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ICES Viewpoint background document: Evaluating and mitigating introduction of marine non-native species via vessel biofouling

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Contents

1 What are the consequences and impacts of biofouled vessels?

Biofouled vessels create novel, mobile habitats characterized by great abundances of opportunistic and non-native species. Vessel biofouling[1] affects the environment as well as the economics of vessel management. If established in new regions, these vessel-transported species can affect gene flow, population dynamics, community structure, distribution patterns and, ultimately, ecosystem function[2]. Biofouling also compromises the operational performance of vessels, their effective range and *maneuverability*, and may even impact on-board safety systems that rely on seawater uptake. Further, biofouling increases hull roughness and frictional resistance resulting in increased power and fuel requirements. Even minor levels of hull biofouling, such as biofilm formation, can add considerable drag, resulting in elevated fuel consumption, emissions, and costs for fleet operations and maintenance. Finally, the recent expansion of the commercial and recreational fleets highlights the urgency in managing ships and recreational vessels to reduce the transfer of potentially invasive species by biofouling.

There is an increase in vessels in operation across the globe (Tournadre, 2014; UNCTAD 2017; Lucintel, 2017; Tickler *et al.*, 2018), most of which pose some degree of biosecurity risk due to the transport of biofouling assemblages. As of 1 January 2017, the total number of vessels in the world commercial fleet (comprising oil tankers, bulk carriers, general cargo ships, container ships, gas and chemical tankers, offshore vessels and ferries and passenger ships) was 93 161 (with a combined tonnage of 1.86 billion dwt), representing a 2.5% increase over 2016 numbers (UNCTAD 2017). In 2014, 64 000 fishing vessels of 24 m or longer, were in operation (FAO 2016). Currently there are between 9000 and 10 000 naval vessels, and around 1000 offshore rigs (https://www.globalfirepower.com/navy-ships.asp, https://armed-forces.eu/navy/ranking_ships, https://www.statista.com/statistics/279100/number-of-offshore-rigs-worldwide-by-region/).

Recreational vessels numbers in the USA and Europe in 2015 were recorded at 11 and 6 million, respectively (USCG Boating, 2016, European Boating Industry, 2016), while in Australia boat ownership increased by more than 36% between 1999-2009 to 800 000 registered recreational vessels (Hollings *et al.*, 2018). Recreational vessels are considered a particularly high risk vector for spread of marine non-native species via biofouling due to their prevalence, spatial distribution, travel patterns (both domestic and international) and connectivity between high- and low-risk hubs (Willan *et al.*, 2000; Davidson *et al.*, 2010; Clarke Murray *et al.*, 2011, 2014; Johnson and Fernandez 2011; Ashton *et al.*, 2012, 2014; Zabin *et al.*, 2014; Ferrario *et al.*, 2017). One estimate of the global commercial shipping fleet wetted surface area (WSA, i.e., the permanently submerged surface area of the vessel available for colonization by marine organisms) is as high as 570 km^2 (Moser *et al.*, 2016). Investigations of biofouling patterns indicate that typically a quarter of the WSA is occupied by biofouling (e.g., Coutts 1999; Gol-

[1] Biofouling is the accumulation of aquatic organisms such as micro-organisms, plants, and animals on surfaces and structures immersed in or exposed to the aquatic environment (IMO 2011).
[2] Transportation does not necessarily translate to introduction as a number of conditions must be met for a translocated organism to be introduced to a receiving area: dislodgement or spawning, appropriate environmental conditions, low predation pressure, availability of nutrients or food sources, etc. Translocation, though, can be viewed as a proxy for the *potential* for invasions, and with a greater translocation of organisms, a greater number of invasions seems likely.

lasch 2002; Davidson *et al.,* 2008, 2009). However, most fouling is concentrated in hydrodynamically protected niche areas[3] (e.g., Coutts 1999; Coutts *et al.,* 2003; Coutts and Dodgshun 2007; Davidson *et al.,* 2008, 2009; Inglis *et al.,* 2010), though even exposed hull surfaces treated with antifouling coatings are settled by some fouling species (Floerl *et al.,* 2004; Piola and Johnston 2008; MPI 2016). Compared to natural habitats, vessels' wetted surfaces support very different ecological assemblages from those found in any other marine habitats, as they are characterized by greater abundances of opportunistic and non-native species.

Biofouling has been shown to be a vector responsible for between 55.5% and 69.2% of the currently established coastal and estuarine NIS globally (Hewitt and Campbell 2010). Some of the most widespread, non-native species with dire ecological, economic and human health impacts are considered to have been transported by commercial and recreational vessel fouling (Fofonoff *et al.,* 2018). The economic costs of vessel biofouling can be illustrated in a case study of the colonial tunicate *Didemnum vexillum* (the carpet sea squirt), which is one of the most aggressive and rapidly spreading fouling-transported species (McKenzie *et al.,* 2017). This invasive organism can encrust a wide range of substrates, fouling artificial submerged structures and overgrowing natural habitats, thereby greatly altering submerged structures and their accompanying biota. As a recent invader in many parts of the world, the extent of its impacts has only recently begun to be studied (Fofonoff *et al.,* 2018). It spread with fouled shellfish and vessels to Europe, North America and New Zealand. Eradication attempts in Shakespeare Bay (~1 km^2), New Zealand, and costing $650 000 NZ dollars, failed. Due to concerns regarding impacts to shellfish farms nearby, an intensive surveillance and eradication program was initiated in July 2006 in Shakespeare Bay and the wider Marlborough Sounds (~750 km^2), and it continued for two years until eradication was no longer considered feasible. Cessation of control efforts resulted in rapid re-infestation (Coutts and Forrest 2007; Forrest and Hopkins 2013). Eradication was attempted at Holyhead Harbour, Wales, U.K., where the species was confined to a small marina and unrecorded elsewhere, at an estimated cost of £350 000 (Kleeman 2009). The eradication process was initially successful, but the marina was rapidly recolonized and *D. vexillum* ultimately spread with befouled vessels all around the UK coastline (Hambrey Consulting 2011).

Yet, economic effects of biofouling go far beyond the cost of control and eradication efforts. They encompass added maintenance costs to shipping and marine infrastructure, damage to valuable fisheries and aquaculture, and added fuel and emission costs. The introduced fouling species tend to form massive populations in preferred habitats. Some species are notorious 'ecosystem engineers': the tube worm *Ficopomatus enigmaticus* forms large reef-like structures in sheltered embayments, altering physical habitat characteristics and affecting benthic community; the isopod crustacean *Sphaeroma quoianum* is a major intertidal bioeroder, damaging and destabilizing marsh banks, whereas the epiphytic bryozoan *Membranipora membranacea* encrusts kelp blades, causing large-scale defoliation, thus damaging a prime habitat inhabited by valuable fish, lobsters, crabs and sea urchins (Fofonoff *et al.,* 2018). Masses of *Amathia verticillata*, *Bugula neritina s.l.*, *Mytilopsis sallei* interfere with coastal infrastructure (wharves, sea-

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[3] Vessel niche areas are sites on a ship that may be more susceptible to biofouling due to different hydrodynamic forces, susceptibility to coating system wear or damage, or being inadequately, or not, painted (IMO 2011). These include sea chests, bow thrusters, propeller shafts, inlet gratings, internal seawater systems, and dry-dock support strips.

walls, docks, pilings, pontoons, lock gates, seawater systems), incurring high maintenance costs. Other invertebrates, such as tunicates (*Botryllus schlosseri*, *Ciona intestinalis*, *C. robusta*, *Microcosmus squamiger*, *Styela clava*, *S. plicata*) and the macroalgae *Codium fragile* ssp. *tomentosoides*, have significant negative impacts on shellfish and finfish aquaculture activities the world over, causing considerable stock loss through attachment to shells, smothering, restricting water exchange through heavily fouled netting, and degradation and loss of equipment (ropes, nets and floats) (Fitridge *et al.,* 2011; Fletcher *et al.,* 2013; Fofonoff *et al.,* 2018). Colautti *et al.,* (2006) estimated that the economic damage to Canadian shellfish aquaculture through smothering cultured species and fouling gear and equipment by tunicates alone may be as high as 88 million CAD per year.

Biofilms composed of microalgae (here, diatoms) can increase vessel surface-friction up to 70%, with increase in power estimated to be between 1.5% and 10.1% (to maintain pre-fouling speeds), depending on the biofilm thickness and percentage coverage (Schultz *et al.,* 2015). A study that converted flat plate drag measurements into shaft power consumption for a mid-sized vessel with a cruising speed of 7.7 m s^{-1} estimated an increase of 11–21% for slime fouling, and 35–86% for light to heavy calcareous biofouling (Schultz 2007). Recent studies concur: a modelling study of the effect of biofouling on ship resistance determined that the increase in the effective power for a heavy slime fouling on a container vessel was 38% at 24 knots (Demirel *et al.,* 2017), whereas a very large crude carrier with light calcareous tubeworm fouling would experience a 34% increase in total resistance at cruising speed (Monty *et al.,* 2016). Although predicting the frictional resistance penalty due to biofouling is complex and not well understood (Lindholdt *et al.,* 2015), Schultz *et al.,* (2011) determined that the primary cost associated with fouling is due to increased fuel consumption attributable to increased frictional drag. Niche areas, such as internal spaces and seawater systems (e.g., pipework, sea chests, and strainers) tend to be difficult to access, and they may not be sufficiently cleaned during routine hull maintenance. Thus, they are considered to be high-risk areas for biofouling (Coutts and Dodgshun 2007; Frey *et al.,* 2014). Biofouled heat exchangers and cooling systems may restrict flow, in turn, reducing efficiency and increasing fuel consumption. The fuel efficiency of ships is consequential, as increased fuel consumption not only represents significant cost increases for an industry operating on very slight margins, but it also engenders concerns that additional fossil fuel consumption will result in increased emission of greenhouse gasses. Total shipping CO_2 emissions per annum increased from 910 million tonnes to 932 million tonnes from 2013 to 2015, and were responsible in 2015 for 2.6% of global CO_2 emissions from fossil fuel use and industrial processes (Eyring *et al.,* 2010; IMO 2012; Olmer *et al.,* 2017). Though international shipping represents a small fraction of global emissions, and is excluded from the Paris Agreement, the IMO introduced recently an energy efficiency standard for new vessels. Additionally, a sulphur cap of 0.5% on marine fuels that will come into force in 2020 will entail drastic shift in the fuel mix (heavy fuel oil currently constitutes 84% of the marine bunker fuel mix) and increase maritime fuel prices[4].

Although the number of quantitative studies on introduced fouling populations remains small compared to the number of recorded introductions, the magnitude of their impacts (as predators, competitors, parasites/pathogens, habitat alteration, etc.) on natural communities is increasingly evident (Godwin 2003; Molnar *et al.,* 2008; Ojaveer *et al.,* 2018).

[4] https://www.iea.org/etp/tracking2017/internationalshipping

2 What causes and drives these vectors and how will they change in the next 20 years?

The risk of invasive species introduction via vessel fouling will be driven by two notable and intertwined factors (1) changes in maritime shipping and boating (increase in vessel number and size, changes in routes, transit speeds and port stays), which may be offset by forthcoming mandatory international regulations, best management practices, and technological developments, and (2) extensive anthropogenic coastal modification and disturbance regimes, including climate change, to donor and recipient regions. We note that recent meta-analyses of the response of marine organisms to climate change have provided strong evidence that organisms' ranges have expanded latitudinally (poleward), across diverse taxa and ecosystems, responding to warming, and cause the disruption of propagule pools and conditions in recipient destinations.

Size and Number of Ships. The global ship-carrying capacity increased almost 75%, from 30 823 tonne-miles in 2000 to 53 589 tonne-miles in 2015 (Asariotis 2016). Existing orders for the mega container ships sector (> 18 000 teu) will double by 2021, whereas the ultra-large container ship (ULCS) fleet is set to increase by nearly one-fifth over the same period[5]. This trend is anticipated to continue into the future, with average growth of 2.2% per year to 2030 (UNCTAD 2017; DNV GL 2017). Total tonnage and vessel numbers will increase for all major ship types to 2030: while the total tonnage of tankers is expected to grow 1.7–1.8 times, bulk carriers, containerships and LNG, are expected to grow between 1.8 and 3 times[6]. Marine recreational boating is also on the rise in terms of number of boats and marinas. The global recreational boating market is forecast to grow at a compound annual growth rate of 3.8% from 2017 to 2022 (Lucintel 2017). The growth in commercial and recreational fleets will result in larger total WSA that, based on current management efficacy, will likely enhance biofouling biomass transport.

Voyage Routes. Shifts in shipping routes are likely to alter direct and indirect connectivity among distant ecosystems, linking new propagule pools to recipient destinations, potentially expanding the diversity of invasive species transported through biofouling. Global shipping routes have evolved since the end of the last century, shifting from direct port to port services along the major East-West routes, which linked Europe, the United States and East Asia, to a "hub and spoke" network, linking the major East-West maritime motorway with secondary North-South services (Fremont 2007). Future changes depend on economic, demographic, political drivers (e.g., trade embargoes, protectionist policies, Suez Canal closure 1967–1975), and security risks (e.g., Somali piracy crisis 2008–2015). Changes to routes may also occur due to climate change, with the most dramatic and direct changes occurring in the polar and subpolar regions. Sea ice coverage across the Arctic has declined since the 1980s, and trans-Arctic shipping routes between Asia and ports in Europe and eastern North America, once thought impossible, may become economically feasible by mid-century, if the ice diminishes at the present rate (Hansen *et al.*, 2016), bringing about the expansion or creation of Arctic seaports (Figure 1; a marked increase in shipping traffic through the

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[5] https://fairplay.ihs.com/container/article/4296821/mega-container-ship-fleet-set-to-double-in-size

[6] http://www.futurenautics.com/wp-content/uploads/2013/10/Global MarineTrends2030Report.pdf

Arctic Ocean is seen from 2014 to 2015). Increasing maritime traffic in the waters around Antarctica may also increase risk of introduction to the sub-polar and polar regions, though to a lesser degree than the high Arctic. Hull surveys already indicate that in niche areas unexposed to ice abrasion, biofouling may survive polar transits (Lewis *et al*., 2004; Lee and Chown 2007, 2009; Chan *et al.*, 2015, 2016; Hughes and Ashton 2017). Climate change may also indirectly trigger alteration in shipping and boating patterns and routes through impact on economic, demographic and political drivers.

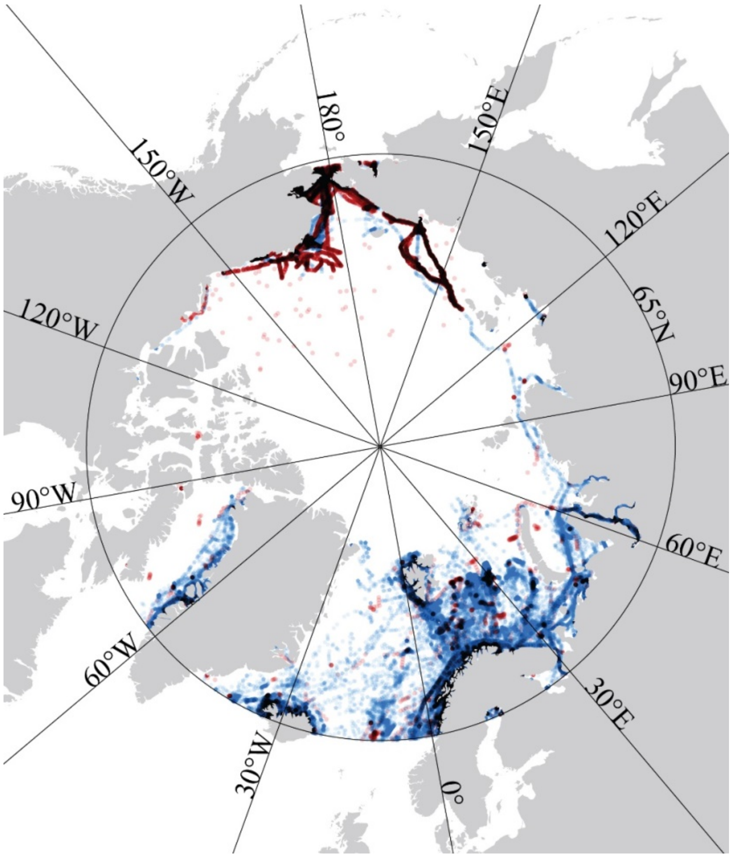

Figure 1. Ships' locations in the Arctic from June 2014 (red circles) and June 2015 (blue circles). The locations show different shipping patterns as well as the relative abundance of ships between the two years. Data source: U.S. Coast Guard Navigation Center. Figure from Drake and First 2017.

Transit Speed. Hydrodynamic sheer stress on biofouling organisms is correlated with species' survival on exposed hull surfaces (Davidson *et al.*, 2009; Coutts *et al.*, 2010b), though protected niche areas can enable species to survive even at high speed transits (James and Hayden 2000; Coutts and Taylor 2004; Coutts *et al.*, 2010a,b).

Despite higher design speeds, average cruising speed across the entire fleet between 2013 and 2015 has been steady, between 11.4 and 11.6 kts. However, since the collapse of oil prices in 2014, the largest oil tankers (> 200 000 dwt) and the largest container ships (> 14 500 teu) have sped up and a statistically significant increase in speed was observed for the next size classes (Olmer *et al.*, 2017). With larger vessels entering the fleet, while fuel prices remain low, average cruising speeds may creep up. Should fuel prices rise, cruising speed may be cut by half [7]. Slow speed transits of recreational vessels, derelict vessels, drilling rigs and barges have been documented to contribute to the survival of a wider diversity of biofouling organisms, including many fragile forms (Coutts 1999; Davidson *et al.,* 2009; Floerl and Coutts 2009; Coutts *et al.,* 2010a, b; Frey *et al.,* 2014; Simard *et al.,* 2017). This differentiation between faster and slower vessels resulting in differing suites of species may justify two sets of management approaches.

Port Stay Duration. Residence time in port determines the opportunity for the exposure of vessels to propagules (thus, the "infection" of vessels) and the likelihood that propagules will be released from vessels (infection of ports) (Carlton and Hodder 1995; Floerl 2002; Floerl and Inglis 2005; Sylvester *et al.,* 2011). A review of maritime transport shows global average times in port of 1.37 days for merchant vessels in 2016 (ranging between 0.87 for container ships to 2.72 days for bulk carriers) (Lloyd's Register *et al.,* 2013). In the future, fully automated ports are likely to further reduce the port stay duration for commercial vessels, as seaports cope with rising global shipping traffic by using artificial intelligence, big data analytics, and automating activities for loading and unloading (Fortune 2018). However, at times of economic downturn and reduced shipping activity, commercial vessels may lay idle in ports for protracted periods, increasing fouling risk, as occurred during the global financial crisis in 2008–2009 (Floerl and Coutts 2009). Presumably, those vessels became heavily fouled before returning into service when trade rebounded. Port stays for recreational vessels, service vessels (exploration/production platforms, barges, tugs, dredges) and fishing vessels are significantly longer than those of merchant vessels, and therefore, will continue to pose a greater risk in this regard.

Environmental Conditions. Once in a new recipient environment, the survival, reproduction, and long-term population persistence of an introduced species is dependent on favourable environmental conditions and habitat suitability (e.g., appropriate salinity, climate, shelter, and food resources) (Byers *et al.,* 2015). Given sufficient propagule pressure to seed a new population, disturbance is thought to play an important role in the success of introduced populations (Clark and Johnston 2009). This is particularly true of anthropogenic disturbances. Thus, future expansion of seaports and shoreline infrastructure is expected to increase invasion risk by increasing both shipping activity and disturbance levels. As temperature controls species reproduction, recruitment and growth, which affect competitive outcomes and community structure, climate change is expected to impact the distribution and relative importance of cosmopolitan fouling species, allowing them to overcome temperature thresholds that have historically acted as a dispersal barrier (Lord 2017). In particular, dramatic increases in establishment rates are predicted for polar and sub-polar regions (Poloczanska and Butler 2010; Goldsmit *et al.,* 2018). For example, due to warmer sea surface temperatures, the Norwegian port of Svalbard may become more susceptible to introductions in the future, and, in a demonstration of the interconnectedness of global shipping, it is predicted to serve as a node to disperse invasive species to other ports (Ware *et al.,* 2014).

[7] https://www.environmentalleader.com/2010/02/maersk-cuts-fuel-use-emissions-30-by-slowing-down/

3 What actions can be recommended to prevent/minimize biofouling on vessels to control this vector of introduction and spread?

Given evidence that fouling-mediated introduction and dispersal of marine non-native species is already having significant environmental and economic impacts (see previous sections) and may increase in the future, the following actions to evaluate and mitigate biofouling introductions are warranted. Recommended actions are listed below.

Management and Regulatory Recommendations: IMO Guidelines. Biofouling-mediated transfer was first formally discussed at the International Maritime Organization (IMO) in 2007 (IMO 2017). Subsequently, the 'Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species' were adopted in 2011 (IMO 2011)[8] followed by approval of the 'Guidance for minimizing the transfer of invasive aquatic species as biofouling (hull fouling) for recreational craft' (IMO 2012)[9]. The IMO will review the uptake of the Guidelines in 2019-2020. However, reliance on self-management with limited oversight and enforcement is insufficient for the vector's control.

This section expands upon the current guidelines and adds parameters that are needed to fully address this issue.

- Biofouling management guidelines suitable for different vessel types and operation profiles should be developed and evaluated. These guidelines should consider, amongst other, vessel design, maintenance regimen, shipping route, port residence time. Different vessels can have greatly different fouling communities due to such factors, so multiple approaches to managing biofouling are necessary.
- Hull form optimization should be undertaken at the design stage to reduce biofouling (i.e., niche area reduction) leading to more environmentally friendly ship ('Green ship') designs. By reducing the niche areas, which typically harbour more organisms than hull areas, the transport and delivery of invasive species or their propagules will be reduced.

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[8] Annex 26 Resolution MEPC.207(62) Adopted 15 July 2011. Measures outlined include: Creation of a biofouling management plan and record book (see IMO, 2011 Appendix 1 for format and content);Vessel surface preparation and use of an antifouling system (special attention to vessel niche areas); Retention of biological, chemical and physical pollutants from cleaning and maintenance periods; In water inspections are recommended (dive or ROV); New vessels should be designed to facilitate easy inspection and treatment; Ships should be provided with biofouling management information through the appropriate authority.

[9] IMO Recreational Boating Guidance (IMO 2012). Measures outlined include: minimizing biofouling in niche areas (use antifouling coating, polish propellers and shafts, caulk recesses and gaps, maintain marine growth prevention system); regularly cleaning and antifouling coating application when necessary; haul-out preferred over in-water cleaning; entering biofouling management activities in craft logbook; cleaning trailered craft, gear, equipment and trailer before moving to another location.

- Measures for reducing fouling-mediated introduction from decommissioned vessels should be addressed as part of the measures undertaken to reduce the negative environmental impacts of ship recycling enumerated in the 'Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships'[10].
- Compliance with the present self-management instruments should be assessed, and vessel-appropriate methodology and performance measure(s) (Zabin *et al.*, 2018) be a required component of vessel maintenance operations, to evaluate efficacy and whether modification (i.e., adaptive management) is needed to meet management objectives. Likewise, when a future standard of fouling (e.g., 'Craft Risk Management Standard for Biofouling on international vessels (CRMS)'[11]) is set, performance measures would be in place. Lacking performance measures, the effect of best practices will remain unknown.

Additionally,

- It is recommended that the siting, layout, design and engineering of seaports and small craft harbours be undertaken with the objective of reducing biofouling in port, such that there are fewer biofouling organisms to contaminate vessels. The reduction of biofouling can be achieved, for example, through modifying the proportion of sheltered, shaded, vertical, and floating surfaces, and using specific texture/materials for the surface cover (Dafforn *et al.*, 2015).

The international efforts to manage ballast water have taken 26 years to reach the current status of regulations and technology development, and at least another six years will pass before the global fleet is fitted with ballast water management systems to go for implementation[1212]. As global attention shifts to address biofouling, it is hoped that the lessons learned regarding regulation, testing and control for ballast water can be expeditiously applied to this equally important vector. **Recognizing that most factors that drive the dispersal of marine non-native species via biofouled vessels are increasing, we advise the highest urgency in setting a timeframe to address the mitigating strategies provided here.**

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[10] 'Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships' (2009) (http://www.imo.org/en/About/conventions/listofconventions/pages/the-hong-kong-international-convention-for-the-safe-and-environmentally-sound-recycling-of-ships.aspx).

[11] Craft Risk Management Standard for Biofouling on international vessels (CRMS) (2018) (https://www.mpi.govt.nz/dmsdocument/11671/loggedIn).

[12] http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Control-and-Management-of-Ships%27-Ballast-Water-and-Sediments-(BWM).aspx (viewed October 9, 2018)

4 Acknowledgement and references

4.1 Acknowledgement

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