biofouling is a complex one, with the nature of the risk being dependent on many factors. The factors include the extent of the submerged hull and niche area available for biofouling and the design speed of the vessel, its trading and operational patterns, antifouling coatings, hull maintenance schedules and several diverse environmental factors.

Additionally, given that the drag created by even a thin layer of biofilm on the hull can reduce the hydrodynamic efficiency of the vessel passing through the water, biofouling has a direct connotation with fuel used and hence GHG emissions. This is highlighted in Section 1.9 of the 2023 IMO Guidelines.

Although hull biofouling may represent the most obvious source of refuge for NIS organisms, the niche areas on ships can harbour different species that may represent a more significant risk of invasion than the hull itself.

Ship operators and owners normally apply some diligence to the effective control of biofouling to reduce hull and propellor roughness on their ships and thus save excessive fuel costs. However, they may not be particularly attentive to niche areas which do not have a direct effect on performance, such as fin boxes and rudder trunk spaces. The 2023 IMO Guidelines recommend that every ship should have a BFMP and a BFRB, which identify the niche areas for a particular vessel and record how they have been maintained (IMO, 2023).

The physical removal of biofouling is a commonplace activity. While the process may be effective, the final fate of the removed debris (e.g. fouling organisms and coating associated biocides and microplastics) from such operations is an area requiring consideration as well. Material generated in a dry dock and left exposed presents the possibility of species leaching out and back into the local waters, and biofouling debris from cleaning a seawater cooler or filter may be jettisoned over the side. There may be a case for treating the debris resulting from a biofouling cleaning exercise as a controlled waste and handling it as such.

Sea chests and internal pipework physical cleaning treatments may not remove all the deceased biofouling material and are likely to be re-colonized at an accelerated rate due to the remains of expired organisms providing settlement cues and habitat for propagules.

Mechanical propeller polishing in port by divers is a service offered by several organizations in many ports. It has recognized advantages in terms of thrust efficiency but usually has no local capture control of the material removed and will likely cause release of various organisms (such as barnacle, tube worms and bryozoans) from the propeller blades and hub into the surrounding environment.

For over a century, paint coatings containing toxic biocides (commonly copper- and/or zinc-based compounds) have been the preferred method of biofouling prevention and control for vessels. The uses of biocides remains, although the use of more clearly documented harmful substances such as TBT has been previously prohibited for use in marine paint coatings. Nevertheless, paint coatings remain the predominant method of biofouling control for shipping, with copper and other co-biocide booster substances being the principal biocide ingredients. Regardless of their method of application, biocidal paint coatings essentially release toxic substances, not only in the immediate area of the hull and fittings, but also into the surrounding waters.

The fate and effects of antifouling paint biocides in local waters remain a matter of environmental concern (Thomas and Langford, 2009; Tamburri et al., 2022; Section 3.2). It is also noted that the use of such noxious substances is coming under growing scrutiny due to the rising levels of copper accumulating in the ocean and coastal regions due to excessive leaching of copper from the paint binder (Lagerström et al., 2020). The use of certain co-biocides in antifouling paint systems such as Irgarol-1051 has been prohibited from use in a ships antifouling paint system.

It has also been suggested that, while the effectiveness of biocide-based coatings will deteriorate over time, both 'erode-in-service' and SPC coatings may represent a potential pathway for microplastics (i.e. polymers) to enter the marine environment (Tamburri et al., 2022).

As elaborated in Section 3.2, paint manufacturers have developed complex solutions to address the quantities of biocide instantaneously released from coatings when immersed in water, including self-polishing coatings (SPC). To address the biofouling and NIS risk from vessels and avoid toxic substances, foul release coatings (FRC) are being introduced which are non-toxic and have hardened and durable qualities. The strengths and weaknesses of these non-toxic coatings are also reviewed in Section 3.2.

Regardless of AFS coating type, extended periods with the ship lying idle such as when laid up from service or queuing at a port presents an opportunity for rapid fouling increase, particularly if the ship is static in waters over 25 oC (Selektope,® 2021).

Ultrasonics have been used successfully in areas such as sea chests and other niche areas. Two questions surround this method of application (Section 3.4):

- The ability to scale up to provide protection for larger hull areas
- Whether there are any detrimental effects to marine life arising from the frequencies used

The use of chemical biocides is a regular approach to biofouling prevention in niche areas associated with seawater cooling systems. This can involve the simple injection of proprietary biocides to the use of applied electrical current to copper anodes. The environmental suitability of such technology is open to question (see Section 3.3)

4.1.1.7.2 Knowledge gaps

As more data is gathered and research carried out regarding shipping as a pathway for NIS, there are some priority areas where data are not available or are insufficient for circumstances associated with biofouling on ships and NIS to be understood.

In-water cleaning

An example of this lack of knowledge is the use of in-water cleaning (IWC). When an IWC system is employed to remove biofouling, there is a recognized possibility that the action of the cleaning machinery may generate a local NIS invasion due to elements of the removed biological material finding their way into the surrounding environment and taking up residence (see Section 3.1). It has also been suggested that where an IWC system is used in a busy port, species may be effectively transferred from one hull onto another. The argument for the use of IWC systems would appear to have substantial merit but the reality is that progress in this mitigation measure appears to have been slow due to environmental concerns relating to matters such as contaminant release and localized species invasions.

The IWC systems with capture processes seek to contain and remove all the dislodged material into a waste stream which can be treated ashore. Such systems retain the removed biological material for disposal ashore and then return the processed water to the working environment. It is noted that some other systems claim that the vigorous physical action of the cleaning process itself will effectively remove all the organisms during the removal process, although this claim requires further verification.

Given that the prime defence against biofouling is the AFS coating, it is imperative that any applied IWC system does not damage the coating in any way. There is also a concern that metals such as copper and zinc, which are used in the preparation of antifouling toxicants, may be locally liberated from the coating in more concentrated quantities because of surface scouring during the cleaning process. Some IWC with capture systems claim to be able to deal with this phenomenon by stripping out such chemicals during a treatment process ashore. However, the capture and debris processing efficacy of the different IWC systems currently available is still largely unknown.

Given the variety of IWC systems and unknown capture efficacies, questions remain about the propagule pressure increase and heightened NIS incursion risk created in an area where cleaning is a common and regular operation. (Propagule pressure is the composite measure of the number of individuals of a species released into a region to which they are not native.)

Port authority concerns have revolved around issues such as the potential pollution of local sediments and perhaps the resultant loss of dredging licences. Other local stakeholders may be wary of possible local ecology damage and the introduction of NIS. This has resulted in relatively few ports around the world currently allowing IWC to take place, with some others permitting limited trials only. More data are needed on these possible risks and more detailed assessments should take place, particularly regarding the long-term effectiveness and sustainability of all forms of IWC.

Wet docks as NIS transfer stations

Another area which has mechanisms not fully understood is the role of ports and harbours as stepping stones for NIS transfer. Vessels arriving in ports from other bioregions can introduce an extensive range of potentially IAS via the medium of the accumulated biofouling carried on their hulls and other underwater appendages (Miller et al., 2018). More information is needed on both the factors that influence the likelihood of NIS transfer and release in ports, and the effectiveness of measures to manage those risks in ports.

When considering the possibility of biofouling species transfers within a port, the local hydrodynamic environment has been identified as a factor that can magnify the intensity of fouling, both on substrates such as the harbour structures and also on the hulls of vessels visiting the port. The influence of port features such as breakwaters, berthing arrangements and confined entrance channels all have an effect on tidal flushing and the potential consequent accumulation of viable propagules for biofouling transmission (Floerl and Inglis, 2003).

In general, to determine the level of this hazard posed by shipping in particular ports, there has been some work done to develop risk assessment methodologies which can be utilized to quantify the biosecurity danger. One such methodology was developed by the Australian Department of Agriculture, Fisheries and Forest (Australian Government, 2011) which analyses the factors determining port inoculation events.

A particularly important knowledge gap regarding harbour facilities and operations is how to design enclosed wet docks that are effective at reducing the risk of NIS transfer. Wet docks are port facilities where the water is enclosed and kept at a certain level to allow for the loading and unloading of ships (Figure 4.5). A ship arriving in such docks is effectively confined within the same water mass as the other ships using the facility. Wet docks may provide an enhanced haven and vector platform for IAS to relocate between ships at berths within the facility. The nature of such a transfer phenomenon is described in Annex III, along with some potential mitigation measures that vessels or ports may employ to reduce the perceived threat.

Notwithstanding the possibility of hull biofouling presenting a risk of direct NIS transfer among the ships, there is another phenomenon which may considerably increase the deposit of NIS onto the dock wall substrate and also among vessels. When all the ships are using the same water for their cooling system demands, there can be an exchange of water between the ships' cooling systems due to the large volume of water

Figure 4.5 Typical wet dock port arrangement.
Source: Phil Brandwood/Flickr (CC BY-NC-SA 2.0)

required for each cooling system and the limited amount of water available in the dock. This mass rotation of shared dock water, with each vessel vacuuming up several hundred cubic metres of dock water every hour, passing it over all the possibly fouled internal components of the cooling system, warming it up and then ejecting it back into the harbour, may represent a considerably enhanced biosecurity risk.

As the detail in Annex III of this report would suggest, wet docks offering communal berths for ships have a clear potential to act as 'hot spots' for the transfer of biofouling species. A more detailed understanding of the complexity of wet dock biological mechanisms, with a particular reference to the influence of ship processes, could assist with more effective port environmental management, reduce the risk of IAS transmission and assist with the compliance with other regulatory demands such as water quality directives.

4.1.1.7.3 Recommendations

When considering the use of paint coatings as a method of biofouling prevention and control, the continued use of biocidal coatings may appear to be effective but their longer-term environmental effects are not fully understood. The use of chemical biocides in the European Union is governed by the Biocidal Products Regulation (EU) No 528/2012[8] which regulates the sale, supply (making available on the market) and use of biocidal products throughout Europe. This regulation is undergoing a review programme of the current biocidal active substances permitted for use in the EU, which may restrict the use of certain chemicals currently used by the paint industry. Consequently, it is recommended that research into the use of non-biocidal biofouling prevention methods be increased and use of non-biocidal coatings be increased.

Given the potential for NIS and consequent infiltrations in port and harbour facilities, it is recommended that such facilities permitting the practice of propellor polishing and IWC should be alert to the possibility of heightened invasion

8 Regulation (Eu) No 528/2012 of the European Parliament and of the Council concerning the making available on the market and use of biocidal products. Available at: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:167:0001:0123:en:PDF

threat and take measures to monitor both the potential short and long-term consequences of such operations on the local habitats that they manage.

Further, it is recommended that existing knowledge of the complexity of port and wet dock biological mechanisms be consolidated and assessed, with a particular reference to the influence of ship processes. Such a consolidation and assessment could produce more detailed understanding and could assist with more effective port environmental management, reduce the risk of NIS transmission and assist with the compliance with other local regulatory demands, such as water quality directives.

Where a vessel is planning to use IWC as part of its biofouling management strategy, it is recommended to determine the exact nature of the paint coating system in place on the hull prior to selecting the most appropriate IWC systems. If the coating is not abrasive-resistant, it will suffer damage and possible detachment when the IWC takes place. An IWC plan for each vessel should have a matched cleaning process and a hard scrubbable coating scheme.

Ship owners and managers should be encouraged to act on the powerful argument that biofouling control and ship fuel savings go hand in hand with their obligation to curb GHG emissions. The 2023 IMO Guidelines recognize that biofouling management practices can be effective at enhancing energy efficiency and reducing air emissions from ships (IMO, 2023). Hull maintenance has been identified by IMO in the 2022 Guidelines for the development of a ship energy efficiency management plan (SEEMP) (IMO, 2022) as one of the tools available to increase fuel efficiency. The 2023 IMO Biofouling Guidelines further support the Initial IMO Strategy on Reduction of GHG Emissions from Ships. Rapid action for implementation of, and compliance with, these Guidelines is recommended.

The consequence of marine biofouling on metallic structures such as ships can have subtle and deleterious corrosion effects on materials such as marine grade steel (Murugan et al., 2020). It is recommended that this phenomenon be highlighted to ship operators and owners with reference to the condition being accelerated on ships having a modicum of biofouling lying idle for prolonged periods in polluted warmer waters.

4.1.2 Recreational and commercial fishing

4.1.2.1 Background

To consider the NIS introduction risk arising from fishing activities, these activities may be broadly classified into two separate categories:

- Recreational fishing, which is defined by the EU as 'non-commercial fishing activities exploiting marine biological resources for recreation, tourism, or sport'.[9] Recreational fishing is carried out by individuals or groups using small-scale fish catching equipment such as rods and lines.
- Commercial fishing, which is carried out on a more concentrated basis, and where the purpose is to sell the resultant catch for commercial gain. Such fishing ranges from large seagoing vessels using advanced industrial scale capture equipment to smaller scale artisanal activity levels, where lower technology fishing gear may be employed, such as hand lines and nets.

Subsistence fishing is usually considered with commercial fishing, because even if the destination of the catches is not commercial markets, policies and management measures must consider livelihoods and community well-being dependent directly on the subsistence catches.

Both recreational and commercial fishing may be carried out in oceanic or coastal waters as well as within rivers, lakes and canals. Both these activities have already been identified as sources of marine litter as previously reported by the GESAMP Working Group 43 (GESAMP, 2021).

Fishing undertakings may present two pathways for invasion from biofouling. There are both a primary pathway caused by the new introduction of an NIS into a fishing area, or secondary pathway by reinforcing the propagule pressure of an existing invader.

Recreational fishing is being increasingly identified as a key pathway for the introduction of NIS (South et al., 2022), while commercial fishing is similarly highlighted by the Australian Government as having acknowledged risk of NIS transfer (Australian Government, 2009*a*).

Although much recreational fishing occurs in freshwater rather than marine systems, many of the NIS transfer challenges are similar in both types of systems. This section of the report will include some information from illustrative freshwater cases, to share the lessons learned from those experiences.

9 Regulation (EU) 2017/1004 of the European Parliament and of the Council of 17 May 2017 on the establishment of a Union framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the common fisheries policy and repealing Council Regulation (EC) No 199/2008. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R1004

4.1.2.2 Recreational fishing – NIS carriage risk

Recreational fishing is an enormously popular global pastime. Rough estimates of the global numbers of recreational fishers vary widely from a minimum of 220 million to a maximum of 700 million (FAO, 2017).

Recreational fishing can be of three types:

- 'Game fishing' in streams, lakes and reservoirs for edible species such as salmon and trout
- 'Coarse fishing' for any fresh-water species such as bream and pike which frequently are not eaten and returned
- 'Sea fishing' in or by the sea for species such as cod and haddock or larger species such as swordfish and blue marlin

Most recreational fishing techniques use a rod and baited line, which is commonly termed as angling. Angling takes place in both coastal areas and inland waterways including freshwater rivers and lakes. It can be carried out by individuals or as part of a group competition, as shown in Figure 4.6.

Figure 4.6 Rod and line recreational fishing.
Source: Stanislav's Video Room/Shutterstock

There are several identified ecological effects linked to recreational fishing, such as the removal of significant numbers of key species from local habitats for human recreation or consumption, along with the deliberate and detrimental introduction of non-native species to enhance fishing experiences for anglers (Ribeiro et al., 2017).

Other impacts can be related to the transfer of species from one bioregion to another via fouling of the angling equipment used or sometimes on the fouling transferred onto small trailered boats used to fish in lakes, rivers and inland waterways. Many of these species' relocation impacts are cumulative over time and only fully manifest themselves at a point when their removal and eradication require considerable effort. Although recreational fishing in some countries may not have been the subject of substantial environmental attention to date, it has been suggested that such activities may need closer regional scrutiny to protect aquatic biodiversity (McPhee et al., 2002).

When considering biofouling and potential invasive species transfer due to recreational fishing, the location of the fishing site and the presence of biofouling taxa in that area will be significant factors. Recreational fishing can occur in most of the world's freshwater systems as well as the nearshore coastal regions, with some areas being critical habitats for the life history stages of many species of fish. Marine biofouling communities may differ in some ways from freshwater biofouling communities (Qian et al., 2022). Nevertheless, the microbial communities creating the fouling in both cases can be manifold and contain the eggs, larvae and juvenile stages of many species found in the local waters.

Figure 4.7 The Killer Shrimp – Dikerogammarus villosus.
Source: S. Giesen/NOAA Great Lakes Environmental Research Laboratory – 1030 (CC BY-SA 2.0)

Assemblages of biofouling in the vicinity of angling may be found on local piers, jetties, rocks and other structures. When carrying out fishing in such areas, the fishing equipment, clothing and footwear such as waders used by anglers at a particular location may become soiled with fragments of the local biofouling material as a direct result of the fishing method. This biofouling material can be of a small quantity and barely visible but can contain the spores, eggs or larvae of the indigenous aquatic community and any NIS previously established in the area. Some of these may be classed as invasive and damaging if relocated to another aquatic environment by the contaminated equipment or clothing. Given that many potentially invasive species can survive in excess of two weeks in such damp angling equipment and clothing (Bruckerhoff et al., 2014), the possibility of live transfer exists if the angler subsequently visits another angling location within that period. In addition to this, the use of live bait not indigenous to the waterways being fished has been identified as a potential NIS risk (Williams et al., 2015).

Case study 1 The spread of the New Zealand Mud Snail, Potamopyrgus antipodarum

This NIS originates from New Zealand where it can be found in freshwater estuaries, streams and inland lakes. The primary pathway of this species to other global regions is attributed mainly to the medium of ships' ballast water and biofouling, as they have a high tolerance to many differing water qualities. Once established in a new location they can wreak havoc, as they are prolific reproducers and can create high population densities which dominate local habitats.

The damage they cause is linked to their high reproductive rate and consumption of local algae, which alters nitrogen levels in the ecosystem. In addition to this, they can also outcompete native invertebrates both for food and territory and consequently reduce the local biodiversity (Therriault et al., 2011). These creatures can now be found in a wide variety of countries, from the Western Baltic and Mediterranean to North America, where they have caused devastation in the Great Lakes and other regional inland waterways and lakes. Their spread is partially attributed to a secondary pathway of spread linked to recreational fishing.

The mud snail transfers result from anglers who have not cleaned their fishing equipment and clothing after use in a particular location. Due to these snails being very small, they may not be clearly visible and are easily overlooked if thorough cleaning is not undertaken. The snail can survive for up to 24 hours out of water and for up to 50 days on damp surfaces (Winterbourn, 1970) and is consequently a prime candidate for transfer from one fishing location to another.

Due to their high resilience, the removal of this creature from infested areas can be extremely difficult. Proposed effective eradication through chemical means may exceed environmental regulatory levels and also could be above concentrations considered safe for most fish species (Geist, 2022).

As a result of the severe impacts of this invader and the difficulty in its subsequent removal, local authority management plans will often seek to engage with local recreational water users such as anglers by issuing informative literature leaflets and other guidance highlighting the nature of the species and its ecological threat. This guidance may often provide advice on best practice cleaning techniques and how to report any sightings of the creature to local environment agencies (State of Oregon, 2010).

Figure 4.8 The spread of the New Zealand Mud snail *Potamopyrgus antipodarum.*
Source: Maňas M., 2014 (left), Judi Lapsley Miller (right). (CC BY 4.0)

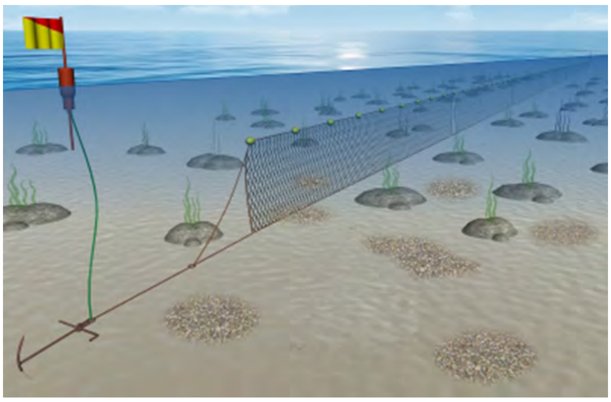


Figure 4.9 Gill net arrangement.
Source: www.seafish.org

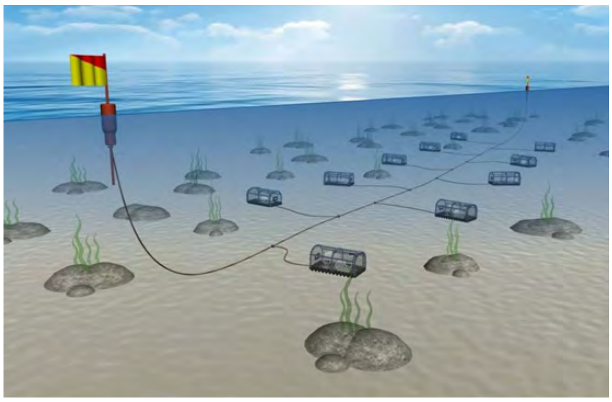


Figure 4.10 A 'fleet' of lobster pots.
Source: www.seafish

Case study 2 The spread of the algae Caulerpa

The genus *Caulerpa* is a group of green algae species that can grow rapidly and form dense mats of weed on the seabed. Normally native to the south-western coast of Australia (Katsanevakis et al., 2016), some species of Caulerpa have become invasive in the Mediterranean Sea, having been introduced by shipping ballast water and hull biofouling along with the aquarium trades. These species can tolerate a wide range of environmental conditions including temperature, salinity and light (Piazzi et al., 2016).

The spread of the invasive *Caulerpa* species has had negative effects on the biodiversity and ecological functioning of the Mediterranean Sea. The weeds can outgrow and displace the native seagrasses such as Posidonia oceanica, which would normally provide important habitats for many fish and invertebrates. They can also alter the physical properties of the sediment, creating conditions that adversely affect both microbial and benthic communities (Najdek et al., 2020). Moreover, such an invasion has had negative effects on human activities such as fishing, tourism and aquaculture (Rizzo and Fernández, 2023).

Since the introduction of *Caulerpa cylindracea* In the Mediterranean Sea in the 1990s, it has spread throughout the area, colonizing almost every coastal habitat from the surface down to a depth of 70 m (Piazzi et al., 2016). Studies have shown that local human activities can play a direct role in the spread of the invasion of *Caulerpa*. These include undertakings such as fish farms and repeated anchoring by small boats and larger craft, where fragments of the weed can be released and carried by the raised anchor into a new area (Houngnandan et al., 2022).

Regional commercial fishing has been identified as a secondary pathway for the dispersion of this species in the Ligurian Sea in the Northern Mediterranean, where fishing vessels employ drift and bottom trawling nets (Relini et al., 2000). When static drift nets are deployed in areas where this weed exists, the nets and associated gear may entrap several kilos of algal fragments of the weed and other biofouling debris, which is then brought on board and remains viable as an invader when the gear is next deployed in a new area. Similarly, the use of mobile bottom trawls in seaweed infested areas can significantly increase the quantity of algae collected, as the otter boards used with these nets act as a plough, cutting and breaking the weed into countless fragments for potential retention in the net and gear.

Figure 4.11 The alga *Caulerpa* taxifolia.
Source: Fish&Dive (CC BY-SA 4.0)

The global scale of the potential NIS transfer caused by the interaction between recreational fishing and biofouling is not wholly calculable. However, there has been some investigation of this carried out in the United Kingdom, where attention has been drawn to the mobility patterns of anglers and the resultant potential threat to biosecurity (Smith et al., 2020).

There have been some notable incursions by aquatic pests where their introduction has been the result of a primary pathway, such as shipping. Then recreational fishing has been subsequently identified as a significant secondary pathway contributing to the spread of the invader. One example of this is the invasion of the Dikerogammarus villosus (aka the Killer Shrimp, Figure 4.7), which is native to the Caspian Sea region of south-eastern Europe and has advanced across western Europe over the last twenty years. The Killer Shrimp is an aggressive predatory invasive invertebrate which consumes large amounts of aquatic insects and larvae that native fish rely on. The Killer Shrimp can be up to 3 cm long and can survive for up to four days out of water (Soto et al., 2023), which makes them extremely viable for transfer by fishing equipment and clothing.

This creature is identified by the UK Environment Agency as number one in its top ten list of invasive species (UK Environment Agency, 2022) and is prevalent in several freshwater and river environments. To try and prevent further spread of this creature, the Agency is working closely with anglers' associations to promote a post-fishing cleaning regime as part of a national strategy (Angling Trust, 2002).

Another invasive predator linked to dispersion by recreational fishing is the New Zealand Mud Snail *Potamopyrgus antipodarum* (Figure 4.8.). This species has become established in several countries where it can spread through entire ecosystem areas and outcompete other species for food. This creature is further described in Case study 1.

4.1.2.3 Commercial fishing – NIS carriage risk

Commercial fishing represents a vital link in the global food security chain. The Food and Agriculture Organization of the United Nations (FAO) estimated that in 2020, global capture fisheries production was 90.3 million tonnes from around 4.1 million fishing vessels (FAO, 2022).

Figure 4.12 'Ghost' fishing gear.
Source: Justin Hoffman/Greenpeace.

Commercial fishing is carried out by a variety of craft, from artisanal coastal fishing boats of less than 24 m in length to ocean-going industrial scale fishing vessels of more than 100 m. As with the section on recreational fishing, this part of the report will not look at commercial fishing vessel hull biofouling, because knowledge of these aspects was fully covered in Section 4.1.1 on shipping and vessels in general. Rather, it will concentrate on other aspects of such fishing operations where biofouling may play a part in NIS transfers. Although biofouling and NIS have been the subject of study in aquaculture (see Section 4.2), the potential of invasive events occurring because of routine commercial fishing practices from vessels has not been the subject of much detailed study, despite acknowledgement that such risk can exist and may vary with the fishing method used.

Commercial and recreational fishing gear employs several capture methods for fish, mollusc or crustaceans. This gear is mainly in the form of nets, pots and lines, as shown in Figures 4.9 and 4.10. Although some equipment, such as trawling nets, may not remain in the water for more than a few hours, or less in a single tow, others such as gill nets may remain submerged in water for days at a time (soak time), allowing for potential biofouling accretion. In a similar manner, pots and traps may be in the water for several days, with both the pot and the retrieval line being prime candidates for growth and accumulation of biofouling organisms.org.

The accrued biofouling and general biological debris on whatever gear is deployed will be local to the area fished and may contain the eggs and larvae of many of the indigenous aquatic species in that area, possibly including previous invaders. When the gear is retrieved, the biofouling will be brought back onto the vessel and may survive for prolonged periods on the nets, lines and floats of the equipment. Should the vessel decide to move to a more distant fishing ground within that period, then there may be a risk of invasive species introduction when the gear is used in the new location. Nets may need cleaning if they pass through clusters of biomass on their way out or return to the fishing vessel. This is normally carried out at the fishing site itself, but may be only carried out in a cursory manner with the remainder of the biomass being retained on nets and pots.

Some countries are alert to the possibility of national fishing fleets introducing such biosecurity risks and provide guidance on control measures that should be applied to prevent the spread of such NIS. Australian National Biofouling Management Requirements (Australian Government, 2009*a*) are an example of a national policy introduced to help the general maritime industry along with vessel owners and operators to manage and control biofouling, thus in turn helping the control of invasive species.

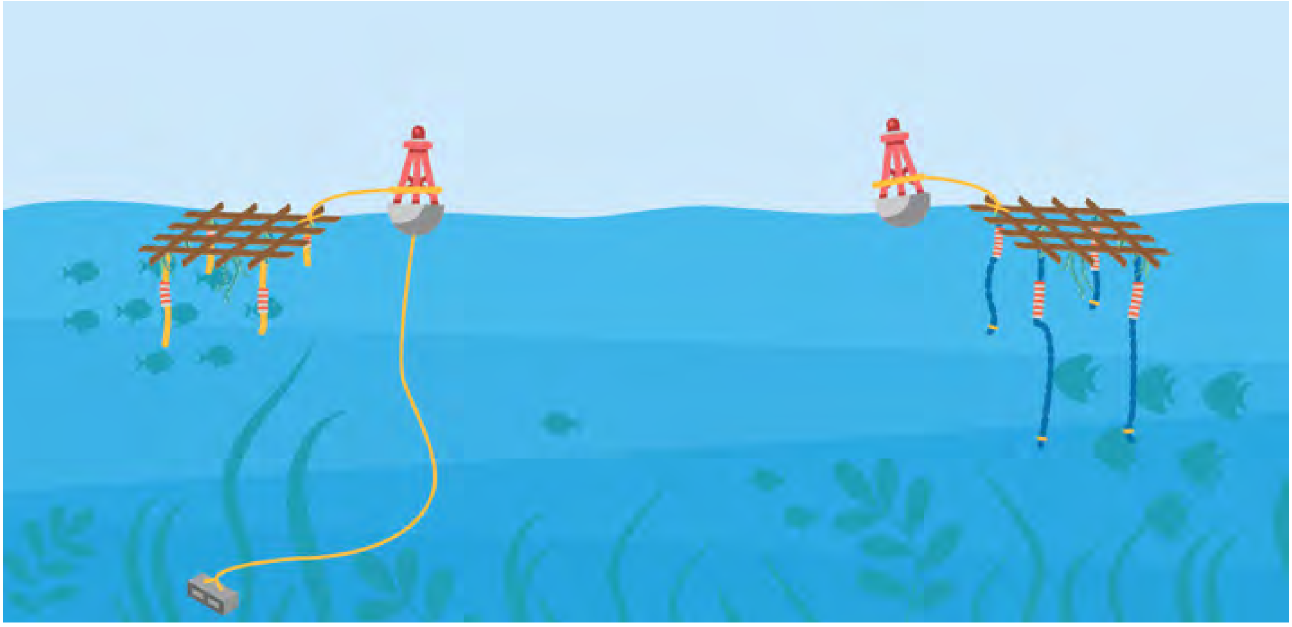


Figure 4.13 Illustration of anchored and drifting FADs as used for fishing.
Source: Marine Stewardship Council.

Case study 2 considers a highly invasive aquatic plant where the introduction and spread of the species is attributed in part to commercial fishing.

When considering commercial fishing practices, there are two more potential pathways for invasive species transfer which are on a scale requiring further attention. These are the issues of abandoned, lost or otherwise discarded fishing gear (ALDFG), along with the use of fish aggregating devices (FADs).

4.1.2.3.1 Abandoned, lost or otherwise discarded fishing gear (ALDFG)

In among all the other debris that can be found floating and subsurface in the world's oceans are the products of fishing operations in the form of lost or discarded fishing equipment. This paraphernalia can include nets, traps, pots and lines. Such items are no longer under control and drift along in local or oceanic currents, continuing to trap and kill fish and entangle other wildlife including marine mammals and seabirds. This harmful feature gave rise to the expression 'ghost fishing' to highlight this derelict equipment (Figure 4.12).

The International Standard Statistical Classification of Fishing Gear (ISSCFG) is a comprehensive classification of all gears and tools used for fishing. It includes categories of equipment used for both artisanal and industrial fishing methods. This standard classification is developed to identify the fishing technology for the compilation of catch and effort data and to support fish stock assessment. It is also used as reference for fisheries statisticians, fisheries technology development and the training of fishers. As part of the work carried out under this FAO initiative, a technical paper was produced to define and classify fishing gear categories (Nédélec and Prado, 1990). This is a useful indicator tool to appreciate the different physical types of fishing equipment that may become an ADLFG biohazard.

The National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program (NOAA, 2015) identifies several reasons for fishing gear becoming derelict. These include:

1. Environmental: Storms, wave action or currents that detach fishing gear from its deployment apparatus.
2. Gear conflict: Entanglement with other vessels or bottom topography such as reefs or rocky bottoms.
3. Gear condition: Breaks loose/cut loose (intent can be accidental or deliberate) due to old age/overuse.
4. Inappropriate disposal at sea.

ALDFG has been highlighted as being responsible not only for the transfer of microplastics and toxins into marine food webs but also for being a significant instrument in the spread of NIS and harmful microalgae (Gilman et al., 2021). The derelict gear may drift through many bioregions during its slow passage and ensnare other debris such as plastic waste items, thus gradually becoming a large tangled heap of material, as shown in Figure 4.12. These slow-moving masses make an ideal pathway for the collection and dispersal of marine species through the carriage of eggs, larvae, fragments, or whole individual potential invaders as they disperse from one region to another. In some cases, they will eventually wash up ashore or become anchored on rocky bottoms, resulting in secure contact with the local environment.

Given the serious potential of this ADLFG phenomenon, the scale of the issue remains unclear, with some historical estimates of global quantity being in the region of 640,000 tonnes, based on 10% of the estimated total marine litter in the ocean (Macfadyen et al., 2009). This figure is uncertain, however, and the collection of more data and detailed reporting on gear loss is necessary to appreciate the scale and impact of this unwanted waste stream (Richardson et al., 2021*a*).

4.1.2.3.2 Fish aggregating device (FAD)

A fish aggregating device (FAD) is a human-made apparatus constructed to deliberately use biofouling and the attendant producer species to attract fish for feeding at both primary and secondary levels of the marine food web. Apart from attracting fish for feeding, they can also act as a reference point for fish schooling purposes (Trygonis et al., 2016). These devices can be made from a variety of items, such as old rope, timber, scrap rafts, nets and plastic containers. They can be anchored to the sea floor in coastal regions or designed to drift in deeper water, as shown in Figure 4.13.

FADs can be of simple artisanal construction used by local island fishers, or can be large complex drifting structures attached to floating marker buoys fitted with electronic markers, such as those employed by the international tuna fleets.

A concern with FADs is that they can also be considered as ALDFG material and have the potential to act as a transport medium for NIS in much the same way as 'ghost fishing' if they are abandoned, or become lost or derelict due to failure of the anchor or the electronic marker. The risk of derelict FADs becoming a stepping stone for sessile organisms through biofouling has been investigated in the seas off Japan (Shuto and Hayashi, 2013). In a similar manner to 'ghost fishing', the number of FADs in use and hence the scale of biosecurity risk that they pose remains unclear, although a study of annual FAD deployment in 2013 gave a conservative figure of between 81,000 and 121,000 (Pew Charitable Trust, 2015). As this estimate is over a decade old, there could be considerably more FADs in the ocean today.

4.1.2.4 Biofouling prevention strategies for fishing vessels and gears

For recreational fishing, the physical cleaning and drying of angling equipment directly after use is an established method of biofouling and hence NIS control. This rudimentary but effective process using brushes and wipes and is actively encouraged by many angling organizations and regional authorities in areas where there is a particular threat of biofouling and invasive species carry-over in angling gear and equipment. Particular attention is required for:

- Clothing, including fishing vests
- Waders and boots
- Fishing rods, reels and lines
- Hooks and lures
- Keep nets
- Tackle boxes

Some angling organizations will provide further guidance on the presence of biofouling risk by promoting campaigns such as the 'Clean, Check, Dry' initiative for fresh-water fishing in the UK. This Environment Agency informative and instructional programme is aimed at anglers to assist with the effective implementation of the EU regulation on Invasive

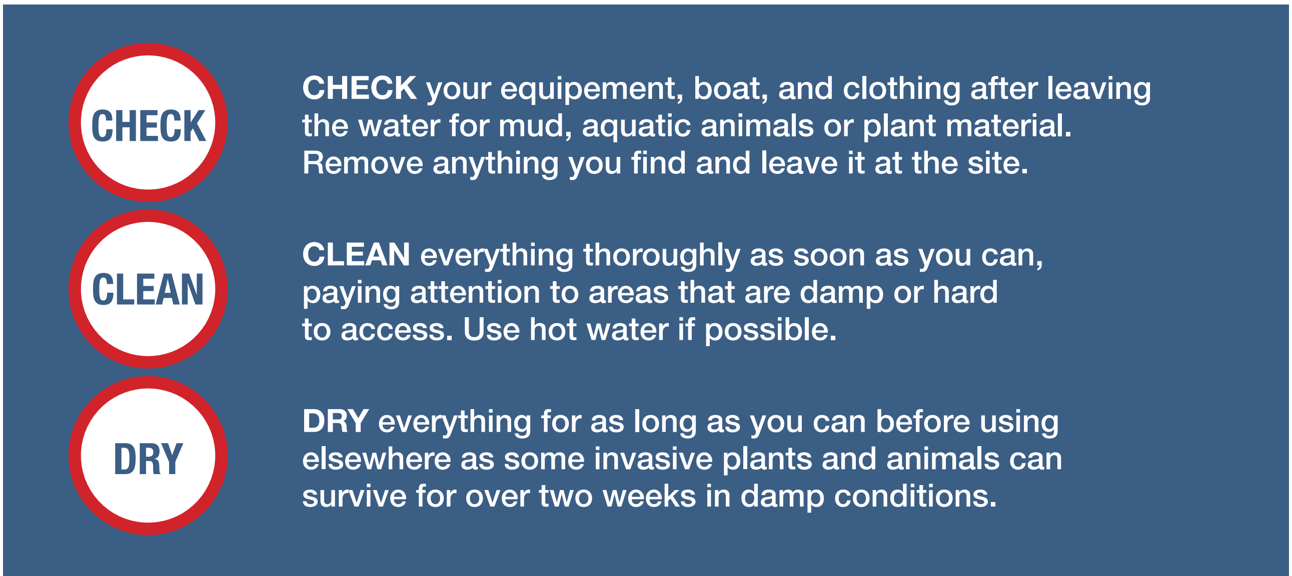


Figure 4.14 Advisory poster used at angling sites.
Source: Exmoor National Park, UK.

Species, EU 1143/2014[10]. The guidance is outlined in the poster shown in Figure 4.14, designed to be displayed in and around popular freshwater angling sites.

Such posters, along with the provision of decontamination cleaning stations for fishing equipment, can be positioned nearby to identify sensitive fishing locations or where angling club competitions may be taking place. It is also noted that some studies indicate that cleaning such equipment in hot water is more effective as a rapid sanitizing method, rather than drying, causing 99% mortality within an hour (Anderson et al., 2015).

In a similar manner to clothing and gear, the cleaning and drying of trailered boats used for fishing before and after using them in a different location is also an important biofouling transfer prevention measure and may be enforced in areas susceptible to NIS incursions. For example, the provincial fishing authority of Alberta, Canada operates an Aquatic Invasive Species Defence Program, including a watercraft inspection regime to detect and respond to high-risk watercraft potentially transporting invasive mussels into the province from infested lakes or rivers. This initiative may use trained sniffer dogs to detect the presence of invasive mussels on watercraft transiting through or operating in susceptible areas (Figure 4.15; Alberta, 2019).

For commercial fishing, there are a few countries which have guidance addressing the issue of biofouling management for fishing activities. For example, the Australian 2009 National Biofouling Management Guidelines for Commercial Fishing Vessels were adopted in 2009 (Australian Government 2009*a*) and amended in 2018. The Guidelines include a set of criteria for fishing vessels to minimize the risk of NIS transfer.

These include:

- Using locally sourced bait wherever possible to prevent the introduction of NIS pests and diseases.
- Returning bycatch to the sea as near as possible to the point of capture.
- If gear is cleaned in port, disposing of biological waste at on-shore facilities.
- Streaming of nets for cleaning at sea to be undertaken as close as possible to fishing grounds.
- Guidance that nets should be dried out regularly or prior to transfer to another boat to ensure living biological matter is not translocated.

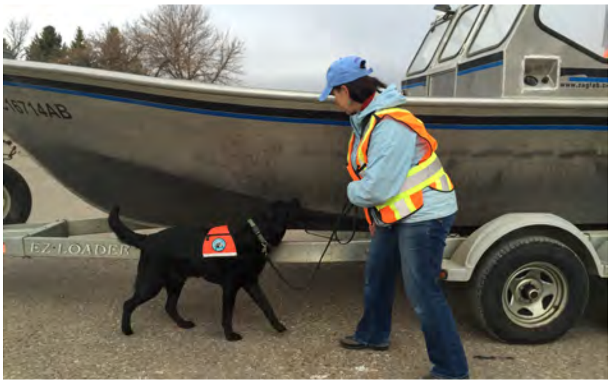


Figure 4.15 Sniffer dog checking for invasive mussel species on a trailered boat in Alberta, Canada.
Source: Flickr (CC BY-NC-ND 2.0).

4.1.2.5 Regulations and guidance on biofouling on commercial and recreational fishing activities, gear and equipment

Operations of fishing vessels and regulations relating to biofouling that would develop on these vessels fall under the purview of the IMO. The 2023 IMO Guidelines are therefore applicable (see Section 4.1.1.6 for further details on these guidelines). However, with respect to fishing operations (rather than vessel operations), including the use and maintenance of fishing gear, they fall under the purview of the Committee on Fisheries (COFI) of the Food and Agricultural Organization (FAO). The Code of Conduct for Responsible Fisheries (CCRF) adopted by the FAO in 1995 is the reference document of principles and standards applicable to the conservation, management and development of all fisheries globally. Although it has been developed as a voluntary set of guidelines, some of its provisions have been made mandatory by other legal instruments building on UNCLOS and the 1995 UN Convention on Straddling Fish Stocks and Highly Migratory Fish Stocks[11]. According to the UNFSA, States must minimize pollution, waste, discards, catch by lost or abandoned gear and impacts on associated or dependent species through measures including the development and use of selective, environmentally safe and cost-effective fishing gear and techniques. They must also protect biodiversity in the marine environment and implement and enforce conservation and management measures through effective monitoring, control and surveillance. Although the maintenance of fishing gear to prevent adverse environmental impact from biofouling falls within the scope of these provisions, the CCRF does not provide the guidance needed.

10 Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1417443504720&uri=CELEX:32014R1143

11 Available at: https://www.un.org/depts/los/convention_agreements/texts/fish_stocks_agreement/CONF164_37.htm

Despite a lack of global mandatory or voluntary guidance on the management of commercial and recreational fishing equipment, some countries have adopted regulatory measures and/or guidance to manage the risk of introduction or transport of NIS via biofouling on fishing equipment. To prevent introductions into the country's waters, biosecurity regulations under customs authorities can be applied. With respect to transfer or spreading within the boundaries of a country's water, fisheries regulations or guidelines under local authorities can be employed (Zabin et al., 2018).

The following is an overview of examples of regulations and guidance for commercial and recreational fishing in Australia and the United Kingdom that include biofouling transported via the vessel, including its fishing gear and equipment.

In 2021, Australia adopted new requirements for managing biofouling on international vessels arriving into Australia, on pre-arrival reporting on biofouling management, assessment and potential inspection (Australian Government 2023*a*; amendment on Australia Biosecurity Act 2015). For national activities, separate guidelines had already been adopted for biofouling on commercial and recreational fishing vessels, including fishing gear. With respect to fishing gear, the 2009 National Biofouling Management Guidelines for Commercial Fishing Vessels (as amended in 2018) make recommendations as listed in Section 4.1.2.4. The National Biofouling Management Guidelines for Recreational Fishing Vessels, which were also adopted in 2009, contain similar recommendations to inspect, clean and dry fishing gear and equipment for each new area of operation and report any suspicious biofouling. However, Australia's state-level regulation also controls the risk of spreading of marine pests across different states, through fishing gear and equipment (Zabin et al., 2018).

In the United Kingdom, recreational fishing is regulated by the Environment Agency (EA), which is responsible for managing freshwater fisheries and the Marine Management Organisation (MMO) is responsible for managing commercial marine fisheries. Guidance on recreational fishing in the UK can be found in the websites of bodies such as the Angling Trust, which works closely with the EA to detect and control NIS in the UK (Angling Trust, 2002). The guidance outlines the principles of sustainable recreational fishing, which include using appropriate gear, releasing fish unharmed, not exceeding bag limits and cleaning regimes to prevent the carry-over of biofouling to another region.

The management of invasion risks from ALDFGs cannot be controlled using the same legal instruments because, by definition, they are not under the control of any entity. The global approach is to limit the risk of loss or abandonment of fishing nets or equipment (including FADs). Although the policies being developed focus on the prevention of marine debris, the policies also mitigate the risk ALDFGs create as a vector for introduction and spreading of NIS. The regulation of ALDFGs is complex because it lies at the intersection of three regulatory bodies: the FAO for its mandate over the regulation of sustainable fisheries; the IMO for its mandate to regulate pollution on the marine environment from vessels, including operational waste and fishing vessels; and the LC/LP for its mandate on disposal of waste or other matters from vessels. Interpretations on the respective scope of each mandate vary, but their overlap is generally acknowledged (Hodgson, 2022). Fishing gear such as FADs that are lawfully placed at sea for fishing are not garbage, as defined by MARPOL below, but they become so if they are not retrieved as they should be and if lost or deliberately abandoned, thereby becoming ALDFGs.

In 2019, the FAO adopted a set of voluntary guidelines on the marking of fishing gear that aim to provide a simple, pragmatic, affordable and verifiable means of identifying the ownership and position of fishing gear and its link with the vessel(s) and/or operator(s) undertaking the fishing operations (FAO, 2019). As fishing gear that becomes ALDFGs is first deployed from a fishing vessel, it also falls within the scope of maritime pollution from ships (regulated under MARPOL Annex V), provided that it qualifies as garbage under these rules. The IMO has long considered fishing gear discarded overboard as garbage under MARPOL and its disposal is forbidden under these regulations. It was also agreed to expand the reporting requirements in the MARPOL Garbage Record Book to include all losses and discharges of fishing gear (not just losses and discharges which pose a significant threat to the marine environment), although the terms of this new requirement are still being negotiated at the IMO. These negotiations include determination of the threshold for reporting and whether mandatory marking of fishing gear will be included in an IMO instrument.

4.1.2.6 Conclusion

4.1.2.6.1 Key findings

Recreational and commercial fishing activities can provide unique opportunities for the transfer and spread of NIS through the medium of biofouling and these are prompting increased regulatory and policy actions.

The increasing popularity of recreational fishing and the development of cross-border angling tourism have been responsible for the introduction of non-native and invasive species in many parts of the world. Although several of the recorded invasive events associated with recreational fishing have been the result of intentional stocking of NIS to provide enhanced angling experiences, many others have been inadvertently introduced via the biofouling accumulated on fishing equipment used in one bioregion and subsequently deployed in another. Fragments of weed and minute specimens of live NIS can readily be collected by fishers' equipment, clothing and footwear. Potential invasive species can survive for up to several weeks on the fishing paraphernalia and be readily available for transfer at another fishing site.

NIS carried in biofouling can have significant impacts on recreational fishing. For example, the introduction of non-native species can disrupt local ecosystems and reduce the populations of native fish species, which can reduce the quality and quantity of future fishing opportunities for recreational anglers.

Recreational fishing has both a local and international element with an increasing number of countries offering fishing opportunities for tourists and hosting international freshwater and offshore angling competitions. The risk of NIS transfer via the biofouling on angling equipment may be considered low for a single fishing event, but the huge global number of recreational fishers taking part in relatively uncontrolled activities daily increases the risk factor severely. The global number of those taking part in recreational fishing is practically incalculable, with figures varying from a minimum of 220 million to a maximum of 700 million.

Current mitigation strategies to address the prevention of NIS spread by organisms encountered in recreational fishing mainly consist of physical removal and the cleaning and drying of the equipment used. This includes the cleaning and drying of the hulls of any small recreational craft used for fishing platforms. Although many countries have permit systems and protected areas as a management control of NIS transferred by biofouling, these can often be weakly regulated and enforced.

For commercial fishing, while there is some detailed information available concerning biofouling issues with nets and other paraphernalia associated with aquaculture and fishing vessel hulls (see Sections 4.1.2 and 4.2.2), there is more limited awareness of the biosecurity risk relating to the fouling presence on fishing equipment such as trawl nets and static nets and pots.

There are several key issues related to biofouling and invasive species that impact both recreational and commercial fishing. One of the most significant issues is the lack of awareness among fishers about the potential impacts of these issues (Ghattavi et al., 2022). Many fishers are not aware of the risks associated with biofouling and invasive species and therefore do not take appropriate measures to prevent their spread. This can result in the unintentional introduction of invasive species and the spread of biofouling to other areas.

Another key issue is the difficulty in managing these issues on a large scale. Biofouling and invasive species have consequences not limited to individual boats or fishing locations, but rather can impact entire ecosystems. This means that effective management strategies require collaboration and coordination among fishers, government agencies and other stakeholders. Achieving such a level of coordination can be challenging, particularly when multiple jurisdictions are involved.

4.1.2.6.2 Gaps in knowledge

Despite significant efforts to prevent biofouling and the spread of invasive species in recreational and commercial fishing activities, there are still knowledge gaps that hinder effective management strategies.

One significant knowledge gap is the lack of detailed understanding of the specific mechanisms that facilitate biofouling and invasive species spread in fishing activities. The processes underlying the attachment and growth of biofouling organisms on fishing gear and equipment are complex and involve a range of environmental and biological factors (Dafforn et al., 2015). Similarly, the mechanisms that facilitate the establishment and spread of invasive species in fishing activities are not yet fully understood. A better understanding of the ecological and environmental factors that influence these processes is critical for developing effective management strategies.

Another knowledge gap is the limited availability of data on the economic impacts of biofouling and invasive species in fishing activities. Although some studies have estimated the economic costs of these issues, such estimates may not accurately capture the full extent of the impacts on local economies and communities (Karatayev et al., 2015). For instance, the impacts of invasive species on recreational fishing opportunities, local fisheries and coastal tourism may not be fully reflected in economic assessments.

There is also a need for better monitoring and surveillance systems to detect the presence of invasive species in fishing activities. Early detection is critical for preventing the establishment and spread of invasive species, but many fisheries lack effective surveillance systems. For instance, current screening methods may not detect the presence of invasive species that are present in low numbers or in hidden locations, such as within fishing gear. More comprehensive and effective monitoring systems are needed to detect and respond to invasive species threats in a timely and effective manner.

As there is a lack of information surrounding the scale and number of ALDFG units currently present in the global ocean, the size of the resultant biofouling hazard cannot be reliably estimated. In a similar manner, the number of rogue FADs remains an unknown entity.

4.1.2.6.3 Recommendations

Notwithstanding that some countries and local authorities provide a reasonable level of information regarding the risk of transfer of invasive species via biofouling, the gravity of both deliberate and accidental invasive species introductions in the recreational fishing arena supports a recommendation for a more widespread and global educational outreach programme to engage with the relevant fishing stakeholders. Such a programme could highlight the issue of biofouling management and create more understanding of the potential damage created by NIS, together with how it can directly affect the very resource which anglers use and enjoy (South et al., 2022).

Collaboration and partnerships between fisheries industries, academia, government agencies and non-governmental organizations are essential to develop and implement effective biofouling and invasive species management strategies and should encouraged, fostered and supported as appropriate.

A better understanding of the broader economic impacts of biofouling and invasive species is crucial for identifying effective management strategies, and securing support from stakeholders and actions to address the knowledge gap identified above regarding economic impacts are recommended.

A strengthening of compliance with permit systems and local bylaws may reduce potentially invasive species events and consequently lower the risk of NIS transfer via fishing gear passing through and accumulating biofouling. Inspection regimes may assist with adherence to local standards and they are recommended, along with surveillance and monitoring systems, such as acoustic telemetry, remote sensing technologies and eDNA analysis, to facilitate early detection of invasive species in more sensitive areas.

It is proposed that more work is required to curb the current global and mainly lackadaisical approach to the marking of fishing gear and the easy 'over the side' or abandonment disposal routes.

Finally, it is noted that the recently ratified UN High Seas Treaty will provide a legal framework for the creation of spatial management tools for the areas beyond national jurisdiction, including Marine Protected Areas (MPAs). The area-based management tools should be developed and implemented with an awareness of the need to address biofouling and NIS in general and particularly longstanding issues such as that of ALDFG.

4.1.3 Recreational craft

4.1.3.1 Brief background

Recreational craft or vessels are classified as boats being manufactured or operated for the purposes of pleasure[12]. Because these boats are not used for commercial purposes, they are, in general, less constrained by rules and regulations regarding their movements and maintenance as compared to commercial vessels. As with other ocean-going vessels, recreational vessels are susceptible to biofouling, thereby posing a risk for the transfer of NIS within the marine environment (Davidson et al., 2010; Ulman et al., 2017; 2019; Peters et al., 2019*a*, *b*). This is particularly important since biofouling on recreational boats is generally unregulated (Zabin et al., 2018), although their role in the transfer of NIS is being recognized more often (Martínez-Laiz et al., 2019; Ulman et al., 2019; Ashton et al., 2022). In addition to posing an environmental risk to marine systems, biofouling on recreational vessels also presents an economic impact, due to the costs associated with biofouling prevention (Champ, 2000; McClay et al., 2015), the maintenance of vessels in terms of cleaning operations and the management of biofouling (Ulman et al., 2019; Watermann et al., 2021). The role that these vessels play in the transfer of NIS is recognized by the IMO with the adoption of dedicated guidance to minimize the transfer of IAS as biofouling for recreational craft in 2012 (IMO, 2012).

4.1.3.2 Role of recreational craft as a biofouling pathway for the introduction and spread of NIS

Biofouling on recreational vessels is recognized as an important pathway for the introduction and spread of NIS, with more than 70% of sampled vessels hosting NIS in biofouling assemblages across regions such as South Africa and the Mediterranean (Peters et al., 2019*a*; Ulman et al., 2019). In addition, recreational vessels can host high numbers of NIS, with up to 20 species being detected across vessels and this is likely to vary across regions (Peters et al., 2019*a*; Ulman et al., 2019). Recreational vessels are able to transport species on the hulls and in niche areas of the vessels (Figures 4.16, 4.17 and 4.18) and although the presence of NIS may often be visible from the surface, this is not always the case. Often, there are instances where the hulls of vessels appear to be free of biofouling, but vessels that appear to be clean can support biofouling in the niche areas (Clarke Murray et al., 2011; Lacoursière-Roussel et al., 2012; Peters et al., 2019*b*) which require underwater inspection. Recreational craft thus act as important pathways for the transfer of NIS and, given that many recreational boats travel internationally, they can act as both primary and secondary pathways of NIS (Inglis and Floerl, 2002; Clarke Murray et al., 2011).

12 Directive 2013/53/EU of the European Parliament and of the Council of 20 November 2013 on recreational craft and personal watercraft and repealing Directive 94/25/EC. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013L0053

Primary introductions can occur as a result of fouled international vessels visiting new regions; however, these vessels can also play a role in the secondary spread of NIS when moving among several harbours or marinas in the region being visited. Resident recreational yachts (i.e. those that are registered in a particular marina to which they return, even after sailing regionally) have been suggested as likely mechanisms for the secondary spread of NIS (Inglis and Floerl, 2002; Clarke Murray et al., 2011; Clarke Murray, 2012). In contrast, transient yachts (i.e. those visiting a location away from their home marina (Floerl and Inglis, 2003) have the potential to act as a primary pathway for NIS transfer (Inglis and Floerl, 2002). A well-documented example of a recreational yacht acting as a primary pathway for NIS is that of the mussel *Mytilopsis sallei* that was transferred on a motor yacht into Darwin Harbour Estuary, Australia (Willan et al., 2000). The species was detected early in the invasion, which led to a rapid response and a successful eradication (Bax et al., 2002). Similarly, evidence for the secondary spread of NIS via recreational vessels is seen in South Africa, where the Skeleton Shrimp, *Caprella mutica,* was detected only on recreational vessels within one marina in the region (Peters and Robinson, 2017). At a later stage, the species was detected on recreational vessels in another marina in the region, where it was known that recreational craft move between the two marinas. Although the primary method of introduction was likely due to a larger commercial vessel, the presence of this species on multiple recreational vessels in two different marinas suggested that *Caprella mutica* was spread intra-regionally via recreational yachts. This demonstrates the crucial role that recreational vessels can play in facilitating the introduction and spread of NIS.

The travel patterns of recreational craft are an important factor when considering their role in transferring NIS. Many recreational vessels travel extensively, visiting several marinas in a single trip (Ulman et al., 2019), resulting in marinas acting as stepping stones for the spread of NIS. Further, recreational vessels typically are allowed to travel to regions where commercial vessel traffic is restricted or excluded, some of which may fall within Marine Protected Areas (Bax et al., 2003) that generally have restricted access for commercial vessels and other craft. Often, these isolated regions visited include islands (Castro et al., 2022) which have a high risk of irreversible impacts by invasions. This, therefore, is consistent with the idea that NIS invasions in such restricted access or isolated regions may be largely attributable to recreational craft, because there is no regulation of their movements when visiting such locations.

Figure 4.16 Biofouling by at least three invasive species (*Ciona robusta*, *Clavellina lepadiformis*, *Watersipora subtorquata*) on the hull of a recreational vessel with inefficient antifouling paint.
Source: K. Peters.

Figure 4.17 A recreational vessel with a relatively clean hull (depicted by the dark blue surface area) and biofouling in a niche area indicated by the joint between the hull and keel.
Source: A. Plos.

Figure 4.18 Biofouling on the rudder (niche area) of a vessel.
Source: A. Plos.

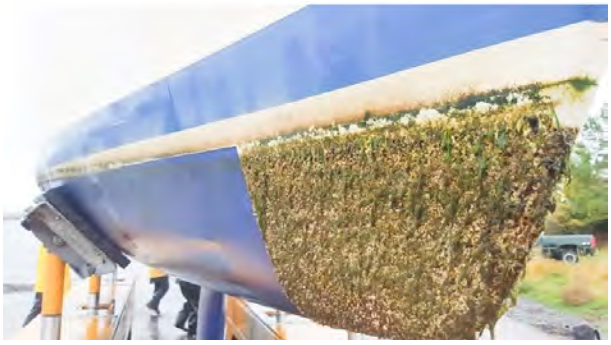


Figure 4.19 Yacht hull with both treated and untreated areas of antifouling paint.
Source: Kari Nurmi.

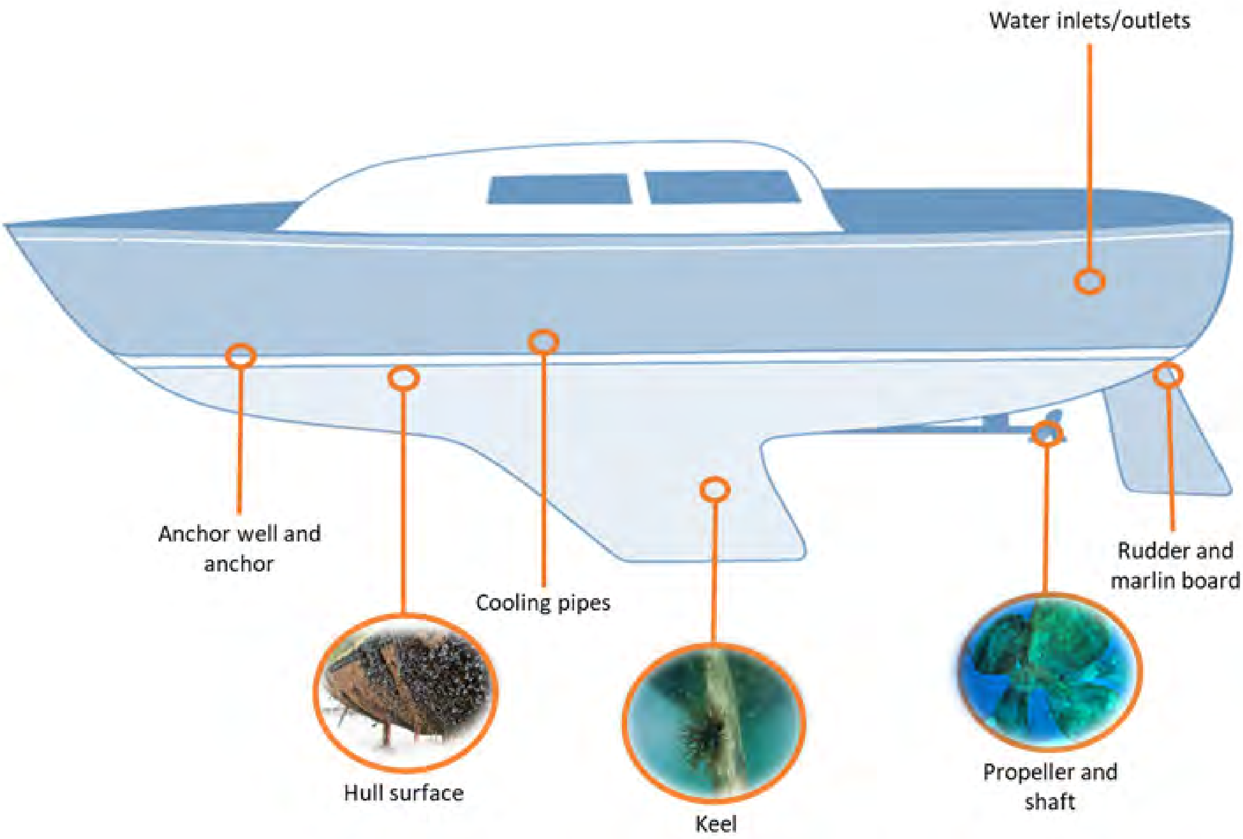


Figure 4.21 Niche areas on a recreational vessel, highlighting areas of concern.
Source: K. Peters, adapted from MPI–NZ.

4.1.3.3 Prevention, control and mitigation measures

4.1.3.3.1 Prevention measures

Many of the current mechanisms in place to prevent biofouling (see Chapter 3 for descriptions) are not effective enough on recreational boats and small localized vessels to prevent biofouling completely. In 2012, the IMO acknowledged that smaller vessels used for recreational purposes posed a more local threat and issued the 'Guidance for Minimizing the Transfer of Invasive Aquatic Species as Biofouling (Hull Fouling) for Recreational Craft' (IMO, 2012). This guidance document was specifically aimed at recreational craft less than 24 m in length, augmenting the guidance issued the previous year for large commercial vessels (see Section 4.1.1).

Although Chapter 3 provides a comprehensive account of biofouling prevention methods, the sections below provide a brief description of management measures specific to recreational craft.

Antifouling paints

The 2012 IMO Guidance on recreational craft states that an appropriate antifouling coating system (see Section 3.2) combined with good maintenance is the best way of preventing biofouling accumulation. This is illustrated in Figure 4.19, which shows a yacht with a section of hull left untreated with antifouling paint to demonstrate the growth potential of biofouling over a period of several months. The types of anti-fouling paint available to both commercial and recreational craft are fundamentally similar in principle of operation, but the detailed compositions often differ, as commercial vessel paint systems are usually designed to last for a period of five years between statutory dry-docking periods.

The 2012 IMO Guidance on recreational craft recommends that recreational craft are hauled out of the water for cleaning at least annually (IMO, 2012). Recreational craft may spend long periods of inactivity alongside marinas or on tidal moorings where regular drying out can occur. Smaller craft are usually lifted out of the water at the end of a summer season and stored in cradles or trailers ashore; however, this may vary across regions. These prolonged static periods mean that toxic biocidal coatings of contact leaching and erode-in-service biocide paints (see Chapter 3) remain popular with recreational craft users, whereas the use of self-polishing coating systems are generally impractical, although they are still in occasional use.

Non-toxic foul release coatings make the finished hull surface ultra-slippery to the extent that no algae or molluscs can effectively attach themselves and will be washed away as the vessel moves through the water (see Section 3.2). However, the overall benefit of non-toxic foul release coatings may not be fully achieved by comparatively static recreational craft, as such coatings require a regular velocity of passing water to wash away any organisms attempting to attach to the hull. Figure 4.20 shows two adjacent underwater yacht hull sections, one treated with a hard toxic paint (the clean section on the left) and another with a non- biocidal product (the fouled section the right,) which required regular brushing during use to remove the shown fouling.

Niche areas on recreational vessels that are hard to reach and areas in the 'shadow' of water flow when the craft is moving (e.g. anchor wells, inlet and outboard pipes) present additional challenges for antifouling paint coatings, as they do for commercial vessels. Build-up of marine growth in such areas can be combated by the use of copper anodes in the system or occasional chemical treatment cleaning, where the cleaning substance used and the disposal of the removed material would require some care. Jurisdictions, like those in New Zealand, are adopting additional regulations for recreational craft to address niche area biofouling as a NIS transfer risk factor. For example, the New Zealand Ministry for Primary Industries (MPI, 2018) has a Craft Risk Management Standard (CRMS) for biofouling on yachts and other recreational craft (see Figure 4.21).

Boat-lifting devices

In addition to antifouling paints being used as a biofouling prevention mechanism, recreational vessels may use floating devices (see Figures 4.22 and 4.23) that ensure the boats are raised out of the water, preventing direct contact with the water. This prevention mechanism focuses on creating an air-drying effect, thus preventing the occurrence of biofouling (see Section 3.7). Such devices also reduce the cost of long-term maintenance with regard to manual cleaning of the vessel and the frequency of antifouling paint applications. Although the floating system itself may be fouled, it will not leave the marina, resulting in a low risk of NIS transfer to other sites. One disadvantage of this system is that its use will only be appropriate for certain types of recreational boats, for example, smaller motorized vessels and yachts with retractable keels. However, there are alternative lifting options and emerging technologies, such as the Air-Dock (www.airdock.com), that address the issue of different types of vessels by accommodating a larger variety of vessels, e.g. motorboats, tri-hulls, catamarans and sailing yachts, such that only the keel will need to be maintained for biofouling before and after sailing.

Ultrasonics

Acoustic methods involving the application of ultrasonic frequencies (< 30 kHz) to vessel hulls and other areas, such as engine cooling systems, can have a significant reduction effect on biofouling settlement (Legg et al., 2015; see Section 3.4). This methodology is becoming popular for both commercial and recreational vessels (Wezenbeek et al., 2018) but does require a power source, which may restrict its use on smaller craft.

Figure 4.22 **a)** A motorized recreational boat suspended onto a floating system to prevent biofouling and **b)** the presence of biofouling on the structure
Source: K. Peters.

Figure 4.23 A motorized recreational boat suspended on a floating system to prevent biofouling.
Source: www.lightasairboats.com

Figure 4.24 Diver-controlled, in-water cleaning devices: **a.** A scuba diver removing biofouling (including the invasive ascidian *Ciona robusta* and the Mediterranean mussel *Mytilus galloprovincialis*) from the hull of a recreational boat, using a metal scraper and a net to capture the material. Source: A. Plos; **b.** Remora. Source: www.remoramarine.com; and **c.** CavitCleaner with Tornado 2. *Source:* www.cavitcleaner.com.

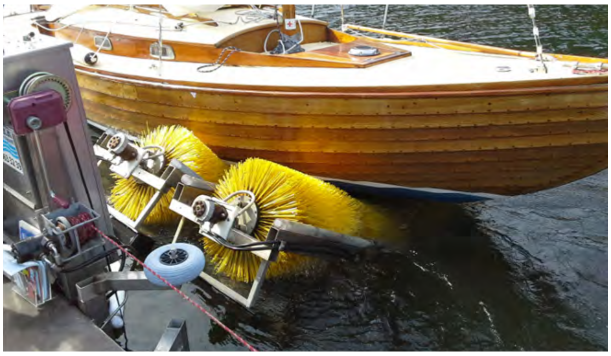


Figure 4.25 An example of a Boatwasher system cleaning the hull of a vessel. *Source:* www.boatwasher.wordpress.com.

4.1.3.3.2 Mitigation measures

To address risks to the marine environment, the two main measures put in place to control and mitigate biofouling on recreational vessels are the manual removal of biofouling and in-water encapsulation systems. Although these mitigation measures are put in place to manage biofouling, they do come with their own environmental risks (see Sections 3.1 and 3.8)

Diver-controlled and remotely operated devices

In-water hull cleaning of biofouling by a scuba diver with the use of scrapers (Figure 4.24), brushes and other devices (Hopkins et al., 2010) is widely used. There is increasing use of cavitation devices such as CavitCleaner and small-scale mechanical in-water cleaning devices such as the Remora and the Nemo Hull Cleaner, typically battery-operated and based on a hand-held drill design with attached rotary brushes (Figure 4.24). Such devices need to have rotation rates and brush types matched to the types of hulls to avoid coating damage. As such, they are best suited to cleaning lighter biofouling rather than heavy infestations of hard biofouling, where dry-docking would be more suitable. Such remotely operated devices are similar in principle to an electrical pool-cleaner design and comprise a cleaning unit with a suction pump and rotating brushes, cameras, LED lights, an umbilical to the surface and video-assisted remote control.

An additional way in which recreational vessels are being cleaned is through the use of automatic systems installed in marinas. These systems clean vessels with rotating bushes, preventing the need for regular, or any, antifouling paint applications (Soler et al., 2020). Boats are driven into these boat-washing berth systems to have the biofouling cleaned. Some of these systems include Naviclean and Boatwasher (Figure 4.25).

As discussed in Section 3.1, all in-water cleaning procedures pose risks that waste material from cleaning is released into the water column, with some sinking to the bottom, increasing the biosecurity risk should organisms survive the cleaning process and resettle onto other substrata, including marina infrastructure, benthic habitats within the marina and other vessels. In addition, manual removal techniques may not completely clean niche areas or areas that are hard to reach, or cause mobile species to flee and settle elsewhere.

In terms of biosecurity, only one of the currently available small-scale mechanical devices (Hulltimo) attempts any capture of debris. The design of this device has an integrated filtration and capture system which requires emptying an on-board bag similar to a domestic vacuum cleaner. Currently, if small vessels only have a biofilm layer, capture of debris would not be required unless local regulations prohibit the release of antifoul coating remnants, so a proactive ‘grooming’ approach is always preferable in terms of biosecurity when capture systems are not available.

Shore-based cleaning is recognized as having a lower biosecurity risk compared to in-water cleaning, given that there is less chance for material to escape directly into the water column during the cleaning process (Woods et al., 2012). There is still, however, a residual biosecurity risk, given that the disturbance during removal may cause mobile species to flee, even though the risk is immensely reduced by removing biofouling outside of the water (see Sections 3.7 and 3.8). An approach for shore-based cleaning of small vessels, by beaching them, has been developed recently, particularly when facilities for safe disposal of removed material are not available (Castro et al., 2020).

In-water encapsulation systems

An alternative approach to the manual removal or use of toxins for biofouling material on recreational boats, is the use of in-water encapsulation (Coutts et al., 2010*b*; Roche et al, 2015; Atalah et al., 2016). These systems create a barrier between the hulls of vessels and the water. This results in an inhospitable substrate for the biofouling community, devoid of light, oxygen and food for biota, as well as increasing temperatures (Atalah et al., 2016; Keanly and Robinson, 2020). The encapsulation results in death and decomposition of organisms themselves and creates a naturally toxic environment that can be enhanced by use of biocides or the addition of freshwater (see Section 3.8).

In addition to mitigating the presence of biofouling on recreational vessels as a pathway for NIS transfer, other management approaches also need to be considered. These may take into account regular surveys for NIS within marinas and isolated regions frequented by recreational vessels. These biological surveys should include searching for NIS on marina infrastructure, benthic habitats and recreational vessels as well as surrounding natural habitats. In addition, the use of settlement plates to survey the species present in the water column as larvae could provide important insights into the presence of NIS within marinas. Along with surveying and monitoring for NIS, creating awareness around the issue of NIS in biofouling assemblages with relevant stakeholders could be a key mitigation measure.

4.1.3.3.3 Regulatory measures and guidance

There are currently no global mandatory regulations for the management of biofouling on recreational craft. However, as previously mentioned, the IMO adopted a guidance document in 2012, for biofouling on these types of vessels (IMO, 2012), that complemented the IMO Biofouling Guidelines adopted in 2011 for larger vessels (IMO, 2011), now superseded by the 2023 IMO Guidelines 3. Although the 2012 guidelines for recreational vessels have been useful, they and the updated 2023 Guidelines may not be readily applicable, practicable or relevant in several local contexts due to current lack of awareness and resource constraints. Regulations developed and adopted domestically for managing biofouling on marine recreational vessels are able to cater to local circumstances. Examples include regulations developed in New Zealand Australia, Canada and a number of states in the USA (Martínez-Laiz et al., 2019). Regulations that are adopted locally take into account varying travel patterns within regions, availability of resources and feasibility of particular management protocols.

4.1.3.4 Conclusions and recommendations

The role that recreational craft play in the transfer of NIS has been demonstrated through the presence of such species in marinas and areas closed to commercial shipping and fishing, and although there are prevention and mitigation measures in place, the implementation of these measures is not consistent and the efficacy of some of the methods used may be region-specific.

4.1.3.4.1 Key findings

- **NIS has been detected in biofouling assemblages on >70% of recreational vessels, in several regions.** Biofouling on recreational craft therefore poses a high risk for the transfer of NIS.
- **Recreational vessels are important primary and secondary transfer mechanisms of NIS.** Primary introductions may be easier to manage with early detection; however, the secondary spread of NIS becomes a larger concern with recreational craft being able to move freely among marinas and isolated, pristine areas.
- **Niche areas of recreational craft are a particular concern for biofouling and the presence of NIS.** This is because niche areas are harder to manage for the prevention of biofouling and further, current mitigation measures may not be effective in niche areas.
- **Marinas act as stepping stones for the spread of NIS via biofouling on recreational vessels.** Vessels are, for the most part, able to move among marinas both regionally and internationally, without inspection for NIS, therefore aiding the spread of NIS present in biofouling assemblages.
- **Isolated regions such as pristine habitats, islands and marine protected areas are at risk of marine bioinvasions by NIS present on recreational craft.** The movement of recreational vessels to these locations is generally unregulated and therefore, any vessels with NIS present in biofouling assemblages have the potential to transfer those NIS, a threat that is posed uniquely by recreational craft.
- **Currently, many recreational craft are utilizing inefficient fouling prevention mechanisms based on activity/use of the vessels.** This results in rapid accumulation of biofouling assemblages and therefore an increased threat of transferring NIS.
- **The regulatory framework for the management of biofouling on recreational craft is limited.** There is no overarching mandatory regulation that is applicable for the movement of recreational vessels as well as the maintenance of vessels. Existing guidelines may be useful, but not necessarily practical in many local contexts.

4.1.3.4.2 Gaps

- **Several studies have demonstrated the relevance of recreational vessels as a secondary transfer mechanism of marine NIS and it would be beneficial to manage these risks.** However, it is unclear whether biofouling on recreational vessels is a substantial concern as a primary vector and examples that demonstrate this are limited.
- **Most of the monitoring information and research considering biofouling on recreational vessels comes from only a few regions.** The vast majority of marinas and recreational vessels are currently understudied and it would therefore be important to extend the sampling range of NIS surveys in marinas.
- **No quantitative measures are available to demonstrate the contribution that recreational vessels have in the introduction and spread of NIS, compared to commercial shipping.** It would be beneficial to determine how crucial biofouling on recreational vessels is in relation to biofouling on larger vessels, with regard to their roles of transferring NIS.
- **There are several gaps in the understanding of biofouling on recreational craft and small localized vessels.** Research that focuses on recreational vessels has grown and continues to increase. There is, however, a clear lack of research focusing on other small, localized vessels such as dinghies, small tugs and small research vessels. Current knowledge is limited on whether these smaller vessels, not used for recreational purposes, play a role in the accumulation and/or transfer of marine NIS and how important that role would be.
- **Considering the growing number of vessel movements on a global scale in addition to global climate change, more research is needed from understudied regions and regions with limited studies.** With changes in ocean temperatures and conditions, vessel movement and climate matching will become more and more crucial and currently, work that addresses this for recreational vessel movement is lacking.
- **There is a lack of information on the settlement patterns of biofouling on recreational vessels across a temporal scale that could inform management practices.** Further studies are needed that focus on tracking biofouling assemblages across varying distances and oceanic conditions.

4.1.3.4.3 Recommendations

- **The implementation of standard protocols (that can be slightly adapted at a local level) regarding hull maintenance would be beneficial.** Some of these protocols could potentially be incorporated into marina rules and regulations. The IMO guidelines, 'Guidance for Minimizing the Transfer of Invasive Aquatic Species as Biofouling (Hull Fouling) for Recreational Craft' could be used as a baseline to develop the protocols. However, the IMO guidelines should be reviewed in future, keeping in mind local contexts. Further, it would be beneficial if there were a standard set of mandatory management measures and an additional set of guidelines that can be implemented on a voluntary basis. This ensures that a particular standard is set as a mandatory baseline management requirement.
- **Monitoring programmes implemented at local/regional levels are necessary, particularly for early detection of incoming NIS and therefore, facilitating rapid response.** In order to achieve this, regional and local task force teams should be put in place to manage the monitoring of NIS as well as the protocol for rapid response actions.
- **Monitoring of settlement patterns of biofouling assemblages in order to inform management authorities.** This could also be used to inform vessel owners, as it could provide information regarding high-risk time periods for transferring NIS (i.e. when species of concern settle onto available surfaces and when high-risk time periods are expected) as well as regions considered as high risk for the transfer of NIS.
- **There is a need for studies that focus on the detection of NIS in marinas and recreational vessels in understudied regions, and those that address the settlement patterns of NIS in understudied areas.** Further, studies that focus on climate matching and forecast changes in climate in relation to the movement or/ travel history of vessels (both recreational and other vessel types) are crucial in order to develop watchlists for regions; this could be linked to the aforementioned monitoring programmes.
- **Currently, there is no known, single database capturing the status of marine NIS across the world.** It would be extremely useful to develop such a database that could be accessible anywhere in the world, to determine which regions have which NIS present in marinas and on recreational vessels. Further, digital records of movement patterns of vessels could be implemented to track vessel movement as a means to identify high risk regions and/or sources of NIS.
- **Workshops that focus on engagement with necessary stakeholders such as with marina members and staff, including antifouling companies, are highly recommended.** During these workshops, participants could be informed about the risk of NIS in biofouling assemblages and practical ways in which they can reduce the spread of NIS could be discussed. This would instil a sense of ocean stewardship and is an approach likely to be well received and beneficial to all involved.
- **The development and implementation of stricter regulations considering the movement of recreational vessels, particularly to pristine and/or island locations, marine protected areas with restrictions on other types of vessels, or areas of concern, is recommended.** This recommendation does not suggest that vessels should be banned from visiting such regions, but rather that there be a set biosecurity protocol in place before vessels are allowed to enter sensitive areas or areas of concern.

4.2 Aquaculture

With the decline of capture fisheries, aquaculture has seen rapid growth over the last 50 years, making up almost 50% of total seafood production as of 2020. In terms of tonnage, the highest volume of aquacultured species consists of freshwater fish (48 million tons) and marine algae (35 million tons), followed by molluscs and crustaceans (<20 million tons) and marine fishes (<10%). However, the FAO has announced as part of its 'Blue Transformation' plan a focus on sustainable aquaculture expansion and intensification to support global food security (FAO, 2022). Aquaculture is the fastest growing form of food production in the world, with many new initiatives for large-scale high-intensity offshore fish farms to increase production.

As biofouling occurs quickly on any surface that is immersed in water, for aquaculture, the potential for NIS issues affects a large part of the infrastructure in a culture system. Aquaculture systems may be broadly divided into open, semi-enclosed or closed systems. Open systems include sea cages and ponds, whereby the cultured organism is immersed in the environment and interacts with the wildlife. With respect to NIS, open systems pose the greater complexity in terms of risk, as a delicate balance needs to be achieved to ensure optimal growth of the target organism in the aquaculture.

Closed systems include land-based factories with recirculating systems supporting the aquaculture. More recently, these systems may also be mounted on floating barges at sea. To some extent, many of these systems may be considered semi-enclosed, depending on the extent to which water is treated before and after it is used for aquaculture. For the most part, treatment measures for static structures (see Chapter 3) may be applied for the management of any NIS which may occur on the exterior of a closed containment system.

In discussing NIS in aquaculture, it is useful to differentiate between the target organism for which the aquaculture is intended, as opposed to the other organisms which may be associated with the farm structure. To achieve better sustainability, some aquaculture systems may intentionally include other organisms either as a secondary product (as in polyculture systems which involve the simultaneous cultivation of a few compatible organisms in the same area) or for other beneficial purposes, such as the recycling of waste. The latter includes integrated multi-trophic aquaculture (reviews by Granada et al., 2016; Knowler et al., 2020), where organisms of different trophic levels are co-cultured in such a way that waste produced by higher trophic level organisms is consumed by detrital feeders and microalgae. Some of these grazers may act as a means for biocontrol of fouling, but effectiveness is varied (Zeinert et al., 2021).

Many aquaculture systems, including semi-closed containment systems, rely on biofilms in the biological filter beds to treat nutrient waste. In open farm systems, besides the primary product, there will be many naturally occurring organisms which are either beneficial or tolerated in farming. For example, open-sea fish farms are often associated with aggregations of wildlife, as they may act as feeding and breeding grounds for other smaller fish species and wildlife (Barrett et al., 2018).

NIS may also occur as epibiosis on the shell and hard surfaces of organisms in aquaculture. This issue is especially pertinent in the case of shellfish aquaculture (see Box 2). It is known, for example, that crabs are often more heavily fouled in cage aquaculture as they are unable to bury themselves in the way they would do in the wild.

4.2.1 The nature of biofouling on aquaculture facilities

Freshwater/inland aquaculture production accounts for 54.4 million tons compared to 33.1 million tons from marine aquaculture in 2020 (FAO, 2022). Inland aquaculture is diverse in its form, from freshwater ponds to high-tech land-based factory farming, but largely focused on finfish farming. Roughly 95% of this type of production occurs in Asia, with China as the top producer. Ponds are the most common culture system, in addition to raceways, cages, net pens and various close containment culture systems (Baluyut, 1989). The growth of freshwater biofouling is often facilitated by anthropogenic activities that contribute to food availability (eutrophic water bodies) or conducive environment (such as warmer water around power stations).

Marine aquaculture, on the other hand, consists primarily of open-sea farming which presents the higher risks for NIS. Sea-based farming may be broadly divided into three classes based on hydrography (Lovatelli et al., 2013):

- Coastal farming consists of farms sited <500 m from the coast, generally in water less than 10 m deep at low tide, aside from fjord settings, which usually occur in a sheltered location within sight of shore, but possibly in deeper waters.
- Farms located 500 m to 3 km from the coast, in deeper 10–50 m depth, may be considered as 'off-the-coast aquaculture'.
- Offshore aquaculture refers to farming located more than 2 km offshore, generally within continental shelf zones, in open ocean environments more than 50 m depth. These systems differ in bathymetry, degree of exposure to currents, wind and wave forces and proximity to benthic habitats.

Box 1 Invasion of the ascidian Didemnum vexillum in New Zealand salmon farms.

Chinook salmon (*Oncorhynchus tshawytscha*) are cultured in open-sea cages located in three main farming regions in New Zealand. Farms typically feature large-meshed predator nets that enclose the individual pen nets and protect stock from seals (Fletcher et al., 2023). The non-indigenous ascidian *Didemnum vexillum* was first detected in New Zealand in 2003. It was found on a farm pontoon which had been refurbished, in the vicinity of a vessel extensively fouled with *D. vexillum*. After transport to the farm site, and in spite of attempts at eradication, it spread onto the seabed below the farm and later, to adjacent mussel farms (Coutts and Forrest, 2007; Forrest et al., 2007). Current biofouling management consists of regular *in situ* high-pressure washing of nets (Fletcher et al., 2023). Pen and predator nets are typically cleaned every two and four weeks. As of now, no cleaning waste retention or filtration is practised (L. Fletcher, pers. comm.), which may facilitate the spread of NIS. However, farmers are encouraged to monitor their sites for NIS.

The New Zealand Government is actively trying to manage the situation, with online guidance documents and resources made available to farmers detailing practices for good animal welfare and biosecurity vigilance. A National Environmental Standard is in preparation that will require all marine farms to have a biosecurity management plan in place by 2025.

More information is available from the NZ Marine Primary Industries website:

https://www.mpi.govt.nz/biosecurity/how-to-find-report-and-prevent-pests-and-diseases/biosecurity-for-aquaculture-farmers/

https://www.mpi.govt.nz/fishing-aquaculture/aquaculture-fish-and-shellfish-farming/national-environmental-standards-for-marine-aquaculture/#biosecurity-manage.

Dr Oliver Floerl, LWP Ltd., Christchurch, New Zealand.

Aquaculture systems may be broadly divided into three groups based on the type of organism in culture. The first form consists of organisms that inhabit the water column, such as fishes and shrimp (see Box 1). The second group consists of benthic organisms such as crabs, oysters, sea cucumber and other products which may be sedentary but not attached to a substrate for aquaculture purposes (see Box 2). The third category consists of the aquaculture of sessile organisms such as algae (Box 3) and some molluscs. These groups highlight different challenges for managing NIS from biofouling, because of the way in which the cultured organism interacts with its containment. Depending on the biology of the species in culture, customized measures are often employed to minimize biofouling.

In terms of production structures, finfish are most commonly kept in open-sea cage aquaculture in the open environment. These may be situated in both coastal and offshore environments, as open cages can withstand moderate physical stress due to sea wave height and current velocity. There is no real standardization of open cage designs, as this often depends on the site characteristics, fish species to be cultured, operation and production scales. Most sea cages utilize floating systems, although there are also now semi- and fully submersible cage designs (e.g. Afewerki et al., 2023). Closed containment aquaculture has gained popularity with the advances in recirculating aquaculture systems (RAS). RAS technology aims to minimize water consumption, control culture conditions and manage waste streams. Although RAS occur in land-based farms, floating closed containment farms have been introduced to enable intensive fish farming in waterways with poor water quality or coastal areas with sensitive habitats.

Models for floating closed containment systems (FCCS) are emerging. As of now, most FCCS function as semi-enclosed systems. Water from the external environment is drawn into the system and treated for aquaculture requirements. Discharges may, or may not, be treated. Examples of FCCS include ‘FishGlobes’ which are rigid closed cages of up to 30,000 m^3 capacity, containing 2,000 tons of fish; Eco Cage (Ecomerden AS) is a 30,000 m^3 flexible cylindrical structure; and ‘FiiZK’ closed cages consisting of heavy-duty PVC tarp-based enclosures (review by Wang et al., 2020). The external surfaces of these systems would experience biofouling. Depending on national classification, conventional antifouling for vessels may be applied to the exterior of the structure. Biofouling from within the FCCS may be discharged into the sea during cleaning.

Each farm system will include cages and either mooring system for open culture (Cardia and Lovatelli, 2015) or shore-or platform-based closed-containment facilities. Typically, there will also be a barge or sheltered platform associated with a cluster of cages, from which farm personnel work. Farms are often serviced by vessels carrying materials and farm products or providing services.

Aquaculture facilities are generally fixed and may stay in place for months to years, making all the immersed parts of the farm structure vulnerable to the biofouling threats and consequences characteristic of static structures (Section 4.2.2.) Within a site, the biofouling challenges are different for each part, depending on the material and configuration of the structures. In general, biofouling is most severe in sheltered corners where nutrients and waste discharges accumulate. The underside of platforms will generally carry higher density of shellfish fouling, whereas the topside of structures exposed to strong sunlight suffer from algal fouling.

Hydrodynamic flow characteristics around open-sea structures and the farm itself will also affect the biofouling community structure. In defining hydrodynamic flow, key factors to consider are water depth, current velocity, near field circulation, dissolved oxygen and the solidity

Box 2 Managing biofouling in the shellfish industry

NIS from biofouling presents a difficult challenge for the shellfish aquaculture industry. In Prince Edward Island, Canada, the shellfish industry began in the 1970s, and included oysters, lobsters, mussels, clams and scallops. However, by the mid-1990s, the sustainability and productivity of the farms had been threatened by invasions of NIS, mainly composed of the blue mussel Mytilus edulis, as well as tunicates such as Styela clava, Ciona intestinalis, Botryllus schlosseri and Botrylloides violaceus. Since 1998, the industry and government agencies have worked together to contain these NIS across different bays and farms and minimize the spread and impact of these species. Responsible practices of harvest were encouraged and restricted in infested areas, and at the beginning the benefits outweighed the costs (Locke, 2009). However, C. intestinalis infestations quickly overgrew the mussels, resulting in competition for food, loose attachment of mussels subsequently leading to loss of mussel stocks, but increasing average stock weight (four- to five-fold). Attempts with a containment strategy were effective only in the short term and at small scales. Practices to reduce the abundance of tunicates include use of a machine that employed multiple high-pressure nozzles to wash off or pierce the fouling tunicates, but the effectiveness of these methods is limited (Paetzold et al., 2012, Davidson et al., 2016).

More information may be found in the ACRDP document Containment and Mitigation of Nuisance Tunicates on Prince Edward Island to Improve Mussel Farm Productivity (https://waves-vagues.dfo-mpo.gc.ca/Library/346732.pdf)

Dr Evangelina Schwindt, Instituto de Biología de Organismos Marinos (IBIOMAR-CONICET), Argentina.

of the nets. The flow regime inside a cage depends on the incoming current or pumping operations for closed containment cages, how the flow interacts with the net structures and the effects of the fish and their behaviour (Klebert et al., 2013).

Closed containment facilities may provide a higher degree of biosecurity than open-cage facilities. Stocks are isolated from the external environment and there are means to actively disinfect discharges, making the biofouling community mostly microbial. However, biofouling on the outside of the structure would still need to be managed similar to, for example, platforms associated with pen structures.

In addition, service vessels may act as vectors for the transfer of biofouling propagules between farms and adjacent ports. Finally, sea farming contributes a substantial portion of marine debris to the ocean (see Section 4.6) and along with microplastics produced by or interacting with the facility (Bowley et al., 2021), also represents a pathway for the transfer of organisms (Campbell et al., 2017).

The movement of aquaculture facilities offshore, combined with the expansion of other offshore, fixed-platform industries such as renewable energy, poses new challenges for managing invasive species (Fernandez-Gonzalez and Sanchez-Jerez 2014). Although biofouling of structures in the offshore environment generally is lower than for inshore structures, the increased presence of hard structures in the top layers of the open ocean provides 'stepping stones' for biofouling to cross natural geographic boundaries. Aquaculture adds further controversy, as it also provides nutrient sources for undesirable species crossing ocean spaces which have been otherwise low nutrient 'deserts'.

Shrimp aquaculture occurs mostly in coastal areas. Most shrimp aquaculture occurs in China, followed by Thailand, Indonesia, India, Viet Nam, Brazil, Ecuador and Bangladesh. In many South-East Asian countries, shrimp farming occurs in ponds developed over mangrove. In many cases, organic waste, chemicals and antibiotics from shrimp farms can pollute groundwater or coastal estuaries. Salt from the ponds also seeps into the groundwater and onto agricultural land. This has had lasting effects, changing the hydrology of wetland ecosystems. As a result of disease outbreaks in many areas, there is now a strong interest in the development of intensive indoor shrimp farming using biosecure RAS.

Production of bivalves and algae in coastal waters takes on a much larger diversity of form. For bivalves, this includes culture on a variety of ropes, mesh bags, trays or poles. Algae may be cultured on lines, rafts, trays or directly on the ground. Sites may be located in coastal or open waters as well as in tidal zones. Crustaceans such as crabs and lobsters are often cultured in land-based aquaculture facilities or in small coastal farms with cages immersed in the sea. Because of the predatory nature of most crustaceans, biofouling may be less severe on the net cages compared to finfish cages. However, NIS may occur as epibiosis on the animals. Sea cucumbers are most often cultured as a by-product in finfish cages, where they also serve to bioremediate sediments under the net cages.

Biosecurity is strongly influenced by both open and closed containment facilities and the business model of the operation. The diversity of business models in aquaculture, from small family-run artisanal farms to industrial-scale operations affects pathways and exposure to biofouling and capacity to manage biofouling issues. In many developing countries, aquaculture is dominated by small holdings which trade with larger consortiums. These marked differences in scale of operations have important implications for biosecurity, as they influence local capacity to manage biofouling issues and the many pathways in which invasions may occur.

4.2.2 Effects of aquaculture on the environment which facilitate the establishment of non-indigenous species

4.2.2.1 General considerations in all aquatic ecosystems

In general, seasonal environmental variability affects the abundance of organism propagules in the environment and consequently the form and severity of biofouling. However, in the case of aquaculture, culture practices which increase and/or provide a regular supply of nutrients within the farm environment can amplify risks of biofouling with any taxa, including NIS. The regular supply of nutrients may allow potentially biofouling taxa to thrive themselves, or overcome biotic resistance of their predators and competitors, during periods of natural environmental stress. This, in turn, may allow them to establish and spread in a new environment (Dumont et al., 2011). Multiple facilities along a coastline may also provide transitional refuges or stepping stones that facilitate invasion by prolonging propagule supply to surrounding natural communities. Similarly, the transfer of biofouled stock among neighbouring farms would expedite the transport of NIS across larger distances than would occur naturally.

In addition to the aquaculture facilities themselves, excessive nutrient discharge and discharges of chemicals (such as biocides and antibiotics used for animal health and veterinary purposes) from aquaculture are detrimental to the surrounding environment, promoting the growth of undesirable species in the adjacent natural habitats, as well as the culture facilities. These impacts on the environment reduce the fitness of native ecosystems and increase its susceptibility to bioinvasion by biofouling NIS.

Biological pollution, by way of the use of genetically enhanced genotypes, may also occur if these farmed animals escape into the environment. Often, these would establish first as biofouling in the vicinity of the farming area, then transfer via other biofouling pathways (such as shipping).

4.2.2.2 Special considerations of bioinvasions in freshwater aquaculture

NIS from biofouling of aquaculture can have major impacts on the freshwater environment, as, unlike the ocean, freshwater water bodies are more discrete. Many freshwater biofoulers are effective ecosystem engineers by their substantial effects on the physical and chemical properties of freshwater habitats (Nakano and Strayer, 2014). Freshwater NIS which are biofoulers include several bivalves, hydroids, bryozoans, some sponges and insects. Molluscs make up the most infamous of invasive freshwater biofoulers. These include Dreissena spp., Limnoperna fortunei and Corbicula spp. Many of these molluscs are estuarine or mangrove species capable of tolerating extreme salinity and temperature conditions.

With respect to biofouling associated with NIS from aquaculture, these are most likely first transferred into a freshwater environment as biofouling on farm products. Once locally established, where geographic distance among connected

Table 4.3 Overview of prevention and treatment strategies widely used

Substrate	Prevention		Removal			
Cage/pen material	Copper metal nets and copper threads in netting	Biocidal antifouling coatings* (e.g. copper, tralopyril)	Netting materials and coatings with non-stick properties	In-water cleaning, net exchange	Air drying	Biological control
Farmed stock	Genetic resistance	Controlling stocking density	Fouling release coatings	Regular cleaning	Air drying, acid/freshwater treatment, husbandry practices (e.g. re-stocking)	Biological control
Water column/culture medium	Spatial and temporal avoidance	Controlling nutrient discharges	Filtration of intake water in closed systems	Ultrasound treatment of intake water (RAS)		
Peripheral farm structures	Biocidal antifouling coatings*		Regular in-water cleaning			

*limited to approved products for use in aquaculture industry freshwater bodies is relatively small, an active spread will occur rapidly by natural dispersal and anthropogenic activities. For large ecosystems such as the Great Lakes and Mekong, the movement of biofouled farm vessels actively contributes to the spread. As geographical distance among freshwater sites increases, the importance of interaction between different industries increases. For example, aquaculture installations in a freshwater body may contribute to biofouling on vessels, which in turn act as vectors for its transfer to another freshwater body.

Box 3 Management of biofouling in seaweed aquaculture

In recent years, several efforts have been made to develop sustainable and resilient seaweed aquaculture with as little impact as possible on the natural area. Biofouling on the seaweed crop is one of the important factors that affects the quality of the produced crop. The biofouling organisms are seasonal and the best way to avoid a biofouled crop is to harvest in the late spring and early summer, before biofouling organisms settle on the seaweed. Biofouling increases rapidly during the summer months (Koester, 2022; Forbord et al., 2020).

Various production and operational methods are developing to optimize kelp quality and growth and to avoid biofouling. For example, hatchery methods based on Mols-Mortensen et al.'s (2005) work in the Faroe Islands are being used by various groups. After the initial hatchery production period, the seeded ropes can be deployed during peak growing seasons in *in situ* seaweed farms. However, if the seaweed is not harvested at appropriate times, the quality of the crop can be severely compromised due to biofouling (Figure 4.26). The biofouling species reflect the species in the natural area. For example, the snail *Lacuna vincta* can appear on the seaweed crop in very high and unnatural densities. The NIS species *Caprella mutica* has also been found on the seaweed crop when the crop was left on the sea-based farm until August.

Figure 4.26. The brown algae *Alaria esculenta* in June, and in August, where biofouling has severely compromised the quality of the crop.
Source: TARI – Faroe.

Partial harvest and re-growth of the same individuals on the seaweed farm has been suggested as a useful method when cultivating *Saccharina latissima* in the Faroes Islands (Bak et al., 2018). Koester (2022) tested the partial harvesting method on *Alaria esculenta* and the results showed a limited re-grow of *A. esculenta* after the first harvest. Biofouling on the *A. esculenta* crop increased significantly between the first harvest in June and the second harvest in August. Koester (2022) concluded that the partial harvest was not a useful method in *A. esculenta* cultivation, neither regarding biomass yield nor quality of crop.

Thus, managing biofouling in seaweed aquaculture is best practised by timing deployment and harvest so it fits into the local environment for avoiding on-grow of unwanted organisms.

Dr Susse Wegeberg, Senior advisor, Aarhus University, Department of Ecoscience, Denmark.

Land-based aquaculture systems based on RAS technology face particular threats from massive microbial disease outbreaks if they are not properly managed. Pathogens and microbes from cultured animals (which may be NIS) may be discharged into the environment during partial water exchange or if diseased fish are not disposed of carefully. Where land-based hatcheries are used to produce fingerlings that are subsequently transferred to open sea cages for grow-out culture, NIS from the containment system may also be discharged into the environment.

4.2.2.3 Role of the aquarium trade

A significant number of NIS can be attributed to the aquarium and ornamental fish industry. With an estimated 2 million people worldwide keeping marine aquaria, the marine ornamental trade is estimated to be worth US$200–330 million a year (Wabnitz et al., 2003). Although it is estimated that only 1–10 percent of marine ornamentals are captive-bred, the high value of the industry and complex dynamics of the trade makes it very difficult to regulate. Captive breeding facilities supplying the trade are often operated by artisanal farmers who do not have the capacity to properly manage biosecurity. Pathways for introduction of NIS include escape, either from a breeding facility or during transportation, or deliberate releases either as disposal of excess unsold or unwanted organisms. These actions inadvertently also result in the release of associated parasites, pathogens and biofouling. Although the numbers of NIS are small in proportion to the numbers trafficked across borders, the impacts of several high-profile invaders such as *Caulerpa taxifolia* indicate an urgent need for better understanding of this pathway, to allow better quality risk assessments to be made (Williams et al., 2015).

4.2.3 Impacts of biofouling on aquaculture that have affected the choice of management measures in use

For the most part, biofouling is recognized in the industry as a significant economic cost and hurdle for efficient production in marine aquaculture. Issues such as the blockage of water intake pipes and nets, damage to structures and contamination of aquaculture products that affect quality drive management practices with varying degrees of success. Where biosecurity regulations exist, there is greater scrutiny to minimize biofouling, which in turn reduces risks of NIS. These concerns may place constraints on the initial selection of farm sites, as well as subsequent requirements for effective measures to prevent further spread of biofouling organisms (Cahill et al., 2022).

4.2.4 Measures used for the prevention of biofouling in aquaculture

4.2.4.1 General developments

Due to its diverse nature, aquaculture relies on a range of methods to prevent and treat biofouling (Table 4.3). The former includes methods that facilitate the avoidance of biofouling or rely on biocidal surfaces. Treatments mostly rely on the removal of biofouling, including in-water IWC, sometimes supported by choice of substrate. In 2004, the CRAB (Collective Research on Aquaculture Biofouling) initiative was undertaken to develop effective biofouling management strategies for the aquaculture industry in Europe. The CRAB project report (CRAB, 2006) provided an overview of major biofouling management methods in the aquaculture industry. Bannister et al. (2019) present a recent review of biofouling management for shellfish, finfish and seaweed aquaculture, covering improvements and new approaches explored since the start of the CRAB project.

The choice of strategy is often driven by the costs of managing biofouling, which include labour and material costs for cleaning of the farm, disposal of wastes and loss of farmed stocks during cleaning (Bloecher and Floerl, 2021; Sievers et al., 2019). In the case of products such as molluscs, there is additional labour cost associated with the removal of fouling on farmed products before sale and reduced market value in the case of badly fouled products. Where biocides may be used to manage fouling, options also take into account the risk of contamination resulting in the reduction in value of farmed products. Where the products are intended for international markets, additional costs arise from provisions required for compliance to different biosecurity and quarantine regulations.

4.2.4.2 Managing water quality

Eutrophication is widespread in coastal waters around urban cities and is especially pronounced in waterways either bordering agriculture or where aquaculture is taking place (Diaz et al., 2012). Nutrient discharges from farming are notorious for causing impacts to water quality and filter feeders also benefit from excess feed particles in the water column. Consequently, these nutrient discharges exacerbate biofouling problems as they encourage the growth of filter-feeding biofouling species which are frequently considered NIS. Reduction of nutrients and waste feed entering the water column from farms would be critical to managing biofouling within a farm, as well as minimizing its impacts on surrounding ecosystems (Price et al., 2015). Measures may include use of the appropriate types of feed and feed dispensers to minimize waste.

There are also emerging concepts such as integrated multi-trophic aquaculture (IMTA) to enhance recycling of nutrients (Loredana et al., 2023). However, care should be taken to ensure species selected do not pose biosecurity risks, especially in open water IMTA.

4.2.4.3 Prevention of attachment

Biofouling represents a serious threat for aquaculture equipment and infrastructure. Methods to deter attachment are commonly in use, to slow the build-up of such communities. For the most part, these discourage but rarely prevent settlement under aggressive fouling conditions.

The most common antifouling coatings applied to aquaculture netting materials use cuprous oxide as the active ingredient or zinc-based biocides. Recently, coatings based on biocides such as Tralopyril are taking up more market share, reporting performances that may rival copper under certain environmental conditions (Sen et al., 2020; Bloecher and Floerl, 2020). Although deemed more environmentally benign, lack of knowledge on potential effects on non-target organisms warrants caution (Oliveira et al., 2016; Grefsrud et al, 2022). In general, such antifouling treatments may last from 2 to 12 months, depending on the environmental conditions (Bloecher and Floerl, 2020, Cardia and Lovatelli, 2015). The other class of coatings consists of formulations designed to facilitate net cleaning. Slippery materials may foul but the biofouling attachments are weak, so the net can be cleaned more easily. Examples include fluorine or silicon-based coatings (Bannister et al., 2019). Swain and Shinjo (2014) noted that copper-biocide treated materials significantly reduced fouling but the coating roughness contributed to significant increase in the drag coefficient. On the other hand, silicone coatings were vulnerable to fouling, but the fouling removal was easy and the smoothness of the coating decreased the drag coefficient. Thus, there is a trade-off between materials.

The economic viability of these different solutions depends on the operational approach, but potential for contamination of farmed stock and environmental pollution are always major considerations. The choice of coating is subject to regulation in some countries (Bannister et al., 2019).

4.2.4.4 Physical removal of fouling

On net cages as well as other infrastructure, physical removal of the biofouling is often carried out using in-water net cleaning. However, the potential consequences from discharge of cleaning wastes into the ocean or freshwater body (e.g. potential spread of pathogens, reproductive propagules and fragments; pollution risks on surrounding benthic communities and exacerbation of biofouling on hard structures around the farm (Floerl et al., 2016) are important considerations (see Sections 3.1, 3.8).

Killing biofouling on farmed stocks or farm structures by immersion in freshwater or other solutions that do not degrade marketability of the species in culture is also widely used. Examples include Jute and Dunphy (2017) for killing polychaete worm *Sabella spallanzanii* on artificial structures in New Zealand; Rolheiser et al., (2012) using acetic acid and lime for *Didemnum vexillum* and sea star, *Evasterias troschellii*; and Cahill et al. (2021) in the use of acetic acid to manage biofouling in shellfish aquaculture. The effectiveness of these methods can be enhanced by determining practical 'therapeutic windows' which match the life-history timing of the culture species and potential fouling species to inform treatment timing and frequency, and also by careful disposal of the removed biofouling organisms.

4.2.4.5 Closed containment aquaculture

Closed containment aquaculture represents the most effective strategy for preventing incursions into the environment. For many years, there have been arguments that aquaculture should be removed from the open aquatic environment, to prevent impacts to natural habitats and fisheries. At the same time, as a result of environmental uncertainties, there has been major advancement in the development of closed containment aquaculture systems, leveraging on recirculating aquarium systems. This industrialization of aquaculture has led to technologies for precision farming that leverages Aquaculture 4.0 technology. Recent examples include floating closed containment farms in Singapore and China.

As these systems are new, the environment regulations around them are vague. With respect to biofouling management, these may be managed as for other static structures with additional measures to regulate biohazards in any discharged water.

4.2.4.6 Border controls

Where products from aquaculture enter international trade, biosecurity protocols can also play a role in management of biofouling communities. There are many national and some international standards for biosecurity, but the standards and their methods of surveillance and compliance vary considerably among countries. Moreover, they commonly only apply to the condition of the fish or shellfish product, including appearance and biochemical test results, and not the production chain that produced the product.

4.2.5 Management of aquaculture biofouling to prevent transfer of non-indigenous species

Closed containment aquaculture represents the most effective strategy for preventing incursions into the environment if stringent biosecurity management is implemented. The long-term sustainability of aquaculture in closed containment aquaculture systems will require further innovation in the development of precision aquaculture in recirculating systems and technologies to reduce energy costs.

Water quality issues. In aquaculture, there is the opportunity to manage water quality in ways that reduce biofouling. Unfortunately, many coastal waters around urban cities or in agricultural drainage have become eutrophic and/or have other water quality problems with contaminants and the altered aquatic ecosystems found in such waters. Such nutrient discharges exacerbate biofouling problems, as they encourage the growth of undesirable or noxious species. Many biofouling species are filter feeders which also benefit from excess feed particles in the water column. This allows the reduction of nutrients and waste feed entering the water column to contribute to managing biofouling at aquaculture sites.

Biofouling on net cages. In reviews by Bloecher and Floerl (2020, 2021) and Bloecher et al. (2019), three preferred strategies emerge for minimizing biofouling present on net cages to reduce the risk of farms acting as vectors for the transfer of invasive species. These strategies are based on the use of efficient antifouling coatings that prevent the need for in-water cleaning; antifouling coatings combined with intermittent cleaning; and non-biocidal coatings combined with frequent cleaning of nets to minimize accumulation of marine growth and its release. The coatings attempt to minimize marine growth, in turn reducing the need for aggressive removal of biofouling organisms. Removal alone brings concomitant risk of release of NIS gametes during net cleaning, which facilitates their establishment in adjacent natural environments.

Biofouling management to prevent NIS. For the most part, a customized approach is needed for different aquacultured species depending on their life cycle and behaviours. This is especially so for sessile organisms which suffer from increased epibiosis under cage conditions. Although they contribute to minimizing biofouling, none is fully effective. For the most part, aquaculture is tolerant of some degree of biofouling. To effectively manage NIS, it may be effective to focus on monitoring for early detection of incursions, conducting frequent risk assessments, applying preventative measures and developing a plan for managing incursions. Many of aquaculture's activities involve trade or movement of goods and vessels across international borders – border controls with high environmental standards would play a valuable role in reducing risk of NIS spread.

4.2.6 International regulatory and policy response measures

The CCRF adopted by the FAO (Section 4.1.2.5) includes an Article 9 on Aquaculture Development. Articles 9.1 and 9.2 on responsible development of aquaculture more specifically conclude that:

- States should produce and regularly update aquaculture development strategies and plans, to ensure that aquaculture development is ecologically sustainable and to allow the rational use of resources shared by aquaculture and other activities (CCRF Article 9.1.3).
- States should establish effective procedures specific to aquaculture to undertake appropriate environmental assessment and monitoring with the aim of minimizing adverse ecological changes and related economic and social consequences resulting from water extraction, land use, discharge of effluents, use of drugs and chemicals and other aquaculture activities (CCRF Article 9.1.5).
- States should protect transboundary aquatic ecosystems by supporting responsible aquaculture practices within their national jurisdiction and by cooperating in the promotion of sustainable aquaculture practices. (CCRF Article 9.2.1).

Given the ecosystem disruptions that NIS can be responsible for, biofouling on aquaculture equipment that would facilitate the introduction and/or establishment of an NIS would clearly fall within the scope of this provision, although NIS are not explicitly mentioned in Article 9.1.

In its Technical Guidelines for aquaculture published in 1997 to support the implementation of the CCRF, the FAO provided general annotations to the provisions of this CCRF Article 9. These annotations envisage adverse effects from NIS, such as the loss of native species or change in species composition through competition, predation or habitat degradation. However, the source envisaged for such introduction is the escape of cultured species rather than biofouling, and biofouling is not specifically referenced. Nevertheless, they recommend that an information and management framework for the protection of inland and coastal environments and resources be in place capable of detecting and predicting ecological changes resulting from all human activities in a given area. They also recommend the use of a risk assessment to evaluate the effects of introductions and refer to the importance of obtaining baseline data and of monitoring, two necessary measures to respond to NIS from any source.

The FAO has been developing new Guidelines for Sustainable Aquaculture (GSA) since 2017, under the supervision of the Sub-committee on Aquaculture under its Committee on Fisheries (COFI), with information from expert consultations, including at regional level. The tentative completion timeline indicates 2024 for their adoption. This development is also taking place in the context of the 2021 COFI Declaration for Sustainable Fisheries and Aquaculture (FAO, 2021), which emphasizes the ecosystem and precautionary approaches. The 2023 draft GSA is a detailed document which heralds the Ecosystem Approach to Aquaculture (EAA) as a guiding principle and contains a section on the conservation of aquatic biodiversity and genetic resources. The latter refers in general terms to introductions and transfers of non-native species with the recommendation that:

- **(i)** A risk assessment be applied to such introduction or transfer.
- **(ii)** Species of wild stocks and farmed types under threat be monitored, together with promotion of their effective conservation.
- **(iii)** Applying a precautionary approach based on sound risk assessment and adaptive management to minimize harmful effects of accidental or deliberate introduction and transfers of aquaculture genetic resources (including NIS), as well as mainstreaming conservation and effective management of aquaculture genetic resources and biodiversity in aquaculture and in the wild by implementing the CBD GBF (see Section 3.10; Draft GSA, 2023, Articles 5.3).

However, it is regrettable that there is no explicit reference to the management and control of biofouling, thereby leaving to each State to adopt their own mechanism with risks of inconsistencies even within a shared ocean basin, unless other agreements can be reached for regional seas or other transboundary contexts.

4.2.7 Conclusions and recommendations

Aquaculture poses a significant risk of introducing invasive species or pathogens. However, there is poor awareness of biosecurity in the global industry, with most biosecurity measures focusing on disease management. Such measures do not entirely address NIS associated with farming, increasing risks that could undermine current or future livelihoods. Although examples of invasions directly caused by biofouling in aquaculture may not be common, the expected expansion of aquaculture globally gives sufficient basis for actions to improve biosecurity in the aquaculture industry to prevent this 'accidental' transfer of invasive species through biofouling.

4.2.7.1 Key findings

Despite the ubiquity of biofouling, little thought is given to its management at the design stages of many aquaculture projects, including design of a cage's structural components (Klebert et al., 2013; Xu and Qin, 2020). This is an area that should be given much more priority in licensing culture facilities in all environments – freshwater, coastal and marine. In addition, given how much biofouling (and antifouling) is affected by hydrodynamics, it would be very useful at the farm design stage to at least consider flow regimes and how these may affect subsequent management requirements (see Xu and Qin, 2020 for a useful discussion). These improvements in planning and design, combined with risk assessments explicitly addressing biofouling and NIS would potentially have beneficial implications for farm management in terms of maintenance, disease management and subsequent product value.

In many instances, aquaculture has had a positive impact in supporting local livelihoods. However, very often insufficient attention has been paid to biosecurity, to ensure that the functional integrity of the ecosystems around farming areas is not compromised. In discussing equitable mariculture, Eriksson et al. (2018) highlighted the risk of introducing invasive species or pathogens that could undermine current or future livelihoods. One of the reasons for the growing interest in offshore aquaculture lies in the lower expected biofouling levels. Although this seems logical, in terms of managing NIS transfer, such practices are only effective if the industry is able to implement effective antifouling measures.

Overall, there is poor awareness of biosecurity in the global industry, with most biosecurity measures focused on disease management. Many of these strategies focus on the use of drug treatments, vaccination and selection for genetically resistant species. These approaches do not contribute to addressing the industry's problems with NIS associated with farmed products. There is poor awareness of biofouling's role in disease transmission and a lack of appreciation of the industry's role as a pathway in the transfer of non-indigenous organisms. This may also be due, in part, to the lack of environmentally friendly antifouling technology suitable for aquaculture and may contribute to the lack of demand to advance such technologies.

A logical first step for all business models for aquaculture is to discourage the culture of NIS in open cage culture systems, given the difficulties in minimizing biofouling as well as to prevent escape of farmed stocks (Nichols, 2018). Minimizing the culture of NIS and genetically selected strains in artisanal and small holder farms is important, despite their individual small scale, given there is frequently a lack of local capacity to practise stringent biosecurity measures.

Non-indigenous and genetically selected species should be cultured in closed containment systems with good biosecurity management. The FAO (2008) highlights that effective management of genetic resources, risk assessment and monitoring can help promote responsible aquaculture and minimize adverse impacts on the environment. It further adds that genetic improvement programmes should not undermine the goals of conserving genetic diversity in wild aquatic species and protecting the integrity of aquatic communities and ecosystems. Large-scale industrial technology to support closed containment aquaculture has advanced considerably in recent years. With precision farming, there is extensive capacity for increasing yields in farming non-indigenous genetically selected species in closed containment systems, with minimal risks to the environment.

Active surveillance programmes are recommended for areas with intensive aquaculture. Early detection and eradication is the best approach to manage NIS in aquaculture. Improvements in planning and design, combined with risk assessments explicitly addressing biofouling and NIS can improve farm management in terms of maintenance, disease management and subsequent product value. Risk assessment and monitoring can help promote responsible aquaculture and minimize adverse impacts on the environment. Surveillance efforts should be coordinated with other maritime stakeholders sharing the sea space, since the issue of NIS affects all maritime industries. Trebitz et al. (2017) provide a useful structure for monitoring (Figure 4.27). The approach considers targeted and broad-spectrum monitoring, leveraging both traditional morphology-based techniques and new eDNA technology for targeted species. The paper provides a good overview of monitoring and decision strategies. In addition, improved means for monitoring and surveillance of biofouling in and around farm environments may include tools such as underwater drones/robotics.

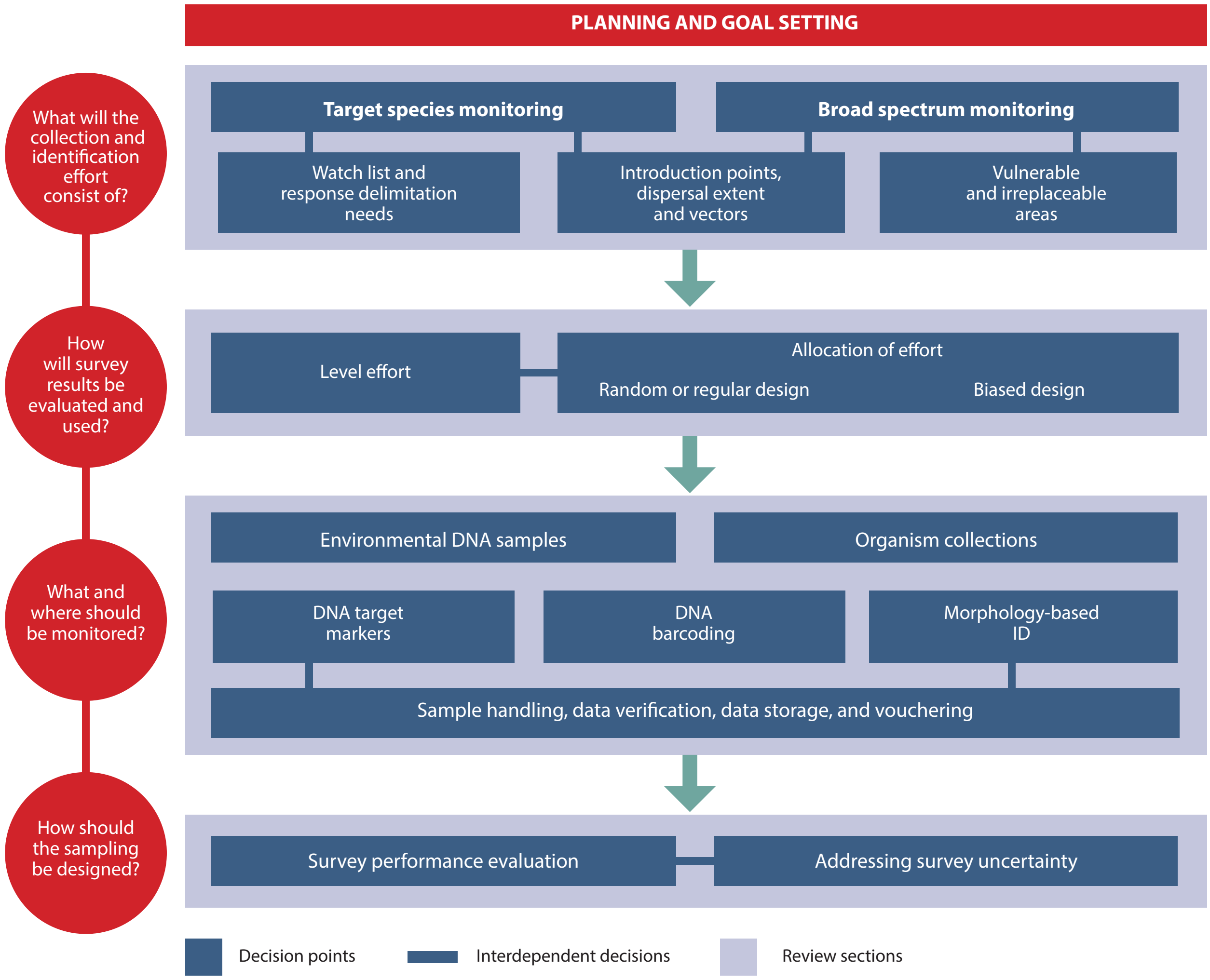


Figure 4.27 Decision matrix for early detection of NIS.
Source: After Trebitz et al., 2017, Figure 1.

Advances in eDNA technology may enable faster surveillance. Holman et al. (2019) demonstrated the use of eDNA metabarcoding of COI (cytochrome c oxidase subunit I) and 18S (nuclear small subunit ribosomal DNA) genes to examine community composition on artificial substrates across the UK. The study detected many non-indigenous species, including several newly NIS, demonstrating the utility of eDNA metabarcoding for both early detection and temporal/spatial monitoring of non-indigenous species. Metabarcoding can greatly improve early detection and monitoring of NIS. However, at the moment, there are incomplete reference libraries and a need for harmonization in screening methods. Better integration of data across eco-regions would be required to facilitate more efficient identification of IAS.

Farms should also observe practices and regulations as for IWC of vessels (see Section 3.8) and limit discharges into the ocean. The argument that discharges of biocides are amply diluted in the open ocean is rapidly eroding with the increasing scale of industry and vessels in the open seas. Standards such as the Aquaculture Stewardship Council (ASC) salmon standard discourage cleaning of nets coated with biocides and have contributed significantly to reduce the use of copper in Norwegian aquaculture. Incentives such as this, in combination with governmental regulations that prohibit IWC of biocidal nets as in other countries (e.g. Chile; Bannister et al., 2019) or require effective capture systems, are needed to facilitate the development of alternative coatings, for example, working towards non-leaching technology as tested in shipping (Ferreira et al., 2020; Silva et al., 2019) and novel technologies that can prevent discharge during cleaning. In-water cleaning is one of the most used technologies in finfish farming. But even though IWC removes biofouling, it carries a risk of facilitating the spread of NIS as well as contributing to nutrient enrichment in the surrounding waters and encouraging biofouling growth. Wastes from IWC should be removed and disposed of as biological waste and not discharged into the sea.

Very good antifouling is needed for open systems, especially industrial scale offshore farms. Open pen facilities pose greater risks of most types of environmental impacts, including NIS compared to closed-containment facilities. As detailed above, farm structures and their associated nutrient sources serve as a rich environment for the establishment and growth of NIS and for allowing NIS to spread across natural geographical barriers. Although there remains much opportunity for technology development (see Section 4.2.7.2), there are existing technologies which are effective when coupled with regular cleaning and good maintenance practices. Large-scale industrial technology to support closed containment aquaculture has advanced considerably in recent years and when properly implemented should pose minimal risks to the environment.

4.2.7.2 Knowledge gaps

Lack of data on biofouling in the aquaculture industry and its role in bioinvasions. There is an overall lack of data on biofouling in aquaculture and how frequently NIS occur on aquaculture installations. This information is needed to better understand the role and impact of different aquaculture systems in facilitating bioinvasions and the importance of individual pathways (e.g. via stock movement, farm structures and support vessels). More information on the role of vessel traffic between farms in the transfer of NIS and pathogens would be useful to inform on longer term management needed, given the potential interactive effects of climate change, aquaculture industry growth and changes in global trade patterns on the emergence of new biosecurity threats to global farming regions.

Poor understanding of the role of microfouling in relation to marine diseases in aquaculture. For many parts of the world, there is a lack of knowledge of microbial ecology and its role in epidemiology of marine diseases in aquaculture. Better understanding of epidemiology for disease and its vectors will strengthen the basis for better biofouling and NIS control, enabling development of more effective NIS and disease monitoring and surveillance systems. Technologies exist, but some of them are expensive and require stronger justification for developing effective operational frameworks and uptake by stakeholders. Better reference libraries to inform on eDNA monitoring and harmonization in screening methods for NIS are needed.

Challenges in the development of environmentally safe, non-toxic antifouling. Because aquaculture is conducted to meet food security needs, the use of recalcitrant biocides that may bioaccumulate either in the environment or within organism tissues cannot be used in the vicinity of farms. For aquaculture, the use of bioactives (chemicals) is constrained by food safety concerns. Appropriate approvals are needed demonstrating no accumulation for specific farmed products. This information is not available for many antifouling coatings used in maritime industries. The additional costs for obtaining biological data for approval for use of bioactive substances in aquaculture are a deterrent for the specialty chemicals industry to develop new biocides for the many niche products in the aquaculture industry.

Limited technologies to prevent biofouling on farm (static) structures. This is an issue for a large part of the maritime issue and more significant in the case of aquaculture as technologies employing bioactive chemicals are further curtailed. Cleaning technologies are also limited, as many are disruptive (e.g. producing loud noise or releasing debris into the water column) to the farm environment.

New technologies to better manage nutrient waste from aquaculture. More technology development to manage nutrient waste from farms is needed. These include methods for efficient dispensing feed, valorization of animal waste and treatment of waste discharges. The reduction of nutrient waste will reduce the extent of biofouling around farms and its surrounding environment. By reducing aquaculture's impact on natural habitats and biodiversity, the overall risk of establishment of NIS is also reduced.

4.2.7.3 Recommendations

Although examples of invasions directly caused by biofouling in aquaculture are uncommon, the expected expansion of aquaculture globally provides a sufficient basis for improving biosecurity in the aquaculture industry to prevent this 'accidental' transfer of invasive species through biofouling. Key considerations include:

Active surveillance programmes for NIS are recommended for areas with intensive aquaculture. For the most part, these should be coordinated efforts with other maritime stakeholders sharing the sea space. Policy development in the global seafood trade would be important to encourage the adoption of management strategies for NIS control.

Planning, design and licensing of aquaculture facilities should give more priority to management of biofouling. This would benefit the industry in terms of reducing the personnel needed for farming, to contain risks for disease as well as minimizing risks of NIS. Biofouling on farmed products will continue to require customized approaches for specific products. These efforts should be integrated with farm design to improve the overall efficiency for farmers.

Technology development for high-intensity farming in closed containment systems. High-intensity farming needs to be conducted within closed containment systems with efficient waste valorization systems to minimize waste discharge. Non-indigenous and genetically selected species should be cultured in closed containment systems with good biosecurity management

Minimal discharge into the environment. This should include restriction on discharges of nutrients, microplastics and bioactive substances into the ocean. Standards such as the Aquaculture Stewardship Council (ASC) salmon standard, in combination with governmental regulations that prohibit in-water cleaning of biocidal coatings, are needed to facilitate the development of alternative coatings and novel technologies that can prevent discharge during cleaning.

Outreach to inform and engage the industry. Farmers should be included as stakeholders in biodiversity management strategies, such that sea farm aquaculture pivots towards roles in regenerative aquaculture. Promotion of robust native biodiversity and the reduction of niches for establishment of invasive species would be a useful approach to reduce risks of invasion. Further development of ecological concepts and technologies for sustainable aquaculture would be useful in this respect, especially in the tropical marine environment, which has high biodiversity but is sensitive to nutrient accumulation. More education is needed to improve biosecurity awareness among farmers to spur development of appropriate methodology and inspection protocols for different marine product sectors.

Harmonization of practices and regulations. These should include practical risk assessment methods and the development of robust science-driven decision matrices that may be applied by administrations, industries and other stakeholders at national, regional and global scales.

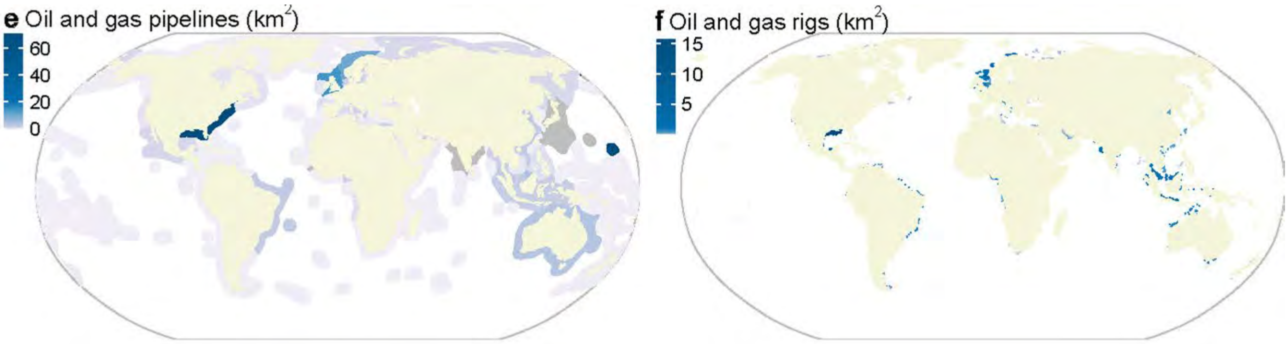


Figure 4.28 Distribution of oil and gas pipelines (left) and oil and gas platforms (right), with colour indication of the physical extent of seabed occupied.
Source: Bugnot et al., 2021.

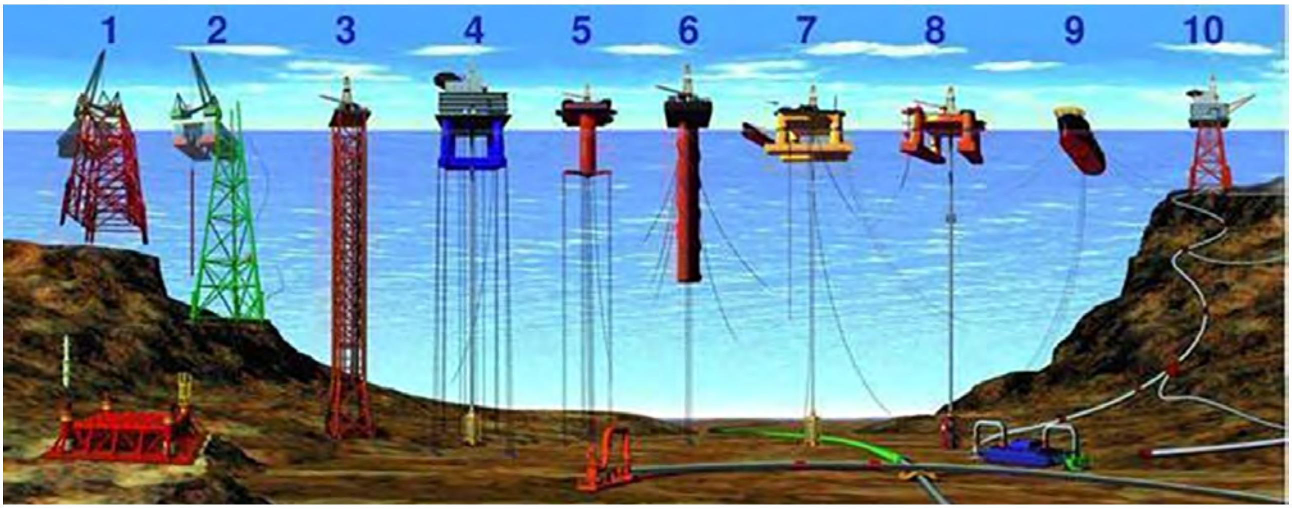


Figure 4.29 Types of offshore oil and gas structures include: **1), 2)** conventional fixed platforms, shown here as a jacket foundation (deepest: Shell's Bullwinkle in 1991 at 412 m/1,353 ft GOM); **3)** compliant tower (deepest: ChevronTexaco's Petronius in 1998 at 534 m /1,754 ft GOM); **4), 5)** vertically moored tension leg and mini-tension leg platform (deepest: ConocoPhillips' Magnolia in 2004 1,425 m/4,674 ft GOM); **6)** Spar (deepest: Dominion's Devil's Tower in 2004, 1,710 m/5,610 ft GOM); **7), 8)** Semi-submersibles (deepest: Shell's NaKika in 2003, 1,920 m/6,300 ft GOM); **9)** Floating production, storage and offloading facility (deepest: 2005, 1,345 m/4,429 ft Brazil); **10)** Sub-sea completion and tie-back to host facility (deepest: Shell's Coulomb tie to NaKika 2004, 2,307 m/ 7,570 ft).
All records from 2005 data.
Source: Office of Ocean Exploration and Research; National Oceanic and Atmospheric Administration (NOAA), US Department of Commerce.[14]

4.3 Marine offshore energy operations

Marine offshore operations here are considered to be the part of the offshore energy industry that is established and has been active for many decades. It mainly concerns oil and gas extraction activities. Marine offshore energy drilling operations have been carried out since the 1930s when offshore production started in estuaries in Louisiana, US (Gramling and Freudenburg, 2006). Approximately 12,000 stationary fixed and floating offshore oil and gas platforms are present worldwide (McLean et al., 2022; Parente et al., 2006; Figure 4.28), plus a total of 560 active mobile drilling rigs which moved between locations for drilling and exploration activities.[13] An estimated 136,000–180,000 km of pipelines were installed as of 2018 (Bugnot et al., 2021; McLean et al., 2022). Operations are concentrated in the Gulf of Mexico and the North Sea (Bugnot et al., 2021), but a total of 53 countries worldwide have offshore platforms present in their waters (Parente et al., 2006).

Many types of oil and gas installations exist, including foundations made of fixed steel jackets, concrete gravity-based, floating concrete or steel, subsea only and many other varieties (Figure 4.29). These installations can be categorized as either stationary, not relocated on a regular basis, or mobile, meaning they are relocated regularly between sites for activities such as drilling or exploration. Mobile systems can be based on floating systems which are kept in place by anchors or dynamic positioning, or jack-up type of installations, which float during relocation but stand on the seabed on legs that can be extended downwards, lifting the rig out of the water for stationary operations.

4.3.1 Role of marine offshore operations in the introduction and spread of biofouling non-indigenous species

Three primary roles in the potential spread of NIS via marine offshore energy (MOE) activities have been identified:

1. Mobile structures may be pathways that actively transport species outside their native range (Wanless et al., 2010; Yeo et al., 2010), when relocated between projects.
2. Fixed platform installations may provide pathways as stepping stones for further distribution after NIS have been introduced to a region (Coolen et al., 2020*a*, *b*; McLean et al, 2022) by creating habitat for NIS in otherwise unsuitable environments.
3. Pipelines may offer novel habitats for fouling species, likely including NIS, when introducing steel and concrete hard substrates on sandy seabeds, interconnecting fixed offshore and coastal structures (Lacey and Hayes, 2020; McLean et al., 2022).

Suppliers and other vessels servicing the mobile and fixed installations are considered as included in the vessels described in Section 4.1.

Mobile oil and gas installations, such as mobile offshore drilling units (MODU) are placed at work sites for periods up to and over five years (Yeo et al., 2010), during which time mature biofouling communities can establish on their submerged parts. Between jobs they are then moved at slow speeds (Iacarella et al., 2019), allowing communities that have established to remain on the structure during relocation (Foster and Willan, 1979; Wanless et al., 2010). Further, the installations are not dry-docked as often as ships, for example, increasing the potential biofouling communities on them. Introduction of NIS is a particular risk when mobile installations are moved between environmentally similar regions across large distances (IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships, 2022).

Box 4 gives examples of NIS introductions via mobile installations:

Fixed structures commonly remain at a site until the productive life of the installation ends, after which the structure is decommissioned and subsequently removed, or left in place, e.g. in the case of derogation from the removal obligation. The productive life of a fixed structure can be several decades; for example, some current active North Sea production platforms were constructed over 50 years ago (van der Stap et al., 2016). These fixed installations do not move NIS, since they remain in place during their productive life (the vessels servicing the installations are considered in Section 4.1). But the fixed structures may provide stepping stones for indigenous and NIS alike, by providing suitable habitat in otherwise unsuitable locations. These include hard substrates near the water surface, or near the bottom when placed in sandy or muddy seabed environments (Coolen et al., 2020*b*; McLean et al., 2022). Some NIS have anecdotally been reported on fixed offshore platforms (e.g. Coolen et al., 2020*a*, *c*; Page et al., 2006; Viola et al., 2018), but data on the magnitude of their presence on the thousands of platforms are unavailable. Any stepping-stone effect of offshore installations is the result of interplay between species' specific characteristics and environmental conditions (Sheehy and Vik, 2010). For installations to facilitate the spread of NIS, for example, the time water currents take to move between installations may determine whether larvae will encounter suitable substrate at their time of settlement. In the southern North Sea, species with pelagic larvae durations of several weeks have been suggested to benefit most from the stepping-stone effect.

13 Statista, 2023, Number of offshore oil rigs worldwide as of July 2022, by type. http://www.statista.com/statistics/1250440/global-offshore-rig-fleet-by-type/. (Accessed 9 February, 2023)

14 https://oceanexplorer.noaa.gov/explorations/06mexico/background/oil/media/types_600.html

Box 4 Illustrations of NIS on offshore structures

An oil rig was stranded on the island of Tristan da Cunha in 2006 after being lost during relocation in the South Atlantic for about six weeks. Upon inspection, it was found to host a mature community which included 62 species not indigenous to the island, including fish associated with the fouling community. Several species were evaluated to pose an invasion risk as they showed signs of reproduction or were observed at some distance from the installation (Wanless et al., 2010). In 2007, the rig was towed offshore and scuttled in >3,000 m water depth (Gard, 2008). A year later, a specimen of one of the NIS was observed in the stranding area after the rig had been removed, suggesting that this species had established in the local environment, but no additional NIS were encountered (Wanless et al., 2010).

A semi-submersible drilling rig was inspected in a dry dock in Singapore after it had been operational in various parts of the world, including the Gulf of Mexico, Eastern Pacific, the Timor Sea and South China Sea. The structure was entirely covered by a community of encrusting and associated species. 53% of the observed decapod and stomatopod species were identified as NIS to Singapore, two of which had already been shown to be invasive elsewhere (Yeo et al., 2010).

In 1975, an oil platform towed from Japan to New Zealand was inspected for presence of barnacles in the fouling community. Out of the 12 barnacle species observed, 6 had not been previously observed in New Zealand waters (Foster and Willan, 1979).

In the Mediterranean Sea, examples exist of NIS observed on mobile platforms, including *Perna perna* in Trieste, where living specimens were found on a platform translocated in Trieste harbour from Senegal (Crocetta, 2011) and 12 NIS were observed on a platform towed from Australia, which was placed in the eastern Mediterranean (Mienis, 2004).

Multiple fixed offshore gas platforms were inventoried in the North Sea. Within a total species richness of 138 species on 6 platforms, 6 NIS were observed. All the NIS had been previously described for the area (Coolen et al., 2020*a*).

This includes NIS such as the Atlantic slippersnail *Crepidula fornicata* (Coolen et al., 2020*b*).

Pipelines, when placed on top of the seabed, will provide novel habitats, in particular when placed in sandy and muddy seabed environments. This effect is similar to that of fixed production platforms. However, the pipelines span thousands of kilometres which, adding to the stepping-stone effect, might allow mobile NIS to move along these pathways during their adult life. This potential NIS pathway has received little attention to date and no data on the impact of pipelines on the spread of NIS are available (McLean et al., 2022).

The magnitude of NIS distribution via the MOE industry has not received much attention in the scientific literature (McLean et al., 2022). Multiple barriers exist that prevent the scientific community from studying NIS on MOE installations. Fixed installations can be challenging to access, for practical reasons, e.g. located very far offshore, in deep waters (hundreds of metres) and restricted by operators. Remotely Operated Vehicle (ROV) video surveys are often not suitable to detect NIS, in particular for small-sized species, which cannot be detected on standard ROV video footage (van der Stap et al., 2016). Acquiring scraped-off fouling samples in a quantitative manner is not possible yet using current ROV systems (Coolen et al., 2022*a*) and available non-quantitative systems are challenging to operate and, due to size requirements, only work on very large working-class ROV systems (Coolen and Ibanez-Erquiaga, 2022).

4.3.2 Consequences of biofouling that have influenced management measures

Prevention of biofouling on stationary installations is almost impossible. Survival rates of NIS inhabiting slow vessels are probably greater than on fast vessels (Ferreira et al., 2006; Yeo et al., 2010 and Section 4.1). The usual stationary operations and slow speed at which these structures are moved limits the effectiveness of antifouling paints (see Section 3.2; Kiil et al., 2001; Ferreira et al., 2006).

In addition, the long lifespans of stationary installations (Coolen et al., 2020*a*) further limits the effectiveness of antifouling coatings which rarely function effectively longer than five years (Section 3.2; Kiil et al., 2001). As a result, all MOE structures that are not cleaned of biofouling on a regular basis are inhabited by a rich community of biofouling organisms in any part of the global ocean (Eikers, 1978; Houghton, 1978; Moss et al., 1981; Forteath et al., 1983; Southgate and Myers, 1985; Relini et al., 1998; Stachowitsch et al., 2002; Yan and Yan, 2003; van der Stap et al., 2016; Schutter et al., 2019; Almeida and Coolen, 2020; Coolen et al., 2020*a*,*c*).

Since the biofouling communities do not cause drag and reduce fuel efficiency as they do for shipping and recreational vessels (Section 2.1), fixed offshore installations are only occasionally cleaned to remove fouling communities, often only when the build-up of biomass exceeds design specifications, causing wave- and current-induced stress on the structure (van der Stap et al., 2016; Almeida and Coolen, 2020). Although the cleaning removes past biofouling communities, it provides new empty habitat available for colonizing organisms and thereby may facilitate the settlement of NIS. As an example, after experimental removal of non-indigenous fouling communities on a platform off the coast of California, the occurrence of the non-indigenous *Watersipora subatra* increased significantly. Therefore, it was advised that fouling removal campaigns be planned, taking the species larval time in the water column into account (Viola et al., 2018).

In general, NIS are neither prioritized by industry nor as part of the scientific debate. There is only anecdotal literature on the presence of NIS on mobile structures (see Box 4) and no data on NIS on pipelines (McLean et al., 2022).

A recent survey among ecologists ranked the spread of invasive species at 10 out of 23 of the most important environmental considerations for decommissioning of platforms, which was lower than other considerations such as seabed disturbance, alteration of food webs and chemical contamination of the seabed (Fowler et al., 2018).

4.3.3 Control and mitigation measures of MOE biofouling relative to NIS

Management of NIS on MOE installations on an offshore project has been reviewed by IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships (IOC Technical Series, 2024). Included are examples of offshore operators invasive species management plans in which 'contractors are required to demonstrate that they represent a "low risk" of introducing these species within the "Invasive Marine Species Management Area". Where a biofouling inspection is undertaken, the inspection must demonstrate that the vessel is free of these species, or if they are found to be present, IWC is required to remove them (or alternatively other controls must be applied)' (Peach and Box, 2016). Other approaches include 'a "threshold" approach that defines acceptable biofouling as being below a certain percentage cover value' above which cleaning is required and 'a "functional group" approach which limits acceptable biofouling to certain functional groups (e.g. microfouling, gooseneck barnacles etc.' (IOC Technical Series, 2024). BHP Billiton has an NIS management plan in place for Australian waters (where regulations are strict), which includes assessment of the risk of NIS presence on mobile and immersed equipment, including mobile drilling rigs. If an unacceptable risk is identified, vessels or equipment may need to be inspected by 'suitably qualified marine scientists with experience in biofouling inspections'. It states further that if biofouling is 'to be removed from hull or immersible equipment.[...] Material removed during hull or immersible equipment cleaning shall not be discarded into the sea, but disposed of in an appropriate manner under local jurisdictional rules (e.g. licensed landfill).'(BHP Billiton, 2011).

Wanless et al. (2010) suggest that drilling rigs should undergo biofouling removal before every tow (in the area where the rig has been operating), to prevent the translocation of potential invasive species. Examples exist where all fouling on mobile MOE structures had to be removed before entering ports, e.g. by lifting the structures on a heavy lift vessel and removing all fouling (IOC Technical Series, 2024). Only anecdotal information is available about this prevention strategy. For example, the Australian government demanded a mobile platform being relocated from New Zealand be cleaned before port entry could be permitted (Hsieh, 2009).

When removing biofouling on mobile structures, various methods may be applied, as described in Chapter 3.

4.3.4 Regulatory measures and guidance

Offshore developments for mining activities, such as for oil and gas exploitation, do not have their own global international organization, making it more difficult for international rules to be agreed upon and resulting in a complex and fragmented regulatory landscape (Trevisanut, 2022); however, the 2023 IMO Guidelines also apply to offshore installations and platforms (see Section 4.1).

Regulations have also been adopted at national or subnational level for biosecurity, that seek to control the risk of NIS being introduced within a country's Exclusive Economic Zone (EEZ) in the context of activities involving offshore installations. Australia is a well-known example. The Australia Biosecurity Act 2015 applies to offshore installations, as it defines vessels to include offshore installations and floating structures (Australian Government 2023*a*). This act imposes biofouling management reporting and potential inspection requirements for entrance into Australia (see Section 4.1 and Australian Government 2023*b*).

National biofouling voluntary management guidelines for the petroleum production and exploration industry were also adopted in 2009. They are very detailed and include biofouling risk management, the management of immersible equipment and infrastructure, recording and reporting (Australian Government 2009*b*).

4.3.5 Cost

NIS have also been documented to impose direct costs to the rig operators by influencing operations, e.g. by clogging water inlets on installations (Sheehy and Vik, 2010); however, these costs have not resulted in widespread regulations or standards for the cleaning of offshore structures with the intent of managing NIS. The cost of preventing the spread of NIS is a factor in the slow adoption of regular cleaning. The structures may have large amounts of surface area exposed for colonization, making costs escalate as a result of both the large area to be cleaned and installations being out of commission during NIS removal activities. To illustrate, the cleaning and relocation of a drilling rig between New Zealand and Australia resulted in the rig being out of commission for 23 days at a cost of AU$370,000 per day (Hsieh, 2009). This high up-front cost of over AU$7 million may have been far lower had NIS been introduced to Australian waters (IPIECA, 2010); however, currently cleaning costs are incurred by the operators, whereas the costs to address NIS usually falls to environmental and regulatory authorities. This different distribution of costs and benefits is a consideration in developing and implementing regulatory and management frameworks for biofouling on offshore structures.

In the case of the installation that was lost and stranded on Tristan da Cunha (see Box 4), the rig had to be salvaged to reduce the risk of species introduction. The liability insurance for underwriting the salvage operation was reported to amount US$20,000,000. Further costs could be expected if any of the NIS had become established and caused economic loss to the local economy of Tristan da Cunha.

Biofouling removal prior to the tow would have resulted in far lower costs compared to the salvage operation and liability insurance (Wanless et al., 2010).

For fixed installations, in-operation biofouling to remove NIS is not common, but when installations are relocated after decommissioning, the presence of NIS may raise concerns, in particular if installations remain submerged during transport, allowing the fouling community to survive. The potential costs of removal of the fouling may be high (IOC Technical Series, 2024).

4.3.6 Conclusions and recommendations

4.3.6.1 Key findings

12,000 stationary MOE installations exist worldwide, plus a total of 560 mobile installations. Furthermore, an estimated 180,000 km of pipelines are currently installed.

MOE installations host NIS, but the magnitude remains unknown. There is no regular reporting of NIS on MOE installations. Currently, available publications on biofouling are limited in the sector (owing to quality of data and data sharing issues); published results are largely representative of the North Sea, Gulf of Mexico and California. When considered by the MOE sector, biofouling is mostly recognized as an engineering problem, not as a biosecurity issue, and low priority is given to NIS in biofouling.

MOE structures provide pathways for NIS to distribute. Concerns exist over the role that MOE installations may play in creating a network of 'stepping stones' facilitating the movement of NIS. Additional biosecurity concerns relate to the potential transfer of NIS from sites of manufacture to deployment, via mobile MOE installations and via support vessels accessing MOE installations.

4.3.6.2 Gaps

Limited data exist on the presence of NIS on MOE installations. Data are mostly anecdotal and if data exist, they are not commonly made available to the scientific community. In particular, the mobile installations may play a role in the translocation of NIS across long-range ecological barriers, but literature is mostly anecdotal.

Stepping stone model validation with empirical data is lacking. The stepping-stone effect from stationary platforms has been modelled but limited empirical field observed data are available to evaluate model performance.

The scientific community is lacking tools and access to offshore installations, hampering the study on NIS. ROV video surveys, commonly used in imaging infrastructure in deep waters, lack sufficient resolution to identify most NIS; deep water installations are unsuitable for scientific divers. ROV methods to quantitatively collect samples from biofouling on MOE installations are needed.

There is no competent international organization to manage MOE globally. Therefore, there is no sector-specific regulation or guidance adopted at the global level to manage NIS on MOE structures.

4.3.6.3 Recommendations

Establish an effective international regulatory framework to manage/prevent the spread of NIS via MOE activities. This should include the introduction of an effective NIS monitoring programme in the MOE industry and resulting NIS data should be made available to the scientific community.

Remove biofouling from mobile installations prior to towing to other regions. This should be included in biosecurity legislation regarding transportation of devices and infrastructure from place of manufacture to place of deployment, and relocation of structures.

Invest in the validation of larval dispersal models. The stepping-stone effects, as shown in the models, should be validated, e.g. using genetic analysis to establish connectivity and vectors for transport. This should then be further developed and applied to all life-stage decision planning of MOE installation, operations and decommissioning and (where applicable) derogation from removal obligations.

Invest in methods to study NIS presence on MOE structures. Sample collection, which is essential for the detection of small NIS, is challenging and in many locations, impossible, using current methods. ROV sampling methods, which would allow quantitative sampling of fouling communities on MOE installations, should be developed.

4.4 Ocean renewable energy generation

As part of societal and governmental objectives to tackle climate change by decarbonizing energy sources, renewable energy technologies are being developed to generate electricity while minimizing the emission of greenhouse gases (Kern and Rogge, 2016; Cooper and Hammond, 2018). For example, the EU Commission committed to an objective of 300 GW of offshore wind energy and 40 GW of ocean energy by 2050 in EU Waters.[15] The UK Government has also set the objective of delivering at least 15% of electricity

15 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions European Wind Power Action Plan. COM/2023/669 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0669&qid=1702455143415.

from renewable sources by 2020 (UK Government, 2019). In Scotland, there is a more ambitious objective to produce 50% of electricity from renewable technologies by 2030 (Scottish Government, 2019). A significant proportion of the extractable resources necessary to achieve these goals can be derived from oceans (Khan et al., 2017; Neill et al., 2017). Reports predict comparable developments in the Asia-Pacific region (GWEC, 2022). The term 'ocean renewable energy' (also known as 'offshore renewable energy') (ORE) is typically applied to resources of wind, waves and tides captured offshore (Figures 4.30 and 4.31). Other emerging technologies targeting renewable energy in the marine environment include floating photovoltaic (FPV) and ocean thermal energy conversion (OTEC) (e.g. IRENA, 2014; ICES, 2019*b*).

Figure 4.30 Fixed offshore wind farm Image..
Source: Hywind Scotland.

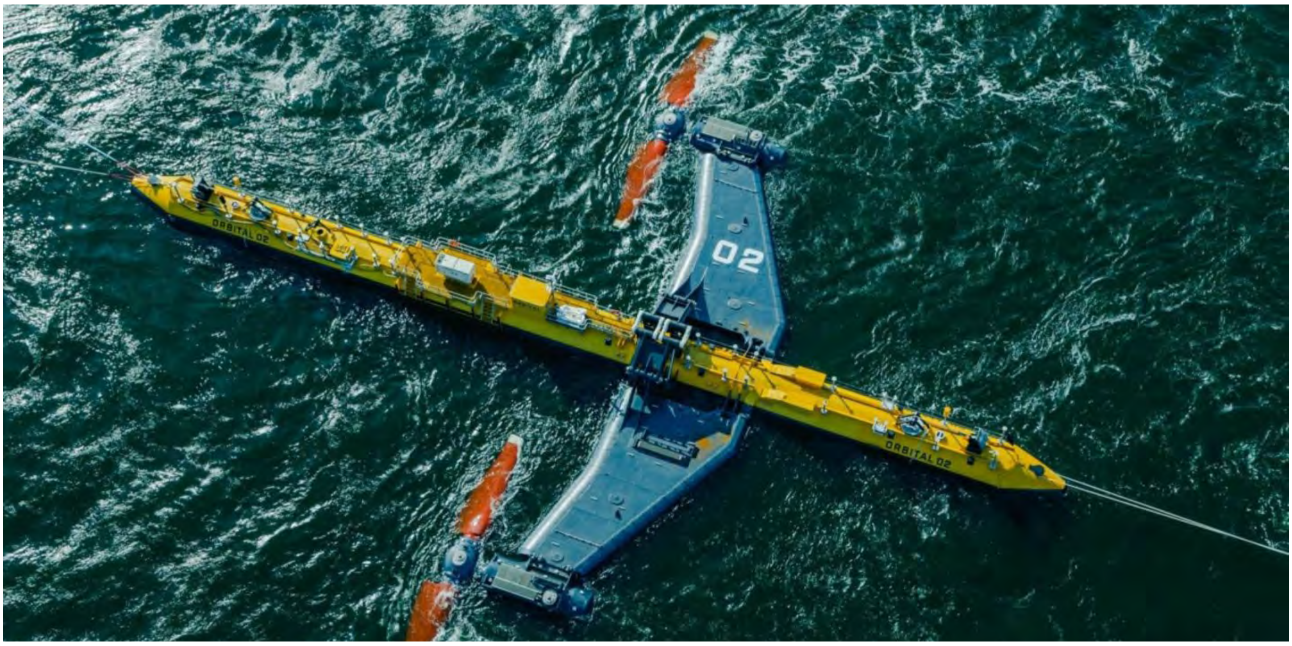


Figure 4.31 Floating tidal current device.
Source: Orbital Marine Power.

Offshore wind turbines may be fixed or floating and are mounted or anchored onto the seabed using several commonly applied mooring systems (Figure 4.32). Offshore wave energy converting devices are most commonly deployed on the sea surface and secured with dynamic mooring systems. Tidal energy can be extracted from current flow, known as 'tidal stream', or from the rise and fall of the tides captured by a 'tidal barrage' (Twidell and Weir, 2015). Many tidal stream devices resemble modified wind turbines and may be surface deployed or fixed to the seabed (Figure 4.32). Current ORE devices represent different levels of technology readiness and scale, from large commercially operating wind farms to individual wave energy converters undergoing field testing.

Biofouling is a significant risk for industries working in the marine environment (Dürr and Thomason, 2009; Figures 4.33 and 4.34). In the offshore wind sector, increased weight and drag from biofouling may compromise functioning and survivability of mooring systems and dynamic subsea cables by increasing structural loading (Langhamer et al.,

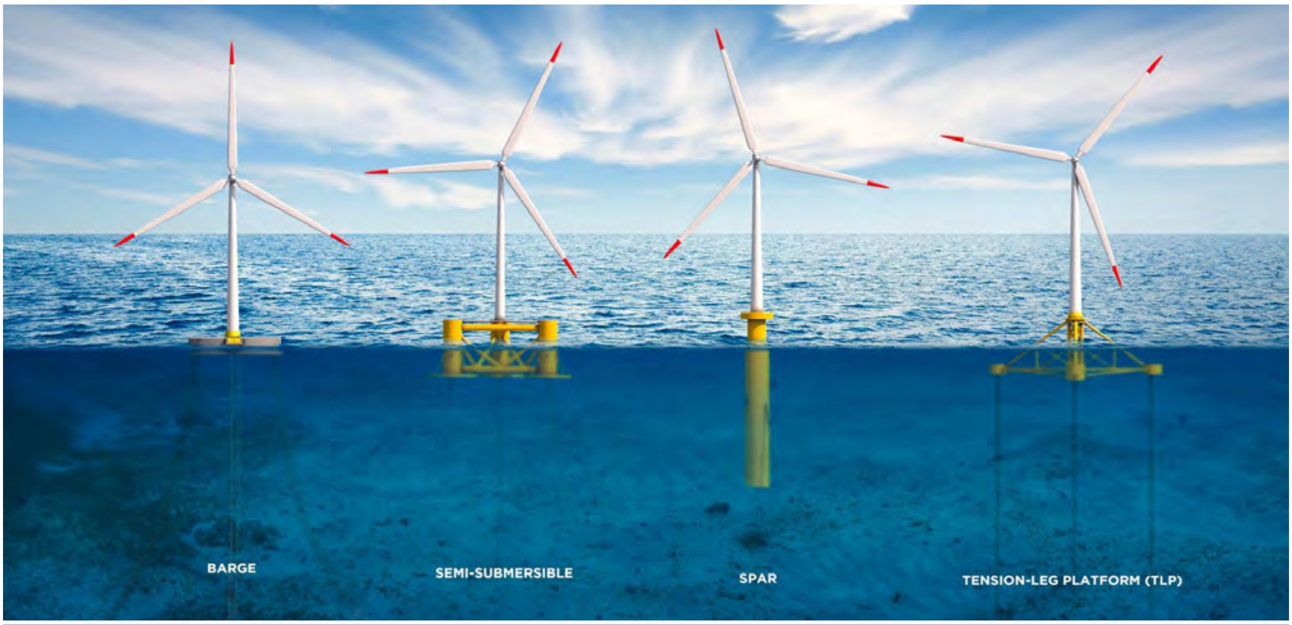


Figure 4.32 Mooring systems used in floating offshore wind technologies.
Source: WindEurope.

Figure 4.33 Biofouling on infrastructure deployed at the full-scale wave test site at the European Marine Energy Centre, Scotland (UK).
Source: Andrew Want.

2009; Yang et al., 2017; Taormina et al., 2018). On wave and tidal devices, biofouling may negatively impact hydrodynamic performance, influencing power delivery (Orme et al., 2001; Walker et al., 2014).

Although marine growth on fixed offshore structures associated with the oil and gas industry has been studied for several decades (Wolfson et al., 1979; Forteath et al., 1982; Relini et al., 1998; Page et al., 2006), in ORE technologies, fouling studies have often relied on limited opportunities to observe fouling from seabed moorings and surface-operating floating structures (Langhamer et al., 2009; Macleod et al., 2016; Nall et al., 2017; Want et al., 2017; Sheehan et al., 2018). As the ORE sector develops, biofouling issues are being recognized that are specific to this industry. Aspects of devices that may be particularly affected by biofouling include: moving parts unique to ORE technologies (Tiron et al., 2015); novel materials that have not been previously deployed in marine environments (Polagye and Thomson, 2010); and deployments taking place in habitats where structures have not been previously installed and studied (e.g. in strong tidal flow areas) (Want et al., 2017, 2021, 2023; Sheehan et al., 2018).

4.4.1 Role of ORE generation as a biofouling pathway for the introduction and spread of non-indigenous species

Fixed artificial structures in the marine environment may act as 'stepping stones', facilitating the spread of non-indigenous aquatic species after introduction to a region via other pathways (Apte et al., 2000; Kerchof et al., 2011; Adams et al., 2014; De Mesel et al.; 2015; Dannheim et al., 2018), posing a threat to local biodiversity with significant impacts on the economy (Sambrook et al., 2014). Studies of connectivity between infrastructures are primarily based on modelling larval dispersal (Hyder et al., 2017; Henry et al., 2018). As the decommissioning of oil and gas platforms and the installation of offshore wind farms accelerate, and with the development of commercialization of tidal and wave technologies, there exists a significant sectoral shift in deployments of large offshore infrastructure – from fossil fuel to renewable energy installations. The estimated global capacity of offshore wind farms is expected to expand more than ten-fold by 2040 (IEA, 2018; Sutherland et al., 2021). Validation of larval dispersal models, e.g. using genetic analysis (Hyder et al., 2017; Coolen et al., 2020b), to establish connectivity and vectors for transport, should be further developed and applied to all life-stage decision planning of ORE deployments.

Figure 4.34 Biofouling survey of decommissioned tidal turbine infrastructure.
Source: Andrew Want.

The introduction of offshore artificial substrates has been shown to increase local biodiversity (Coates et al., 2014; Lindeboom et al., 2011; Coolen et al., 2020a) and may enhance commercially valuable fisheries (Wilhemsson and Langhamer 2014; Streich et al., 2017). Although these effects are generally considered to be 'positive', less favourable impacts, including the risk in exacerbating the spread of NIS, should be considered (Smyth et al., 2015). Marine growth has the potential to colonize any structure placed in the marine environment (Wilson and Elliott, 2009; Wilson et al., 2010). In the ORE sector, infrastructure includes devices, floating platforms, foundations, moorings, subsea cables and scour protection (Figure 4.35). Vessels used in supporting this industry may also play a role in the movement of fouling species from harbours to ORE sites (Nall et al., 2015), as well as the transport of devices between locations, e.g. from points of manufacture to deployment (Loxton et al., 2017). Siting of ORE installations and maintenance scheduling need to be carefully thought out to minimize connectivity with NIS already established in supporting harbours (Hemery, 2020).

The infrastructure associated with ORE provides hard substrate habitats in areas typically dominated by soft sediments (Wilson and Elliot, 2009). Further, the installation of fixed offshore wind turbines provides settlement opportunities for organisms throughout the entire water column, from foundations to the surface-breaking monopile – a situation not normally seen in nature (Dannheim et al., 2018). However, studies of offshore wind farms and oil and gas platforms found NIS limited to upper levels, i.e. similar to intertidal habitats (Coolen et al., 2018; Viola et al., 2018); there is little evidence of NIS on deeper submerged infrastructures, such as subsea cables and protective armouries (Taormina et al., 2018; Vinagre et al., 2020). It should be noted that, given the large number of existing hard substrates in the marine environment, from natural rock outcrops to numerous wrecks and offshore infrastructure, it may prove challenging to determine the role that ORE deployments play in promoting range expansion of NIS (Dannheim et al., 2020).

There are relatively few published studies on biofouling or NIS in the ORE sector, partly owing to the early readiness level of these technologies, and to concerns with confidentiality in industry reports (Shields et al., 2011; Copping and Hemery, 2020). Although initiatives to collect and make available data in this sector are under development (e.g. Dannheim et al., 2018; 2023 submitted), more needs to be done to collect and share data globally (Coolen et al., 2022*b*; Vinagre et al., 2020). Currently, assessing the impacts of ORE installations on epibenthic organisms receives less attention than 'charismatic

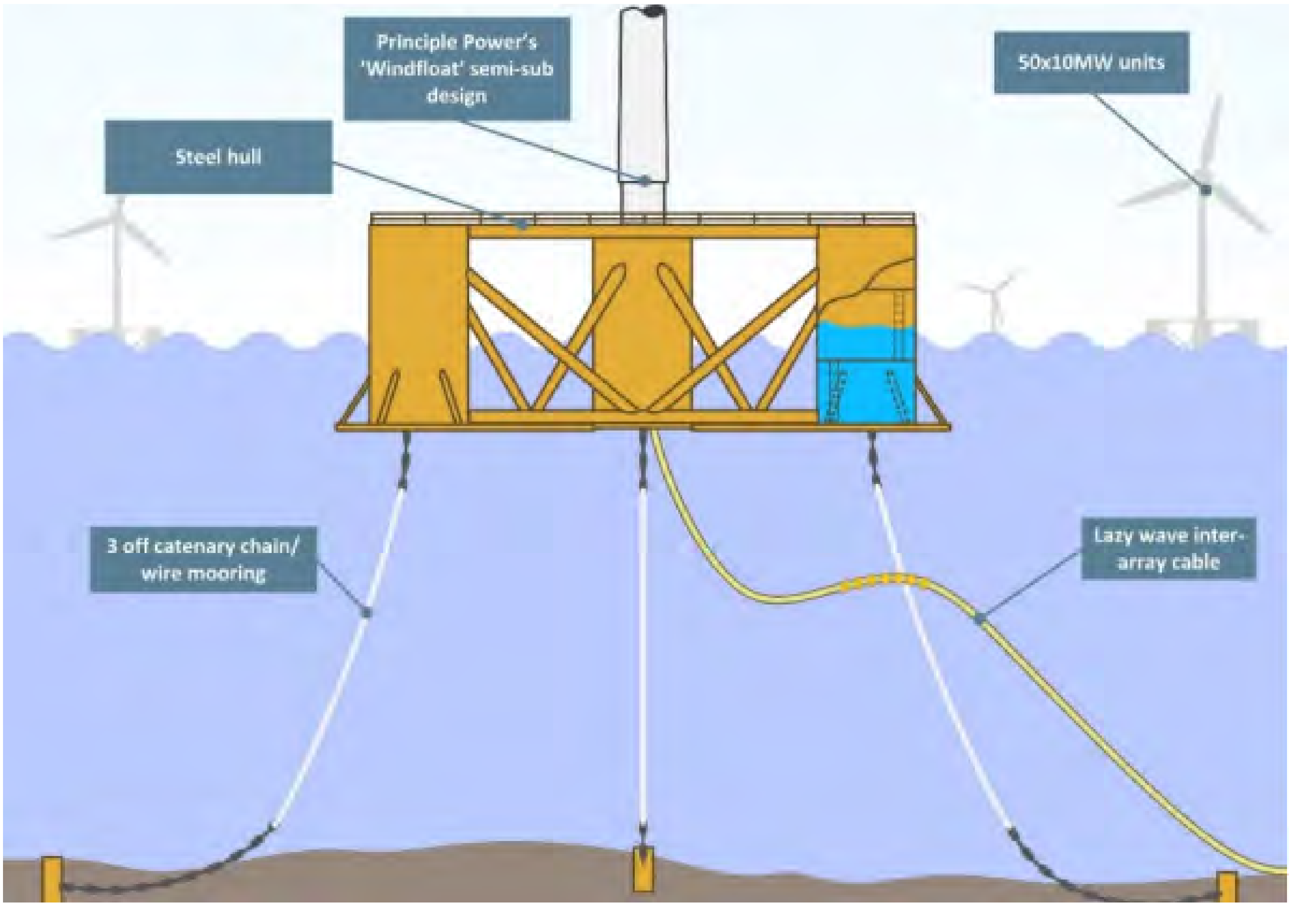


Figure 4.35 Components for the base case floating wind platform.
Source: Carbon Trust, 2020.

Figure 4.36 Fouling on a waverider buoy used to assess wave resource. Source: Want et al., 2017.

Figure 4.37 Vindeby (Denmark) decommissioning in 2016. *Source:* Orsted.

megafauna' from regulators during the consenting process (Copping and Hemery, 2020). In light of issues around biosecurity, a rebalance of priorities by regulatory bodies might be welcomed. Another key obstacle is the challenge faced in conducting surveys and scientific research in hydrodynamically demanding areas targeted by many ORE deployments. High current flow conditions may not be practical for survey work using scientific divers or ROVs (Gormley et al., 2018). Earlier biofouling studies in the ORE sector have included assessments of biofouling on offshore wind structures (Wilhelmsson and Langhamer, 2014; Coolen et al., 2020*a*, 2022a; van der Molen et al., 2018), wave and tidal devices (Nall et al., 2017; Want et al., 2017, 2023) and buoys used in the ORE sector (Langhamer et al., 2009; Macleod et al., 2016). In addition, recent studies in the ORE sector have focused on the effects of biofouling on the functionality of sensors (e.g. data buoys, acoustic Doppler current profilers and cameras) used to characterize energy resources and monitor device performance (Want et al., 2017) (Figure 4.36).

4.4.2 Prevention of biofouling

Generally speaking, biofouling is not a high priority for the ORE sector, which often sees the issue as secondary to engineering concerns. This echoes the O&G sector, where the importance of marine fouling was initially overlooked and underestimated (Edyvean, 1987). The development of coating technologies and other antifouling mitigation methods is not progressing as in some other sectors (e.g. shipping; but see for example project OCEANIC – http://oceanic-project.eu; and project SeaSnake – https://www.seasnake.eu). Testing of antifouling mitigations should be aimed towards applicability in hydrodynamically energetic seas targeted by ORE technologies, e.g. rapid tidal currents (Want et al., 2021). The efficacy of antifouling coatings is expected to be reduced in high-current speeds where greater shear stress and increased flow may accelerate the dissolution of antifoulant compounds (Kiil et al., 2002) and coatings may be impacted by sediment abrasion (Walker et al., 2014). Furthermore, the effectiveness of standard antifouling treatments, such as the use of protective coatings, is expected to be limited when applied to so-called 'niche' areas, featuring greater structural and hydrodynamic complexity, e.g. couplings, manifolds, etc. (Edyvean, 1987; Coutts and Taylor, 2004).

Sitings of ORE installations are typically informed by resource characterization, i.e. devices are placed in areas to maximize energy capture. However, determining the best location may also provide opportunities to manage threats to the local biota and habitats (Adams et al., 2014; Hyder et al., 2017; Coolen et al., 2018; van der Molen et al., 2018). As expected with the early stages of ORE technology, studies providing necessary evidence to inform decision-making by regulators and policy-makers regarding decommissioning (as well as derogation of mandatory removal) are lacking (Hyder et al., 2017; Knights et al., 2024). As of 2021, only a few of the wind farms, including at Vindeby (Denmark), Yttre Stengrund and Utgrunden (Sweden) and Beatrice and Blyth (UK) have been decommissioned (Figure 4.37). As such, the oil and gas sector currently provides much needed guidance regarding this issue (Smyth et al., 2015). The expanding ORE sector provides an important opportunity to better manage biosecurity risks.

A comprehensive study of test sites and supporting harbours used by the European Marine Energy Centre in Scotland reported no evidence of non-indigenous aquatic species at full-scale wave and tidal testing sites (Want et al., 2017, 2021, 2023). It may be that hydrographic barriers in high-exposure locations inhibit successful settlement and growth of NIS.

4.4.3 Control and mitigation measures of biofouling (including potential environmental risks, regulations and guidelines)

Installations of ORE technologies are contributing to a network of potentially connected natural and artificial substrates spanning hundreds of kilometres across international jurisdictions (Henry et al., 2018). Biosecurity legislation regarding transportation of devices and infrastructure from place of manufacture to place of deployment (including harbours accessed en route) should be considered. This extends to relocation of structures. Biosecurity legislation should consider the potential for transfer of NIS by support vessels travelling between harbours and ocean-based industrial locations. Although there is a general lack of global and regional regulations to limit the risk of transfer of NIS through ORE activities, some biosecurity measures are in place at national level in some countries such as Australia, where the same rules apply to ORE platforms and devices as for the offshore energy sector (see 4.3.3). At regional level, OSPAR and HELCOM are also focusing on the introduction of NIS and have identified risks from offshore renewable installations (OSPAR ORED, 2021). Guidance from these bodies can be expected in the future. In the meantime, additional measures of relevance to the transfer of NIS are those that are established at national and regional levels on baseline data required prior to activity deployment and included in the environment impact assessment as well as ongoing monitoring (see Section 4.3.3).

Mid-depth biofouling monitoring systems have been recently deployed at a wave-exposed site in Chile (Navarrete et al., 2019, 2020) and at wave and tidal test sites used by the European Marine Energy Centre in Scotland (Want et al., 2017, 2021). This sector would benefit from the ability to gather critical depth and time-dependent data including seasonal and successional studies (Underwood and Anderson, 1994). Monitoring seasonal recruitment onto settlement panels or other small-scale substrates of organisms with planktonic larvae has been shown to be an effective method of identifying important life history stages of problematic fouling species (Sutherland and Karlson 1977; Marraffini et al., 2017; Susick et al., 2020) and to allow active design of ORE technologies, installations and operations in order to reduce the potential challenges from biofouling.

Established native biofouling communities may inhibit subsequent recruitment of NIS (Viola et al., 2018). Removing biofouling may inadvertently provide increased space resource and recruitment opportunities for NIS. With knowledge of local fouling communities and NIS, scheduling of antifouling operations can be timed to most effectively reduce the risk of recruitment of nuisance species and maximize the benefits of antifouling strategies (Want et al., 2017; Viola et al., 2018).

When considering removal of ORE installations as part of the decommissioning process, the positive benefits of leaving in place artificial substrates need to be weighed against the negative impacts of increased connectivity of larvae, including those including those of NIS (Smyth et al., 2015; Hyder et al., 2017; Topham and McMillan, 2017; Birchenough and Degraer, 2020; Coolen et al., 2020*b*; Knights et al., 2024). These would be considered in the context of applicable regional and national regulations on offshore decommissioning, and the condition for platforms and other devices to remain in place as artificial reefs (Lyons, 2014).

4.4.4 Economic impact (including costs of loss, costs of management)

Invasive species may pose a threat to local biodiversity and community structure and may result in significant impacts on the local economy; eradication of the tunicate *Didemnum vexillum* from marinas in Wales has been costly and only partially successful (Sambrook et al., 2014). The invasive NIS *Styela clava* has spread through temperate waters, displacing native species and potentially impacting important bivalve fisheries and aquaculture (Clarke and Therriault, 2007; Want and Kakkonen, 2021). Offshore wind farms and other artificial hard substratum have been described as directly impacting the tourist sector in the Baltic Sea by contributing to blooms of Moon Jellyfish (*Aurelia aurita*) (Janßen et al., 2013). While this species is native to these waters, the potential impacts of NIS to recreational activities may be a serious concern to locations dependent on tourism-related economies (Eno et al., 1997). Cost-benefit analysis of natural capital resources and ecosystem services may be necessary to inform all stages of ORE deployments, including decommissioning (Hyder et al., 2017).

Although there are still high levels of uncertainty, given the early stage in development of the sector, it is recognized that biofouling, including NIS, will impact performance and survivability of ORE devices and infrastructure. Installation, operation and maintenance costs for ocean renewables are likely to be at elevated levels and comprise a significantly larger proportion of project costs and the overall levelized cost of electricity (LCOE) than equivalent energy generation technologies (OES, 2015). Key economic factors purportedly linked to biofouling in this sector include increased subsea generator failure and operational downtime (Gray et al., 2017). Furthermore, logistical and vessel costs (Morandeau et al., 2013) resulting from deployment and retrieval of equipment and infrastructure will be elevated within the particularly challenging, energy-rich marine environments into which the technologies are being deployed. This creates strong drivers for developers to pre-emptively design equipment and antifouling systems that reduce servicing requirements and costs as an essential part of their economic development (Topper et al., 2019).

4.4.5 Conclusions and recommendations

4.4.5.1 Key findings

ORE installations host a large number of biofouling species, some of which are NIS. ORE devices and infrastructure create suitable substrates for epibenthic organisms. Communities on artificial substrates are typically similar to those found on naturally occurring rocky features.

Currently available publications on biofouling are limited in the ORE sector. Issues with confidentiality and data sharing create barriers to knowledge exchange. These barriers are exacerbated by the early development stage of some of these technologies. Further, published results are largely representative of North-West Europe.

Concerns exist over the role that ORE installations may play in creating a network of 'stepping stones', facilitating the movement of NIS. Additional biosecurity concerns relate to the potential transfer of NIS from sites of manufacture to deployment and via support vessels accessing ORE installations.

Biofouling and biosecurity are seen as lower priority issues in the ORE sector, when compared with engineering and physical science-based issues. When considered by the sector, biofouling is primarily recognized as an engineering problem affecting device performance and infrastructure survivability, not as a biosecurity issue.

Biosecurity risks from ORE installations are not the same as those associated with existing offshore energy industries, i.e. oil and gas. Valuable lessons can be learnt from surrogate industries, but ORE installations are being deployed in areas with unique biofouling communities and hydrodynamic conditions, i.e. different geographic regions, rapid tidal flow conditions, etc. and will require risk management frameworks appropriate for those conditions.

Hydrodynamic forces in renewable energy-rich regions targeted by the ORE industry may create hydrographic barriers mitigating the spread of NIS. Risk of introduction of NIS appears to be higher in more sheltered habitats such as marinas and harbours. Some studies indicate that offshore areas with rapid tidal flow or extreme wave exposure may be at lower risk from NIS.

The assessment of environmental impacts of ORE deployments focuses primarily on so-called 'charismatic' megafauna. Although regulators do include assessment of impacts on epibenthic communities in the consenting process, greater attention is focused on larger vertebrates, i.e. marine mammals, bird sand fish, and not species prominent in typical biofouling communities.

4.4.5.2 Knowledge gaps

The number of publicly available studies in the ORE sector is limited and largely confined to North-West Europe. Although initiatives to collect and make available data in this sector are under development, more needs to be done to collect and share data globally. Barriers exist in the sharing of data related to assessing biosecurity risks from NIS, especially regarding proprietary rights. Greater understanding of biosecurity issues by sector stakeholders (e.g. industry and regulators) is necessary.

A key obstacle to studying biofouling in the ORE sector is the challenge of collecting scientifically rigorous data in high-exposure environments. Access to devices and infrastructure for study may be limited. High current flow and extreme wave conditions may not be practical for survey work using scientific divers or ROVs. ROV video surveys, commonly used in imaging infrastructure in deep waters, lack sufficient resolution to identify NIS.

A critical knowledge gap exists in the characterization of fouling on ORE devices and infrastructure deployed at 'mid-depths'. Detailed inspection of ORE infrastructure provides important information on biofouling. Existing studies have often relied on limited opportunities to observe fouling from seabed moorings and surface-operating floating structures. Complete assessment of biosecurity and understanding of fouling in these habitats requires data from throughout the water column.

Existing studies of connectivity of biofouling organisms are primarily based on unvalidated larval dispersal models. Models of larval dispersal are typically based on known life-history processes and oceanographic data. Limited validation has occurred through molecular analysis and further studies, including long-term monitoring of NIS, are necessary to validate these models.

Decommissioning studies of ORE devices and infrastructure are lacking. As expected with the early stages of ORE technology, a paucity of evidence exists to inform decision-making by regulators and policy-makers regarding decommissioning (as well as derogation of mandatory removal). With only a few wind farms having been decommissioned (Figure 4.38), the oil and gas sector currently provides much-needed guidance on this issue.

The effectiveness of standard antifouling treatments is less well understood in habitats targeted by the ORE sector. Greater shear stress and increased flow may accelerate the dissolution of antifoulant compounds when applied in high-current speeds. Coatings may be impacted by sediment abrasion in tidal channels. Structures featuring greater structural and hydrodynamic complexity may create additional so-called 'niche' areas, limiting the use of protective coatings.

4.4.5.3 Recommendations

Mitigation of biosecurity risks in the ORE sector would benefit from greater research funding and sharing of industry data. As part of the consenting/licensing process, procedures to support non-proprietary data collection and access to these data should be considered. Biofouling characterization of under-represented regions of the world is essential.

Validation of larval dispersal models to establish connectivity and vectors for transport should be further developed. Use of molecular analysis and *in situ* monitoring of biofouling should be included in studies. Validated models should be applied to all-life stage decision planning of ORE deployments, i.e. siting choices, operations, decommissioning. Molecular analysis techniques, e.g. eDNA and improved resolution of image capture may be suitable for improved monitoring of NIS presence, especially when applied in deep-water studies

Siting of ORE installations and maintenance scheduling need to be carefully thought out to minimize connectivity with NIS already established in harbours or other industry support facilities. Biosecurity legislation should consider the potential for transfer of NIS by support vessels travelling between harbours and ocean-based industrial locations. Such legislation should also include place of manufacture, harbours accessed en route to deployment, as well as potential relocation of structures.

Considering issues surrounding biosecurity, increased prioritization by regulatory bodies towards management of epibenthic organisms would be welcomed. Greater engagement of biosecurity issues with sector stakeholders (e.g. industry and regulators) should be introduced during the consenting process; currently, epibenthic organisms receive less attention from regulators than 'charismatic megafauna'.

Testing of antifouling mitigations should include applicability in hydrodynamically energetic seas targeted by ORE technologies. Studies of biofouling and the efficacy of antifouling strategies should be supported to better understand under-studied habitats important to the ORE sector, i.e. .rapid tidal currents and mid-water depths.

4.5 Ocean-observing infrastructure

4.5.1 The nature of biofouling on ocean-observing infrastructure

Ocean observations (e.g. environmental monitoring and maritime surveillance) are widely implemented by various local, regional, national and international research programmes, agencies and organizations (e.g. California Harmful Algal Bloom Monitoring and Alert Program, Great Barrier Reef Marine Monitoring Program, European Ocean Observing Program and Global Ocean Observing System) to understand and address issues ranging from global climate change (e.g. sea surface temperature, storms and sea level rise) and ocean pollution (e.g. acidification, hydrocarbons, plastics and noise) to specific issues, such as marine pathogens and the movements of marine mammal and commercial ships.

Although some ocean observations are made through remote methods (e.g. satellites, aircraft and drones) many of these data are collected by in situ sensors on marine platforms (Whitt et al., 2020). The various sample collectors, electrodes, optodes and acoustic or imaging sensors can be operated or deployed as:

a) Spot check, sample collection or hand-held units;
b) Ship-based surveys over time, space and depth (issues associated with vessels biofouling are included in Section 4.1);
c) Long-term (days to months) deployments on *in situ* platforms, including surface and/or subsurface buoys/moorings, vertical profilers, seafloor cabled nodes, drifters, gliders, autonomous underwater vehicles (AUV) and autonomous surface vehicles (ASV).

Spot checks (a) and ship-based surveys (b) are not prone to issues associated with biofouling (either operational limitations with biofouling impacting data collection or the possible risk of the transfer and introductions of NIS) because exposure to seawater is limited and operators can continue to clean and maintain instruments. Alternatively, long-term deployments (c) are commonly impacted by biofouling (Figure 4.38).

Biofouling of deployed instruments and platforms has long been considered a limiting factor and one of the main obstacles to ocean observations and autonomous long-term environmental monitoring in aquatic environments (Delgado et al., 2021). In environmental monitoring, deployed instrumentation has historically been used to collect data on physical-chemical parameters of seawater (e.g. temperature, dissolved oxygen levels, inorganic nutrients and chlorophyll content, turbidity, contaminants content) which, for example, allow the quality of its condition to be determined. More recently, the use of monitoring instrumentation accompanied the growth of maritime sectors such as the offshore renewable energy and the aquaculture sectors. For example, in the case of ORE installations, instruments/platforms (e.g. acoustic doppler current profilers, buoys carrying sensors or profilers) are often used to measure oceanographic parameters such as waves or currents, performing a vital role by providing information on optimal settings to maximize energy conversion (Want et al., 2017).

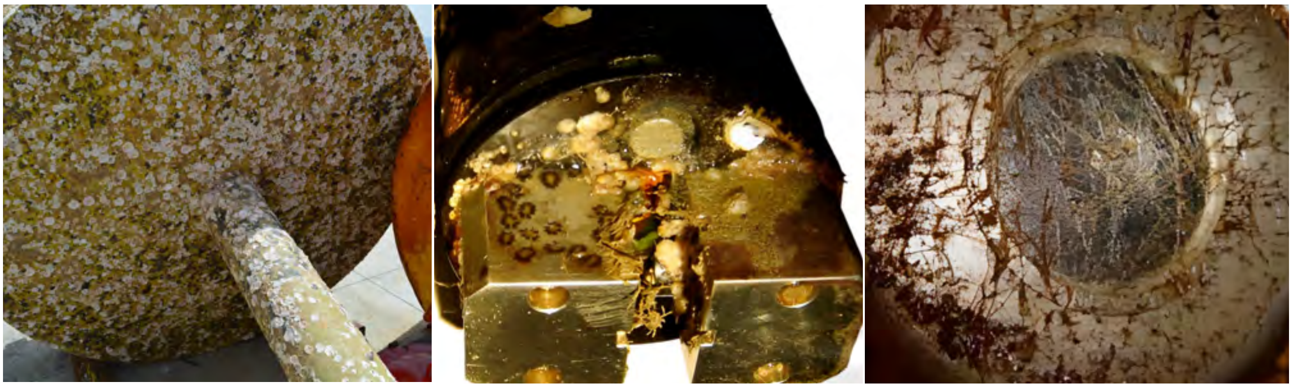


Figure 4.38 Biofouling in ocean-observing systems: 'cleaned' bottom of monitoring buoy (left), fluorometer (centre) and transmissometer (right).
Sources: Left: Pedro Almeida Vinagre/WavEC; centre and right: L. Delauney, in Delauney et al., 2010.

Biofouling, at both the microbial biofilm and macrofouling levels, affects the functionality and maintenance of instrumentation (e.g. optical windows and electrodes) and affects their data acquisition capability (e.g. by totally covering the sensors) or the feasibility of data usage (e.g. in the case that sensors can acquire data but in a deficient way) (Delgado et al., 2021; Matos et al., 2023), making the modelling and interpretation of data inaccurate or invalid. For the examples provided above, in addition to all the economic costs associated with maintenance/repair/replacement of instrumentation, in the case of environmental monitoring, it may affect the adequate determination of water quality and decision-making in case mitigation measures are deemed necessary. In the case of the ORE sector, biofouled instrumentation may render to developers a misrepresentation of oceanographic parameters, potentially leading to a decrease of optimal performance and power conversion.

4.5.2 Role of ocean-observing infrastructure as biofouling pathway for introduction and spread of NIS

As with all artificial structures placed in the marine environment, ocean-observing instrumentation/platforms will present a (hard) substrate to which the microbes and higher organisms can adhere and settle, where no hard substrate should naturally exist. Although representing reduced individual surface area available for biofouling colonization in comparison with other offshore structures (e.g. ORE), many ocean-observing infrastructures exist in the marine environment across geographic regions (for example, the Global Ocean Observing System comprised 13 ocean-observing networks with 8,765 operational platforms across 84 countries in 2022).[16] Therefore, ocean-observing infrastructure represents a potentially greater number of 'stepping stones' for the propagation of NIS, possibly to broader geographical areas, as described in Sections 4.3 and 4.4. This concern may be especially high where a large number of NIS has already been identified (e.g. in the North Sea, Vinagre et al., 2020). Furthermore, more equipment might mean more maintenance activities and consequently more frequent transport by vessels to coastal infrastructure, such as ports, thus increasing the potential for introductions in coastal areas.

Although ocean-observing activities continue to increase and estimates of submerged surface area of associated infrastructure are difficult to generate, the total surface area of all the associated monitoring activities likely only represents a very small fraction of anthropogenic surfaces placed in marine systems. Ocean-observing infrastructure is typically of relatively small size, allowing it to be generally managed and maintained by simply deploying and then recovering/replacing individual samplers/sensors and/or the entire platform. This means that all associated biofouling can be removed, handled and disposed of appropriately (commonly cleaned on a ship deck, on a dock, or in a laboratory) to avoid the possible spread of NIS.

4.5.3 Economic impact

Numerous oceanic instruments and platforms are placed at depths and distances from shore which creates difficulties in frequent access for maintenance of the instruments/platforms themselves or to inspect the integrity of the anti-fouling mechanisms protecting them. As estimated by the Alliance for Coastal Technologies (ACT, 2003), biofouling may represent up to 50% of operational budgets, associated with reduction in deployment periods, loss of data due to sensor drift, frequent maintenance requirements and a shorter lifespan of the instrumentation.

The costs of inappropriate decisions based on data rendered unavailable, inaccurate, or unreliable due to biofouled monitoring instruments has not been estimated, but must be a consideration – and, in worst case scenarios, could be very high.

16 https://www.ocean-ops.org/reportcard/

4.5.4 Prevention and control of biofouling

The antifouling solutions implemented in ocean-observing infrastructure, like those being used for other infrastructures placed at sea, such as ORE devices (see Section 4.4) or ships (see Section 4.1), include paints, coatings, bioinspired textures and mechanical cleaning. Nevertheless, the physical characteristics and operational requirements of the different observing systems, especially of data-acquiring sensors, demand tailored application of such solutions. Extensive reviews of the various antifouling strategies available for marine instrumentation are provided by Manov et al. (2004), Whelan and Regan (2006), Lehaitre et al. (2008), Delauney et al. (2010), Lobe (2015) and Delgado et al. (2021). A summary of solutions is presented in Table 4.4 (adapted from the above research).

For the mechanical components such as instrument housings, acoustic transducers or other surfaces, fouling release coatings have been the most efficient antifouling solution. Their slithery character enables self-cleaning of the coated surfaces in high-energy environments, such as moving platforms (e.g. gliders and AUVs) or wave environments, and allows for easy cleaning of biofouled surfaces during maintenance activities (Lejars et al., 2012).

For sensors, specifically their sensing areas, addressing biofouling formation and growth is more complex and is of extreme importance. This is because biofouling can compromise the readings and thus, the information collected can no longer be deemed reliable (Delgado et al., 2021; Matos et al., 2023). Optical sensors and electrode-based sensors, especially of the membrane-based type, are the most susceptible to data drift and inoperability due to biofouling. Optical sensors are generally easier to keep clean, using, for example, wipers, high-pressure jets and ultrasonication. Because membranes cannot be coated with either biocide or non-stick coatings, the biofouling protection relies on strategies like wipers, light blocking, biocide injection and passive inhibitors (Delgado et al., 2021).

Table 4.4. Antifouling strategies used for sensors

Instrument	Protected component	Antifouling strategy
-	Sensor housing, transducers and other surfaces	Paints with active biocides (e.g. copper compounds, copper oxides and co-biocide chemicals) Self-polishing paints with biocide Non-stick coatings (e.g. based on silicone materials or fluorinated polymers)
-	Optical sensors and membrane sensors	Liquid sterilization; UV sterilization
Photometer	Optical window	Coatings Ultrasonication cell
Fluorometer	Optical window	Coatings UV light Copper bezels Copper wiper + plate Copper tape + wiper
Turbidity meter	Optical window	Shutter/wiper mechanism + biocide chamber + copper alloys
Scattering Combined scattering and fluorescence	Optical head and optical window	Wiper + copper plate
Multi-parameter: CTD (conductivity, temperature, depth), ODO (optical dissolved oxygen), pH Combined fluorometer-turbidity and CTD	Optical head, optical windows, sensor housing, conductivity cell, temperature sensor	Active flow control; Passive flow prevention Light-blocking Active biocide injection; Passive inhibitors Copper faceplate + wiper
Multiparameter UV-probe	Optical window	Compressed air-module
Multiparameter modules	Optical head, optical windows, pH and temperature sensors	Central wiper Copper guard Copper mesh Copper tape
Multispectral radiometer Hyperspectral radiometer	Optical head and optical window	Copper wiper + shutter Copper plate
Spectrometer	Optical window	Pressurized water cleaning Compressed air or brush

To date, the most successful strategy has been the combination of measures that enable extended deployment times, including less frequent maintenance downtimes, for example using the combination of wipers or shutter systems with biocidal materials (e.g. copper-based). Some antifouling solutions that seem promising for future applications include UV irradiation (e.g. Richard et al., 2021), laser (e.g. Lu et al., 2021), surface microtopography (e.g. Brzozowska et al., 2017) and chlorine generation as biocidal agent (e.g. Pinto et al., 2021).

4.5.5 Management of biofouling to prevent transfer of non-indigenous species

The maintenance and cleaning obligations, if any, designed to control biofouling associated with ocean-observing devices depend on many factors, including the location of the device within or beyond national jurisdiction, whether the device is static or dynamic, whether it is registered with an IMO number or not and the entity in charge of the deployment, among others. There is no global regime applicable to all ocean-observing devices. Those that are deployed within a country's EEZ would in most situations fall under the jurisdiction or control of that country and therefore its national regulations. For gliders and floats that may travel through several jurisdictions, the situation is even less clear, although, overall, the government with jurisdiction and control over the instrumentation would be responsible for its maintenance and cleaning as well as the introduction of NIS by the device.

4.5.6 Conclusions and recommendations

4.5.6.1 Key findings

Ocean-observing infrastructure has shown rapid development (e.g. in terms of materials, data communication protocols and data analytics, power management and storage) to multi-type, multi-purpose systems in the recent years and such development is expected to increase.

Biofouling represents up to 50% of operational budgets of the ocean-observing systems, associated with reduction in deployment periods, loss of data due to sensor drift, frequent maintenance requirements and a shorter lifespan of the instrumentation.

In terms of ecological impacts, **there is great potential for NIS to use ocean-observing infrastructure as 'stepping stones'** across geographies **or for their introduction** with transportation of systems to other regions for maintenance/decommissioning (introduction by the vessel or the system itself).

The demand from the research community for antifouling solutions, which in some cases need to be tailor-made, **needs to catch up with the rapid development of observation systems**, which will require stronger synergies between the systems and antifoulants developers.

It seems that **the most successful solutions use strategies in tandem** for both the active surfaces and the components in the immediate vicinity **and include the combination of wipers with biocidal materials** (mainly copper, copper alloys and copper-based paints) **or the combination of wiper/shutter systems with bleach injection and biocidal materials** (copper components).

4.5.6.2 Key gaps

There is a lack of data on biofouling-related maintenance activities (e.g. location, frequency, type of infrastructure, transportation to port) and biofouling data to inform on NIS propagation across the oceans or introduction to coastal areas.

4.5.6.3 Recommendations

Targeted monitoring and surveillance for NIS should be driven by an initial risk screening protocol (e.g. as in the UK) **used to identify high-priority marine NIS to facilitate targeted risk-based monitoring and surveillance** (Miller and Macleod, 2016). This 'species-based' approach in risk analysis is complemented by pathway analysis, which encompasses the geographical routes by which NIS are transported, either by natural or human-assisted means (both direct and indirect) and the transport vectors (e.g. ships, contaminated gear, tsunami debris).

Early identification of NIS can be enhanced using environmental DNA (eDNA) from water samples. Monitoring of NIS on infrastructures could be provided by a **biofouling sensor technology that could differentiate between microfouling and macrofouling** and therefore predict the risk of species of concern occurring on a device (Miller and Macleod, 2016).

Future research on antifouling solutions should focus on the **development of transparent, non-toxic approaches that can be applied to optical surfaces without affecting the analytical performance of the instrument** (Delgado et al., 2021).

4.6 Marine debris

4.6.1 Biofouling in marine debris

Marine debris is defined as any persistent, manufactured or processed solid material discarded, disposed of, abandoned, or outflowed in the marine and coastal environment (CBD, 2012). Marine debris is classified based on size, buoyancy and materials. Particles of plastic marine debris exceeding 20 mm are classified as 'macro-debris' and those smaller than 5 mm are classified as 'microdebris'. Cylindrical or disc-shaped granules smaller than 5 mm are called 'meso-debris' or 'nurdles' (Hammer et al., 2012). Macro-debris sometimes exceeds several metres in dimension and after the tsunami of the Great Tohoku Earthquake, floating decks of about 20 m in length were transported across the Pacific (Gewin, 2013). The relative longevity of floating debris is in general as follows: vascular plants/animal carcasses < macroalgae < driftwood < tar lumps/skeletal remains < plastic litter < volcanic pumice.

Glass and plastic are common debris materials and the percentage of plastics is rapidly increasing. Large-scale production of plastics started in the 1950s and following a rapid increase in production the 1970s, they have been frequently recognized as marine debris (Carpenter and Smith, 1972; Venrick et al., 1973; Wong et al., 1974). Production of plastic products reached 30 million tons per year in 1988 and reached 368 million tons in 2019 (PlasticEurope 2020). Eriksen et al. (2014) estimated that over 250,000 tons were floating as more than 5 trillion pieces of marine debris worldwide. 275 million metric tons (MT) of plastic waste were generated in 192 coastal countries in 2010, with 4.8 to 12.7 million MT entering the ocean (Jambeck et al., 2015). The global release of primary microplastics (microplastics directly released into the environment as small plastic particles) into the ocean was estimated at 1.5 (0.8–2.5) million tons per year (Mtons/year) and primary microplastics released even outweigh that of secondary microplastics originating from the degradation of large plastic wastes (Boucher and Friot, 2017).

Despite the increasing progress in characterizing the plastisphere, less well understood is the spread of marine NIS and pathogens rafting on marine debris. Various marine organisms have been transported by rafting, contributing to their long-distance dispersal in or across the ocean (Gathorne-Hardy and Jones, 2000), sometimes causing trans-continental invasions. In general, larger and more stable floating objects carry larger and more diverse biofouling organisms. The first reports of marine organisms (i.e. bacteria, diatoms and hydroids) encrusted on floating plastic debris appeared in the scientific literature in early 1970s (Carpenter and Smith, 1972). Marine debris, plastics in particular, are now considered as an important emerging vector for the spread of NIS because they can be long-lasting, are capable of slowly drifting across vast ocean regions and act as an ideal substrate for recruitment of NIS (Audrézet et al., 2020).

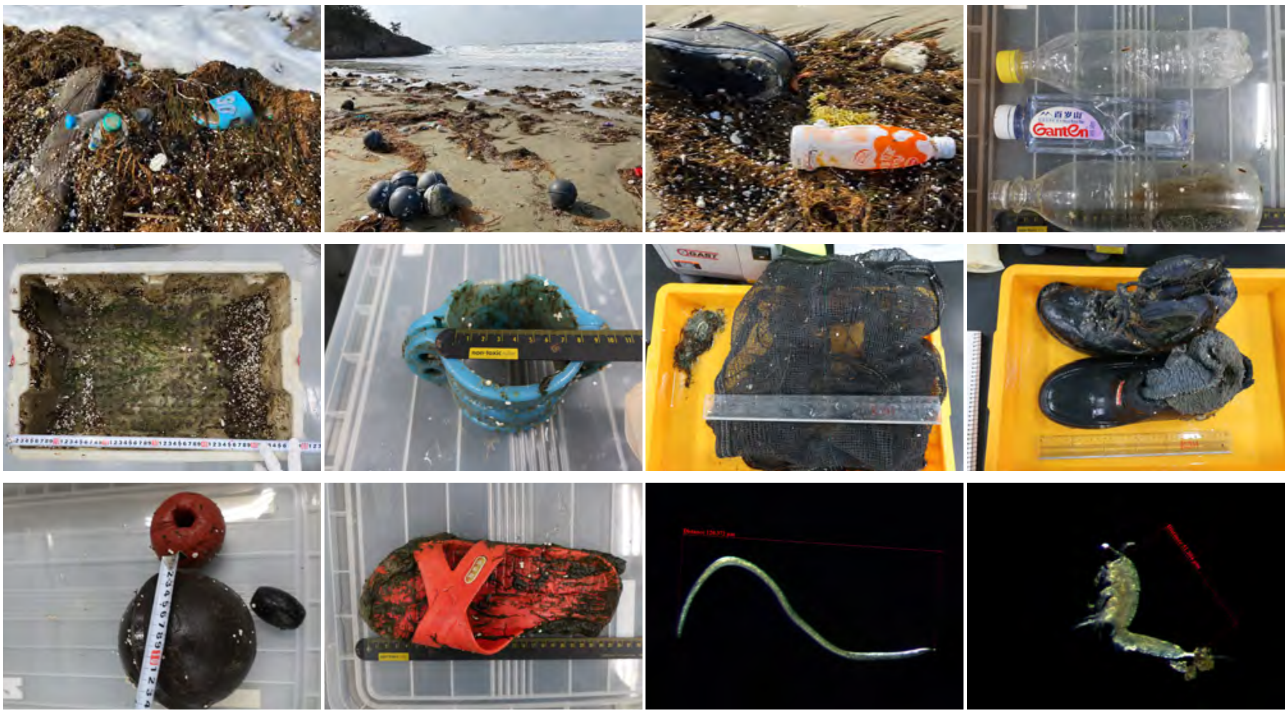
The ease of attachment by biofouling organisms depends on the material, shape, texture of the surface and the type of organism (Figure 4.39). With the passage of time, due to the development of biofilms and colonization by various other organisms, the differences due to the initial surface properties become smaller (Minchin, 2007). The buoyancy differs depending on the materials, their state of degradation and attachment of biofouling organisms. Marine debris with low buoyancy and larger submerged portions tends to have more biofouling (Ye and Andrady, 1991; Bravo et al., 2011; Muthukumar et al., 2011). Marine debris with negative buoyancy sinks to the seafloor, providing substrates for biofouling in soft sediments and may act as a stepping stone for introductions.

The degree of biofouling depends on latitude. Biofouling is high in low latitude areas and lower in high latitude areas, especially higher than 60 degrees, and is almost absent in polar regions due to ice. Ghost nets are abandoned or lost fishing nets that drift about the oceans, driven by currents and tides – many host particularly large biofouling communities. Ghost nets spread throughout a wide range of depths, trapping various animals and providing substrates for diverse sessile organisms. Large ghost nets may exceed 6 tons and become difficult to dispose of (Richardson et al., 2021b).

Currently, about a thousand species are reported to be transported by rafting (Thiel and Gutow 2005). Debris may provide substrates for sessile organisms and transport them over long distances (Bravo et al., 2011; Kiessling et al., 2015; Rumbold, 2020). In addition to anthropogenic objects, floating objects of biotic origin (e.g. macroalgae, seeds, wood and animal remains) and abiotic origin (e.g. volcanic pumice, tar lumps) are also important vectors for long-distance dispersal, however, they are not dealt with in this chapter because they are not fabricated objects. Nonetheless, if drift giant macroalgae such as kelps and *Sargassum* from mariculture, or tar lumps from oil-spills produced by human economic activities cause significant introductions of non-indigenous organisms, they might also need to be treated as marine debris.

To illustrate the magnitude of these events, massive amounts of *Sargassum horneri*, which is known to be the major golden-tide seaweed in the north-western Pacific coasts, have drifted from offshore waters and washed up on the beaches of Korean coasts (Byeon et al., 2019). A massive mixture of golden tide and marine plastic debris was also found on the western coast of Korea in January of 2021 (Figure 4.40). The mixture included various types of plastic debris such as buoys, nets, containers, bottles and shoes.

Figure 4.39 Biofouling on various types of floating marine surfaces.
Source*:* K. Ranatunga.



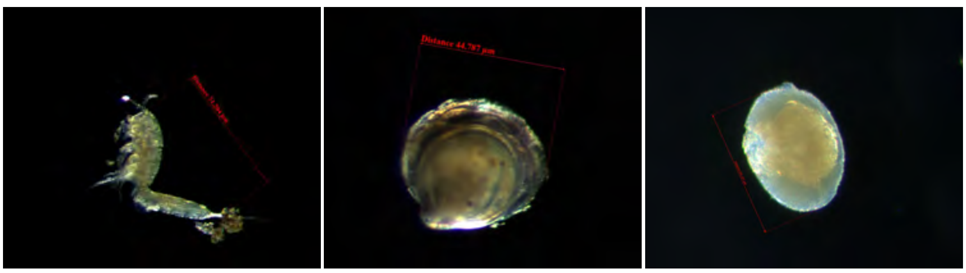


Figure 4.40 Mixture of seaweed *Sargassum horneri* and marine plastic debris washed ashore on the beach and coexisting meiofounal biofouling on the surface of the marine plastic debris on the western coasts of Korea in 2021.
Source: Korea Institute of Ocean Science and Technology.

Not only macroscopic invertebrates but also diverse meiofaunal biofouling organisms (40~1,000 µm), which included nematodes, harpacticoids, ostracods, caprellids, polychaetes and bivalve larvae, were found on the surface of the plastic debris (Baek et al., 2023). The above findings suggest that marine plastic debris with seaweed may act as a vector for dispersal of hitchhikers and also may provide a cosy habitat for those organisms while they are drifting through oceanic currents.

Lower density polymers, such as polyethylene (PE) plastic objects, are buoyant and usually do not sink on their own. However, marine debris also may lose buoyancy due to degradation or fouling by marine organisms and may eventually sink to the seafloor, but it can still provide substrates for those organisms and thereby function as stepping stones for invasions (Bryan et al., 2012). Low-density plastics have been reported on the seafloor, and among the possible reasons for this are biofouling organisms that increase the specific density of the floating material they colonize (Fazey and Ryan, 2016) and enhance microplastic deposition to marine sediment (Kaiser et al., 2017).

4.6.2 Diversity of fouling organisms

The species diversity of the fouling on marine debris has been described in various reports from a number of oceans (Barnes, 2002; Thiel and Gutow, 2005; Farrapeira, 2011; CBD, 2012; Goldstein et al., 2014; Holmes et al., 2015). Currently, about a thousand species have been reported and some of them are considered as obligate fouling species (Thiel and Gutow, 2005). Based on the reports, Bryozoa, Crustacea (barnacles), Cnidaria (hydroids), Mollusca (bivalves)and polychaetes are major animal taxa (Winston, 1982; Aliani and Molcard, 2003; Barnes and Milner, 2005; Zettler et al., 2013; Gall and Thompson, 2015; Kiessling et al., 2015). Bacteria, microalgae and fungi commonly form biofilms and some are toxic and can be cysts of microalgae, causing harmful algal blooms (HAB; Maso et al., 2003).

Marine debris caused by the tsunami generated by the 2011 East Japan earthquake was associated with 289 living invertebrate and fish species (Carlton et al., 2017, 2018) and 84 species and varieties of marine algae and cyanobacteria, 49 of which were genetically identified (Hanyuda et al., 2018; Hansen et al., 2018). Of the macroscopic invertebrates and fishes, 59.6% were detected on vessels and 24.5% were found only on vessels. Mean species richness was greater on large-sized objects (5 to 12 m in length, including vessels and docks) compared to small objects (<1 m in length). Some of the fouling species found on the tsunami debris were estimated to pose high invasion risks (Therriault et al., 2018).

Species diversity of the fouling organisms differs between the floating objects of biotic origin and abiotic origin (including anthropogenic debris). In general, biotic substrates are short-lived due to degradation and digestion by organisms, but their species diversities are higher (Donlan and Nelson, 2003; Thiel and Gutow, 2005). However, the floating dock of Misawa showed exceptionally high species diversity (Figure 4.41), because of the high species diversity before the drifting began and its large size, allowing the survival of the entire community.

Figure 4.41 Fouling organisms on Misawa Fishing Port floating dock (tsunami debris generated by 2011 East Japan earthquake) cast ashore from Japan to Oregon, USA coast in June 2012.
Source: Oregon State University.

4.6.3 Function of marine debris as vectors for dispersal of marine organisms and causing trans-ocean invasions.

Marine debris is one of the major vectors for the long-distance transport and primary introduction of marine NIS, and also acts as a vector for short-distance secondary introductions in the areas where the invasion was first established. For example, on the coasts of the UK, marine debris is considered to be the third most important vector for the introduction of marine NIS, after ship transport and fisheries activities, and 9 % of the NIS were estimated to have brought by anthropogenic flotsam (= marine debris; Minchin et al., 2013). Plastic debris provide new surfaces for colonization by microbes and macro-organisms constituting novel ecosystems, unique from that of the surrounding water and other marine particles, and also serve as stepping stones that cause the expansion of their distribution (Debroas et al., 2017; Ward et al., 2022).

4.6.4 Preventing biofouling by marine debris

Unlike the topics of other subsections of this chapter, marine debris is usually undesirable in its own right. Whereas activities such as shipping, ocean monitoring, aquaculture, etc. are conducted by economists and societies to produce desired benefits, debris is discarded or lost material with no 'benefit' intended other than to be rid of the material. Moreover, there is no competent authority for all marine debris. Competent international, regional, national and local authorities can only regulate production, use and waste management, including debris clean-up or recovery; they cannot regulate the exposure of marine debris to biofouling that may result in them providing a pathway to IAS.

4.6.5 Mitigation and management of biofouling of marine debris (including regulations and guidelines)

Existing international and regional regulations applicable to marine debris focus on preventing material and waste generated or used in different sectors of the economy from becoming marine debris, thereby also limiting the amount of debris that may act as a pathway (e.g. MARPOL Annex V for operational waste from vessels and the LC/LP on the screening of dredging sludge to prevent its subsequent placement at sea with plastic debris). Under the impetus of the United Nations, maritime sectors have recently undertaken a review of regulations and debris sources with a view to tightening them and aiming to eliminate their contribution to marine debris. For example, the IMO adopted an Action Plan to Address Marine Plastic Litter from Ships in 2018 (IMO, 2018) that has resulted in several amendments to existing instruments; for example on the on the reporting of lost containers and guidelines on the transport of plastic pellets and ongoing discussions on the treatment of ALDFGs (see Section 4.1.2.5). Amendments and guidelines have also been adopted and more are in discussion under the Stockholm, Rotterdam and Basel Conventions, which have strengthened their joint work programme, including joint actions to manage hazardous substances from plastic products; this includes the trade of plastic waste and the sound management of chemicals and waste (BRS Conventions, 2023). In addition, a new global instrument on plastic pollution is being negotiated with a tentative adoption year of 2024. The objective for the instrument is for it to be based on a comprehensive approach that addresses the full life cycle of plastic. The fourth session the Intergovernmental Negotiating Committee (INC-4) is scheduled for April 2024.

However, all these efforts will at best limit the introduction of plastic debris in the marine environment. It will not prevent existing and new debris from acting as pathways for NIS. Monitoring of marine debris for NIS therefore has a critical role to play to anticipate and manage introduction where possible.

In order to reduce marine debris from land-based solid waste, improvement of the waste treatment system is most effective and perhaps the sole practical solution. Waste treatment systems are diverse depending on the region and application of a single prescription is not practical. If plastic wastes are designated as hazardous wastes in regional regulations, it will be hard to find acceptance from the production side. However, it may be possible to apply this to the wastes that potentially release toxic substances by degradation, or are prone to decompose and form microplastics (Mendenhall, 2018).

4.6.6 Recommendations

No specific management recommendations are proposed at this time, beyond the need to address knowledge gaps in this area that will provide the basis for future recommendations. For example, higher proportions of expanded polystyrene (EPS), commonly known as 'styrofoam', are observed in Asia for both macro- and microplastics EPS compared to other regions (Chan and Not, 2023). Fishery activity, tropical cyclones and open dumping were highlighted as major factors contributing to the high proportion of EPS in the Asian region. The authors recommended that bans may be an effective way to reduce input of EPS into the marine environment. On the other hand, the South Korean Government implemented a new policy to replace EPS buoys with alternative buoys, increase the mandatory recovery rate of used EPS buoys and ban the use of flame retardants such as HBCDs (hexabromocyclododecanes) in EPS buoys (Eo et al., 2018).

4.6.7 Gaps

Methodological standards for measuring and evaluating marine debris are not established. It is recommended to standardize various methodological approaches such as marine collections using nets, or collections along beaches (Póvoa et al., 2021).

Suitable collection, quantification and viability measures of various adherent organisms by different types and sizes of marine plastic debris are recommended, to provide the knowledge required to evaluate the possibility of introduction of the organisms beyond their bioregion (Baek et al., 2023).

5. EMERGENT ISSUES

5.1 Increased ecological connectivity via stepping stones

Stationary marine structures likely act as stepping stones for NIS. Connectivity is referred to here as the process by which the dispersal of larvae between otherwise isolated epibenthic populations may be facilitated by non-mobile, stationary marine structures acting as stepping stones. These structures may be used by biofouling larvae to disperse using ocean currents, one generation at a time, across ecological barriers. Native species likely use this pathway, which can be considered a positive effect, but NIS may use the same routes, potentially causing negative impacts.

A stepping-stone effect is potentially created by any type of structure that is placed in the marine environment. Marine offshore energy (mostly oil- and gas-related, see Section 4.3) and ORE structures (see Section 4.4) are commonly mentioned as potential stepping-stone vectors for NIS. However, other structures such as non-mobile ocean-observing infrastructure (see Section 4.5), aquaculture (see Section 4.2), shipwrecks (see Section 4.6) and coastal infrastructure (see Section 4.1.) likely play a similar role.

The stepping-stone effect is likely to be most impactful in sandy seabed environments. The stepping-stone effect is likely to be particularly impactful in environments lacking hard substrates, e.g. near the water surface and in sandy or muddy seabed environments. Biofouling species would be unable to recruit in these locations if artificial structures were absent.

The stepping-stone effect of increased connectivity has been modelled but needs to be validated with empirical field observations. The stepping-stone effect has been modelled based on larval dispersal characteristics and oceanographic data but limited empirical field observed data is available to evaluate it. There is a clear need to validate these larval dispersal models, e.g. using genetic analysis to establish connectivity and vectors for transport. These validated models could then be applied to all-life stage decision planning of infrastructure deployments, operation and decommissioning (including derogation of removal obligations). Currently available publications on epibenthic connectivity are limited and are largely representative of North-West Europe.

Improved understanding of the stepping-stone effect will aid in decisions on deployment and decommissioning. Changes in this dynamic network of artificial structures may help facilitate or impede connectivity depending on location-specific risk of NIS movement. Greater understanding of population connectivity may thus play a valuable role in marine planning decisions, including consenting new installations and decommissioning of existing infrastructure.

5.2 Improving response capacity

Improvements are necessary in the timeliness and effectiveness of responses when the presence of an NIS is detected. An important set of synthesis messages from this report are targeted at improving the speed and accuracy with which the presence of NIS, including NIS using biofouling communities as a pathway, is detected and the species identified (See Sections 3.11 and 5.1). However, the full benefit of such improvements currently may not be realized because in many ports and coastal areas, response capacity for acting on such information is inadequate. This is particularly serious for sectors like aquaculture and sensor deployment, where the sectoral regulatory authorities might not be administratively linked to port authorities and other agencies or authorities involved in emergency response preparedness (Sections 4.2, 4.5). However, ineffective responses can also occur, even when the sectoral regulatory authorities have responsibility for preparing biosecurity plans (Sections 4.1, 4.3, 4.4) but find the port authorities have their emergency response capacity focused on other types of marine activities where accidents like ship strikes or chemical leaks may occur.

Whatever approaches are used detecting NIS from biofouling pathways, effective management of NIS risks must ensure that:

- Actors doing the monitoring in turn have a designated port authority to inform when the presence of an NIS is detected or assessed as highly likely; and
- Response capacity of the port authorities is sufficient to respond immediately with appropriate biosecurity measures, given the information on elevated NIS risks.

In addition, including consideration of risk of NIS in marine spatial planning can facilitate both reduction of the risk of NIS presence through more effective design and more precautionary allocation of sectoral uses within the port or coastal planning area.

GLOSSARY

Antifouling
A physical or chemical treatment, method, approach or technology used to prevent and/or inhibit the settlement and /or growth of biofouling on a surface.

BFMP
Biofouling management plan

Biofilm (syn. **slime layer**, **microbial film**)
A film that grows on underwater surfaces composed by microscopic organisms in conglomerations of extracellular proteins, polysaccharides and lipids. It may represent the earliest stage of biofouling settlement and is typically the precursor to macrofouling settlement and growth. See also microfouling.

Biofouling
The biological component of **fouling**, i.e. the unwanted attachment of organisms to underwater surfaces. Biofouling communities may have taxa in common with the natural **Epibenthos** communities and may also include **non-indigenous species** or **cryptogenic** species. See also **microfouling** and **macrofouling**.

Coastal industry infrastructure
Artificial structures that serves activities at sea such as navigation, production, leisure, e.g. ports, marinas, cooling towers, water purifying units.

Cryptogenic
Species of a known identity whose evolutionary and biogeographic origins are not yet known and thus cannot yet be resolved as either **native** or **non-indigenous** with certainty.

Ecosystem services
The benefits provided by the natural environment to humans, such as the production of food and water (typology: Provisioning), the control of climate and disease (typology: Regulating); nutrient cycles and oxygen production (typology: Supporting); and spiritual and recreational values (typology: Cultural).

Epibenthos
Organisms that colonize natural underwater substrates (e.g. soft sediments, rocky shores). They can be sessile (fixed to the substratum) or move just over the substratum. Unlike **biofouling**, it is not perceived as a nuisance, but as a natural component of aquatic ecosystems.

Epibiosis
Spatial association between a substrate organism (basibiont) and other sessile organism (epibiont), without direct trophic relationships between the two (e.g. living coral (epibiont) on oyster (basibiont) reefs, submerged aquatic vegetation) (Wahl, 2009). Some **biofouling** taxa are epibionts of farmed aquatic species.

Established
A non-indigenous species that is able to develop self-sustaining populations.

Fouling
Accumulation of material of inorganic or biological (**biofouling**) origin on underwater surfaces (e.g. ship/boat hulls, harbour/port walls and pontoons, fishing nets, mollusc shells). It also constitutes a potential **vector** of introduction and spreading of aquatic non- indigenous species. It is sometimes used as a synonym to **biofouling** but that is incorrect, because some inorganic material can also foul structures and vessels.

IAS – Invasive aquatic species
Animals, plants or other organisms that are introduced into places outside their natural range, *negatively impacting* native biodiversity, ecosystem services or human well-being.

Introduction
The intentional or unintentional human-assisted (i.e. anthropogenic) movement of a species, subspecies, or lower tax on outside its natural range (past or present). It is normally used to indicate primary introduction, i.e. the first arrival of the species in the new area. See also **spreading**.

IWC – In-water cleaning
Mechanical removal of biofouling performed underwater.

Macrofouling
The macroscopic (i.e. visible to the human eye) component of **biofouling**. It is composed by multicellular sessile and sedentary organisms such as macroalgae and invertebrates (e.g. barnacles, bivalves and tubeworms), colonial organisms (e.g. bryozoans, ascidians, hydroids and sponges) and their associated motile invertebrates (e.g. decapods, amphipods and polychaetes). See also microfouling.

Management
A term in itself, commonly used broadly in the **biofouling** literature and discussions to include prevention, control, mitigation, eradication and occasionally even compensation. Individual sources using the term should be checked for intended scope of actions included as 'management'.

Microfouling
The microscopic component of **biofouling** that forms **biofilm**. It is composed of unicellular or microscopic organisms, such as bacteria, fungi, microalgae, protozoans, as well as early life stages of macroalgae or metazoans (i.e. spores, larvae). See also **macrofouling**.

MOE – Marine offshore energy
Different types of installations at sea to obtain renewable energy (electricity).

Native species (syn. **Autochthonous**, **Indigenous**)
A species that occurs naturally in a given geographical region, including the region where it has evolved, or that it has reached and occupied using natural dispersal systems, as determined by paleontological, archaeological, biogeographic, molecular and other evidence. See also **non-indigenous species** and **cryptogenic**.

Niche area
See Annex II for full description.

NIS – Non-Indigenous Species (syn.: **Alien**, **Allochthonous**, **Exotic**, **Introduced**, **Non-native**)
A species, subspecies, or lower taxon forming a self-sustaining reproductive population outside of its natural biogeographic range and beyond its natural dispersal potential, which has been transported by direct or indirect human activities into a region where the species was previously absent. See also **cryptogenic**, **invasive alien species**, **native species**.

Pathway
For the purposes of this report, this includes the suite of processes that may result in the **introduction** of a **non-indigenous species** from one geographical region to another. Pathways can be broadly classified into three types: 1) those that involve intentional transport, 2) those that involve unintentional transport and 3) those that involve movement without direct transport by humans (i.e. via artificial corridors). This is slightly more focused than the CBD definition, which includes 'any means that allows the entry or spread of a pest'.

Propagule
Any non-adult biological material that is used for the purpose of propagating an organism to the next stage in its life cycle. May include dispersive gametes, seeds, spores or regenerative tissue.

Spreading (syn. **Secondary spreading**)
the dispersal of a non-indigenous species beyond its primary location of introduction. It can be human-assisted or by natural means.

Vector
the human-mediated physical mean or agent of **introduction** or **spreading** of a **non-indigenous species** to a new geographical area, including a wide variety of physical means or agents, from ballast water to biofouling and aquaculture. See also **pathway**.

ANNEX I

Membership of the Working Group 44

GESAMP WG44 members, report authors and report contributors

(In alphabetical order by last name)

Current Chair, Mario Tamburri, University of Maryland Center for Environmental Science, USA

Previous Chair, Katja Broeg, Maritime and Hydrographic Agency (BSH), Germany

Nina Bloecher, Trondheim, Norway

Marnie Campbell, Deakin University, Australia

Joop Coolen, Wageningen Marine Research, Netherlands

Jung-Hoon Kang, Korea Institute of Ocean Science and Technology, South Korea

Hiroshi Kawai, Kobe University, Japan

Youna Lyons, Centre for International Law, Singapore

Agnese Marchini, Universita di Pavia, Italy

Koebraa Peters, Cape Peninsula University of Technology, South Africa

Pei-Yuan Qian, Hong Kong University of Science and Technology, China

Kamal Ranatunga, University of Sri Jayewardenepura, Sri Lanka

Evangelina Schwindt, Instituto de Biología de Organismos Marinos (IBIOMAR-CONICET), Argentina

David Smith, Plymouth Marine Laboratory, UK

Serena Teo, Tropical Marine Science Institute (TMSI), National University of Singapore, Singapore

Pedro Almeida Vinagre, WavEC Offshore Renewables, Portugal

Andrew Want, University of Hull, UK

Anna Yunnie, PML Applications Ltd, UK

Report Editor
James Curtis Rice, University of Toronto, Canada

Report Contributors
Oliver Floerl, LWP Ltd, Christchurch, New Zealand

Susse Wegeberg, Aarhus University, Denmark

Secretariat to the Working Group
Pia Haecky, IOC-UNESCO Consultant

Henrik Enevoldsen, IOC-UNESCO Technical Secretary for GESAMP

ANNEX II
Niche areas

The 2023 IMO biofouling guidelines define niche areas as: 'a subset of the submerged surface areas on a ship that may be more susceptible to biofouling than the main hull owing to structural complexity, different or variable hydrodynamic forces, susceptibility to AFC wear or damage, or inadequate or no protection by AFS'.

Due to their nature and location, niche areas are considered to foul more easily than the flat sides of a ship's hull and thus represent an elevated invasion risk in terms of biosecurity (Miller et al., 2018). In an attempt to quantify the ratio of hull to niche area WSA, a study was carried out which estimated that 10% of the total global WSA consisted of niche areas (Moser et al., 2017).

Common niche areas are those such as:

- seawater chests and gratings
- seawater inlet pipes, valves, strainers and internal cooling systems
- keel and box coolers.
- thrusters and thruster tunnels
- stabilizer fins and boxes
- propellor shafts and struts
- bilge keels
- rudder hinges and stocks
- anchors and cables, including chain lockers
- dry-docking support areas
- cathodic protection anodes

Some of these are identified in Figure A1.

Niche areas – Seawater chests and gratings
These are often highlighted areas in a ship when it comes to biofouling. A ship may have several of these seawater inlet points situated along the length of hull to supply and sometimes discharge seawater from and to services such as machinery heat exchangers, ballast and fire pumps, etc. (Palermo, 1992). The purpose of a sea chest is to minimize the openings in a hull by having several inlet pipes in each chest to provide seawater to the required services on board.

A sea chest is a watertight box recessed into the underwater area of the hull. It has an external protective grating on the side exposed to sea and is fitted with internal pipework suctions. The sea chests are effectively out of the main flow of water passing along the flat sides of the hull as a vessel makes way. They have been specifically identified as 'hot spots' for biofouling growth and the carriage of NIS (Frey et al., 2013). Larger sea chests may also be fitted with baffle plates which can increase the internal refuge areas within the chest for species development.

The size, number and complexity of sea chests may increase both with vessel size and complexity (Coutts and Dodgshun, 2007) and can provide an environment for larger adult organisms which would not survive on the flat hull surfaces (Leach, 2011).

Sea chest sampling results carried out on a ship operating in South Australia revealed a variety of species co- existing within the sea chests, of which some were non-indigenous to the region. This included some introduced European Green Crabs which were assumed to have entered the chest as juveniles and had grown to the point where they could not exit again via the gap between the grating rails (Coutts et al., 2003).

The Ministry for Primary Industries in New Zealand commissioned research on vessel biofouling found that over 80 % of species sampled were found in niche areas such as sea chests. (Bell et al., 2011).

To illustrate a typical sea chest arrangement, Figure A2 demonstrates a ship's sea chest arrangement for the supply of cooling water to onboard services. On larger ships, there will normally be a minimum of two sets of sea chests, each with external grating covers, as shown in Figure A3, to prevent the intake of larger pieces of debris which could damage internal components. The lower sea chest is used at sea to avoid cavitation and suction loss when the ship is rolling/pitching in a seaway. When the vessel hull is in closer proximity to the sea bed, such as when operating in a river or alongside in a port, then there is a risk of sediment-laden water being drawn into the ship's systems. This would increase the chance of clogging up internal systems and of picking up and carrying benthic organisms, which could become invasive species. In such a case, the higher sea chest would be used to mitigate the uptake of such sediments.

Progressive biofouling accumulation on either the external gratings or on the internal surfaces of the sea chests can seriously restrict cooling water supply to a ship's internal machinery or can result in the reduced performance of essential safety items, such as fire and bilge pumps.

Niche areas – Seawater inlet pipes, valves, strainers and cooling systems
To avoid corrosion and biofouling problems associated with the use of seawater as a direct cooling medium for the main and auxiliary engines on board ship, a heat exchanger system

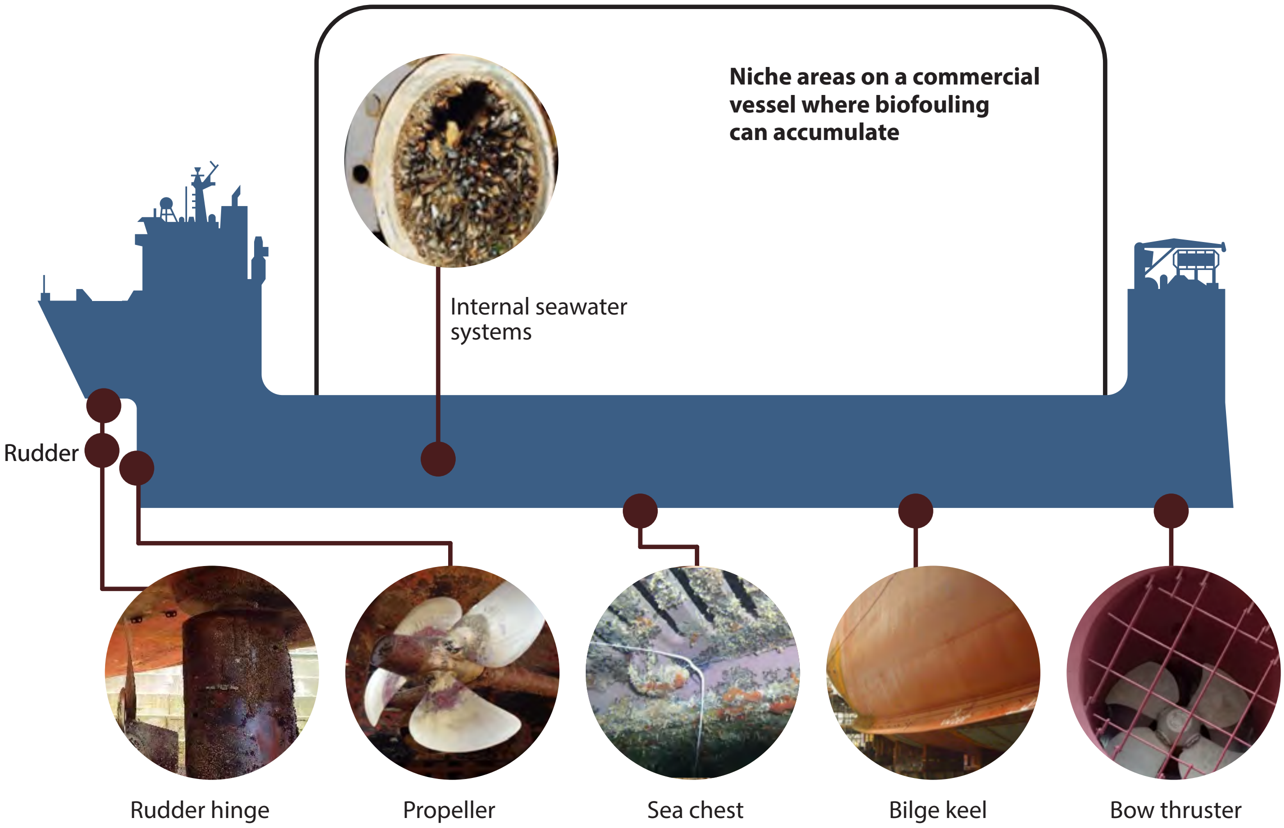


Figure A1 Niche areas in a commercial vessel.
Source: After MPI, 2018.

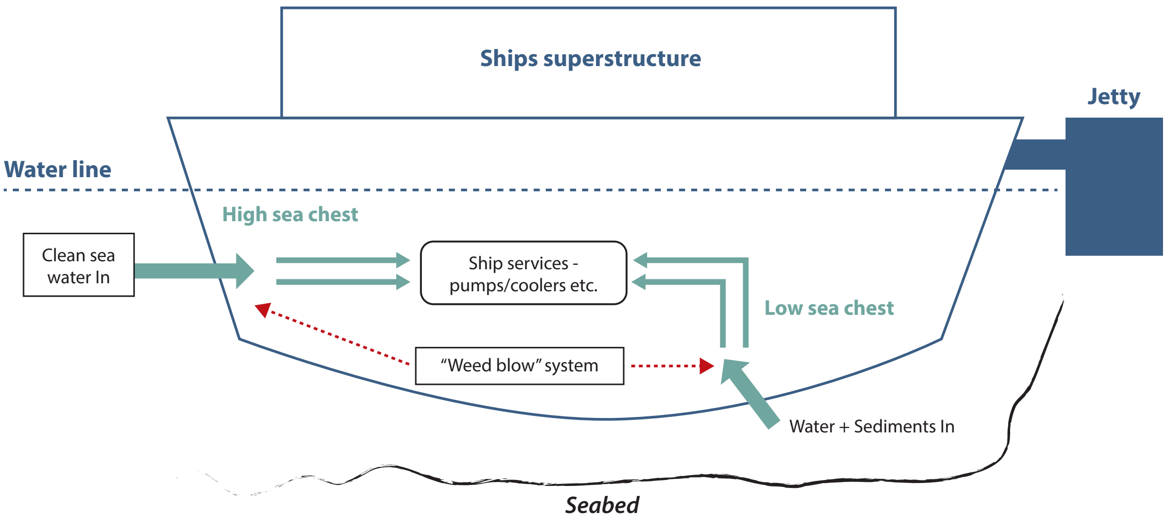


Figure A2 High and low sea chest arrangement.
Source: David Smith.

is employed. This has a chemically controlled freshwater closed circuit which supplies the cooling medium for the machinery. The heated freshwater is passed through a heat exchanger, usually of a 'tube and shell' or 'plate' design, which is connected to an open loop seawater system designed to carry the excess heat in the water being discharged over-board to the local waters.

Figure A3 Sea chest grating external biofouling.
Source: David Smith.

A simplified schematic of a seawater cooling system and its principal components is shown in Figure A4.

Incoming seawater at ambient temperature enters the system via the sea chest and strainer, both of which can be isolated by fitted sea valves. The seawater circulating pump creates the flow of cooling seawater to the heat exchanger. The heat exchanger accepts the heated freshwater arriving from the various items of machinery on board, such as diesel engines, oil coolers and evaporators. Seawater is passed sea through the exchanger in sealed tubes or plates and comes into contact with the surrounding heated freshwater. The heat is transferred to the seawater as it passes through the exchanger. The cooled water is the returned to the machinery distribution arrangement while the heated seawater is passed overboard to the local environment.

Due to the number of components involved in a seawater cooling system and its connecting pipework, there are numerous areas where biofouling may settle within the arrangements and be transported between bioregions if they are dislodged or undergo a reproductive event.

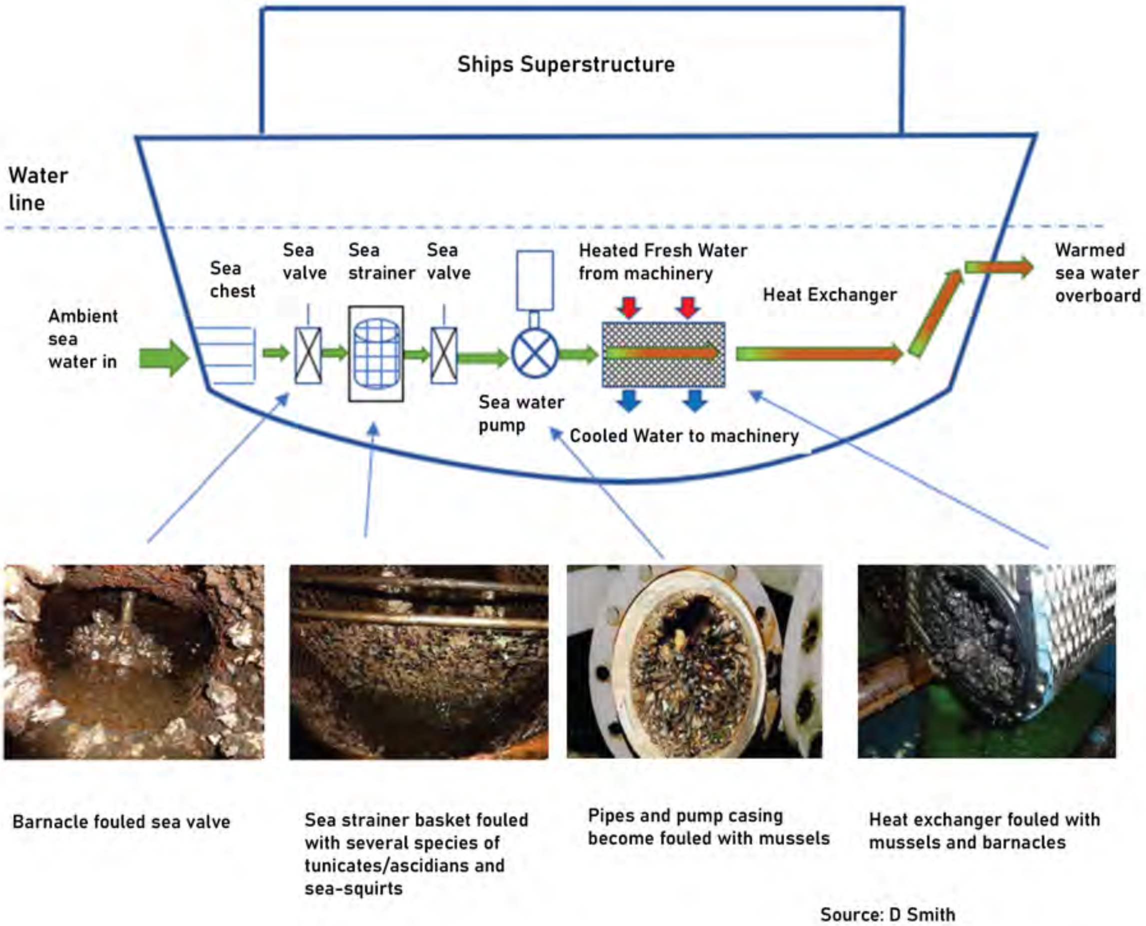


Figure A4 Common seawater cooling system components.
Source: David Smith.

Given that a sea chest may be considered as a localized environment away from the hydrodynamic forces of the main hull, it has been said that the combined nature and degree of biofouling in sea chests and internal components can be wholly independent to that of the external hull (Growcott et al., 2016).

As with sea chests, severe biofouling contained within the individual components of a seawater cooling system can result in internal system failures due to the detrimental accumulations shown in Figure A4.

In addition to this, it has been noted that there may be a knowledge gap relating to the potential transfer of invasive species between ships berthed in wet docks and basins (see Annex III).

Niche areas – Box and keel coolers

For smaller or specialized ships which operate in shallow water, or in areas of high sediment loading, the design of the vessel may incorporate box or keel coolers to provide cooling water to the prime machinery. Such a design removes the requirement for an open raw seawater cooling system as described above and replaces it with a closed loop freshwater-cooling system which utilizes heat exchangers fitted to the hull.

Figure A5 Niche areas – Manoeuvring **(a)** bow and **(b)** stern thrusters.
Source: David Smith.

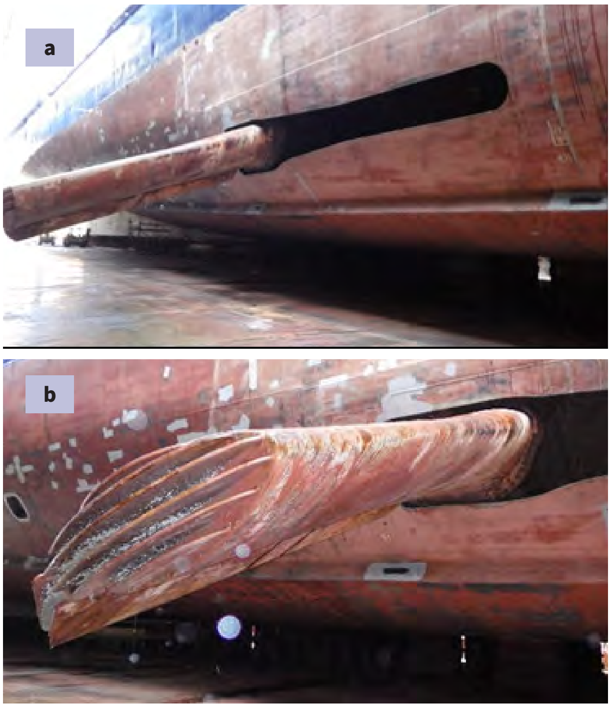


Figure A6 Niche areas: Active stabiliser fins and boxes.
Source*:* David Smith.

Figure A7 Niche areas: Propellers, shafts and struts.
Source*:* David Smith.

Figure A8 Niche areas: Bilge keels.
Source: David Smith.

Figure A9 Niche areas: Rudders, hinges and rudder stock.
Source: David Smith.

Figure A10 Niche areas: Anchors and cables.
Source: Lee Adamson.

The heat exchangers are essentially freshwater radiators place either in cavity boxes within the hull (box coolers) or on brackets on the external hull surface (keel coolers). Figure A4 shows such arrangements.

Box coolers are contained in what are basically large sea chests which allow seawater to naturally circulate around the coils of the heat exchanger. They are often fitted with a system to prevent biofouling growth around the coils of the cooler which would cause a reduction in heat transfer. As with sea chests, the accumulation of silt within the construction of the box and the settling of biofouling organisms represents a potential biosecurity threat.

Keel coolers are often mounted in protective frames on the surface of a vessel's hull and are thus exposed to the laminar flow of water as the vessel makes its way through the water. However, subject to design, biofouling will attach itself not only to the mounting frames and cooler coils but also to the area between the cooler grid and the hull which is partly isolated from the main water flow.

The quantities of fouling accrued in sea chests or box coolers along with the internal heat exchange systems can be considered as being of critical importance to the operation of the vessel. The following areas may also become considerably fouled and act a transport medium for many invasive species as shown in Figures A5–A12.

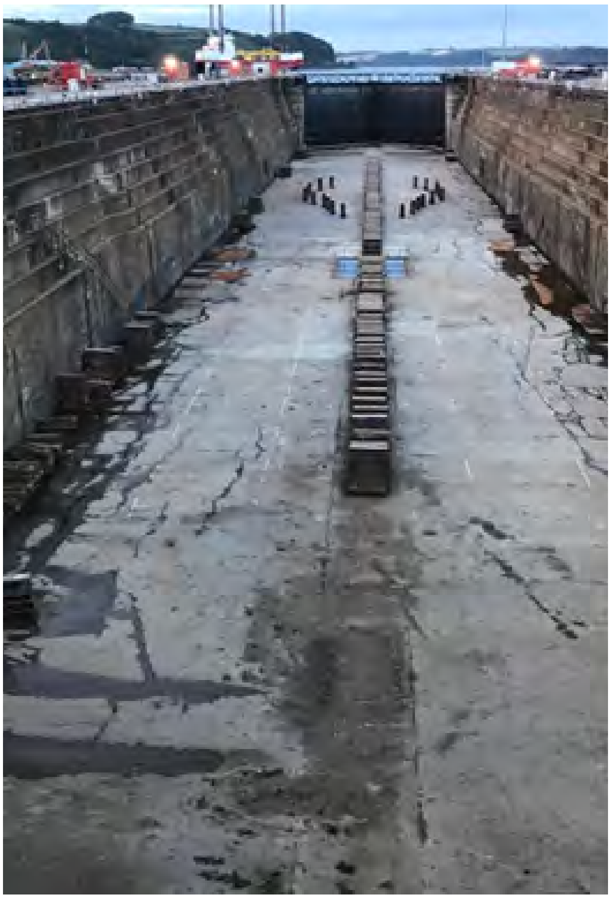


Figure A11 Niche areas: Dry-docking support blocks.
Source: D. Smith.

Figure A12 Niche areas: Cathodic protection anode.
Source*:* D. Smith.

ANNEX II

Marine biofouling in ports: Wet docks acting as 'hot spot' biofouling transfer stations

The GEF-UNDP-IMO Glofouling Partnership (Glofouling Partnership Project, 2018) is a global initiative to counter the environmental issue of IAS and the resulting harmful ecological and financial damage that can occur when such invasion events are introduced through the medium of biofouling on ships' hulls and other marine structures such as those found in the oil and gas industries.

One of the key objectives of the Glofouling project is to develop a Global Knowledge Hub and also identify areas where current information may be lacking but is relevant to the understanding of how IAS is transported via biofouling in ships at both local and international level.

One such knowledge gap identified by the Working Group 44 is where enclosed wet docks (see Figure A13) may provide an enhanced haven and vector platform for IAS to relocate between ships at berths within the facility. The nature of such a transfer phenomenon is briefly described along with some potential mitigation measures that vessels or ports may employ to reduce the perceived threat.

Vessels arriving in ports from other bioregions can introduce an extensive range of potentially IAS via the medium of the accumulated biofouling carried on their hulls and other underwater appendages (Miller et al., 2018).

To determine the level of this hazard posed by shipping in particular ports, there has been some work done to develop risk assessment methodologies which can be utilized to quantify the biosecurity danger, such as that described by the Australian Department of Agriculture, Fisheries and Forestry (Australian Government, 2011), which analyses the factors determining port inoculation events.

Figure A13 Ships berthed within a wet dock facility.
Source: Rob Atherton/Shutterstock

When considering the possibility of biofouling species transfers within a port, the local hydrodynamic environment has been identified as a factor which can magnify the intensity of fouling both on substrates such as the harbour structures and on the hulls of vessels visiting the port. The influence of port features such as breakwaters, berthing arrangements and confined entrance channels all have an effect on tidal flushing and the potential consequent accumulation of viable propagules for biofouling transmission (Floerl and Inglis, 2003).

Wet docks are port facilities where the water is enclosed and kept at a certain level to allow for the loading and unloading of ships. A representative wet dock arrangement is shown in Figure A14. Such docks are often found upstream in rivers and allow for ship cargo operations to take place near hinterland industrial areas, regardless of tidal constraints. They provide sheltered conditions where a ship can always remain afloat. Ship access to the dock is via a lock system fitted with sealing gates and pumps to regulate the lock water level from the external tide height to that of the operational depth of the dock.

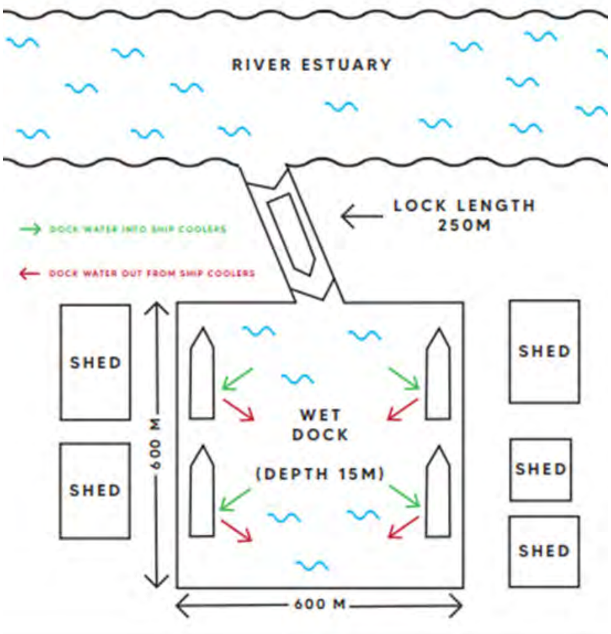


Figure A14 Typical wet dock arrangement.
Source: H. Eustice.

Once berthed within such a dock, conventional transfers of hull biofouling organisms may occur through the deposit into the dock water of detached biological material because of physical contact with tugs and berth fenders or the spontaneous release of fertilized cells arising from other stimuli such as temperature and salinity changes (Minchin and Golasch, 2003).

Due to the nature of water enclosure in a wet dock, they may represent a significant increase of biofouling risk, as opposed to ports, which are open to sea or river environments. There appears to be a lack of study concerning the biofouling transfer mechanisms within such enclosed port areas. An area of particular note is the possible effect of a ship's cooling water system in these docks and the consequent potential for berthed ships to exchange different biofouling species more rapidly within the confines of the dock itself.

While hull surfaces are a commonly acknowledged transport pathway for biofouling and IAS, there have also been studies carried out to highlight the biofouling accrued by ships in their internal seawater cooling systems and the enhanced biosecurity risk that this may also represent (Growcott et al., 2016).

For ships, external sea or dock water is used as a cooling source for the main and auxiliary engines via an internal heat exchanger system (Jones and Little, 1990).

A simplified schematic of a typical seawater cooling system and its principal components is shown in Figure A4 (Annex II).

For a ship berthed in a wet dock, incoming dock water at ambient temperature enters the cooling system via the sea chest and strainer. The seawater circulating pump creates a rapid flow of cooling water to the heat exchanger. The heat exchanger contains heated freshwater arriving in a closed circuit from the various items of machinery on board such as diesel engines, oil coolers and refrigeration plants. Dock water is passed through the exchanger in sealed tubes or plates and comes into contact with the surrounding heated freshwater circuit. The heat is transferred to the pumped dock water as it passes through the exchanger. The cooled freshwater is then returned to the machinery distribution arrangement, while the heated dock water is passed overboard back to the dock again.

The cooling systems are often fitted with internal biofouling growth prevention measures but, as can be seen from the photos in Figure A4 (Annex II), they are not always effective in removing all the biofouling accumulation.

To realize the potential scale of the cooling water biofouling issue related to ships in wet docks, the temporal volumes of cooling water that ships can take up and discharge in the dock need to be considered.

With regard to larger vessels in the region of 200 m in length or more (as represented in Figure A14), while the main engines would not be running in the dock, there could still be a considerable cooling water demand for extra generator power requirements associated with cargo handling etc. For the purpose of demonstration and subject to vessel type, an estimate for a vessel of this size in port could involve pumping

Figure A15 Typical copper anode arrangement in a sea chest.
Source: A. Forrest.

through some 450 m3/hour of water from the dock into the internal cooling system and back out into the dock.

The total stored water capacity of the representative dock in Figure A13, with an operating depth of 15 m, would be in the region of 54,000 m3 of dock water. Thus, with five ships in the port exchanging a total of approximately 54,000 m^3 of dock water every 24 hours, around 10% of the total water available is being processed daily through the berthed ships' cooling water systems. This represents a substantial quantity of circulated dock water, which has the potential to double every day that the vessels remain in port.

This mass rotation of shared dock water, with each vessel vacuuming up 450 m^3 of dock water every hour, passing it over all the possibly fouled internal components of the cooling system, warming it up and then ejecting it back into the dock, as shown in Figure A14, may represent a considerably enhanced biosecurity risk. Once again, detachment of material or spawning events within the cooling system will increase the propagule pressure within the wet dock water mass.

Further to this, given that different species may have been brought into the dock by vessels from varying geographical regions, the enclosed dock and the circulating gyres of warmed dock water created by the berthed vessels cooling water pumps introduce the prospect of each vessel more rapidly sharing its biological load with others and departing the port having been duly seeded with additional species.

It is recognized that the use of the entrance lock facility may result in some exchange of dock water with the adjacent river estuary or coastal region, as would water quality supervision through the use of pumps to exchange water or allowing 'free flow' of river water through the locks for limited periods when tidal constraints allow.

When considering the potential mitigation measures to reduce this latent risk of biofouling and hence NIS transfer when ships are berthed in wet docks, the following can be considered:

The biofouling of the internal components of a ship's cooling water system has been traditionally addressed using biocidal agents such as copper ions produced by electrically fed anodes in the sea chest (as shown in Figure A15) or the direct injection of low concentrations of cleansing chemicals such as sodium hypochlorite either supplied to the ship in bulk drums or produced by electrolysis systems on board.

While these methods can be reasonably successful if maintained correctly, they may have some deleterious effects by passing their low concentration toxic substances overboard into the receiving dock water, potentially affecting other untargeted organisms in the vicinity.

The undesired chemical side effects of these biocidal type systems and their questionable environmental standing has resulted in the development of more ecologically friendly solutions, such as those employing the use of fitted transducers. These are designed to transmit ultrasonic frequencies, creating non-inertial cavitation which is professed to destroy the biofouling organisms within the cooling system in a localized manner without the use of harmful compounds.

It is worth noting that the use of this ultrasonic technology is not limited to seawater cooling systems and has been employed to counter marine biofouling in other areas of a ship, such as on propellors and rudders

Given the large quantity of cooling water that is taken up and discharged by the cooling pumps fitted to a ship, it is often the case that the cooling water pump capacity may be set at a fixed rate to accommodate all the calculated heat exchange requirements when the vessel is at sea with her main engines and all other associated machinery running. When in a wet dock, it may be useful to be able to control the pump speed directly to reduce the throughput of cooling water rather than using a by-pass system to alter the water flow to the heat exchanger.

Investigative work by Theotokatos (2016) showed that the use of variable speed pumps (VSP) for the cooling systems could not only reduce the annual power consumption of a ship but also increase system performance by closer control of key temperature parameters. Another advantage of using VSP in this case would be the reduced volume of water being circulated between ships in a wet dock and hence a lower risk of NIS spread within the dock.

Possibly the most effective measure to combat the movement of NIS within a wet dock, and indeed at any port facility, would be not to use the ship's machinery to generate electrical power when at a berth but instead use a shore electrical supply. This technology is termed 'cold ironing' and was first introduced several years ago as a measure to reduce GHG by ships in port. By effectively removing the demand for generated power, the need for significant quantities of cooling water is also removed and the cooling water pumps may be stopped altogether subject to vessel design. This would significantly reduce the risk of NIS transfer from the cooling water system. It is observed that, while this technology is available in certain North America and European Ports, it is yet to be implemented on a larger scale.

In conclusion, it is noted that wet docks offering communal berths for ships have a clear potential to act as 'hot spots' for the transfer of biofouling species. A more detailed understanding of the complexity of wet dock biological mechanisms, with a particular reference to the influence of ship processes, could assist with more effective port environmental management, reduce the risk of NIS transmission and assist with compliance with other regulatory demands, such as water quality directives.

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