Management of Biological Invasions (2018) Volume 9, Issue 3: 195–208
DOI: https://doi.org/10.3391/mbi.2018.9.3.03

Open Access

Management in Practice

How will vessels be inspected to meet emerging biofouling regulations for the prevention of marine invasions?

Chela J. Zabin[1,*], Ian C. Davidson[2], Kimberly K. Holzer[2], George Smith[2], Gail V. Ashton[1,3], Mario N. Tamburri[4] and Gregory M. Ruiz[1,2]

[1]*Smithsonian Environmental Research Center, 3152 Paradise Drive, Tiburon, CA 94920, USA*
[2]*Smithsonian Environmental Research Center, 647 Contees Wharf Road, Edgewater, MD 21037, USA*
[3]*British Antarctic Survey, Natural Environmental Research Council, High Cross, Madingley Road, Cambridge, CB3 0ET, UK*
[4]*Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, 146 Williams Street, Solomons, MD, 20688, USA*

Author e-mails: zabinc@si.edu (CJZ), davidsoni@si.edu (ICD), holzerk@si.edu (KKH), smithgeo@si.edu (GS), ashtong@si.edu (GVA), ruizg@si.edu (GMR)

**Corresponding author*

Received: 8 November 2017 / Accepted: 18 May 2018 / Published online: 18 June 2018

Handling editors: Sonia Gorgula and Katherine Dafforn

Abstract

International and national guidelines and regulations to limit the inadvertent transfer of non-native species on the submerged surfaces of vessels and mobile infrastructure are progressing. However, methods to assess compliance must be developed to assist both regulators and industry. While there is a history of biofouling inspections in maritime industries, including commercial shipping and infrastructure, such surveys are tailored for vessel safety and performance rather than being driven by biosecurity purposes. Thus, these inspections are likely inadequate for confirming compliance with biosecurity regulations. To determine regulatory compliance, agencies will likely rely on a combination of risk profiling, assessment of documentation of biofouling management, archival data and images, and real-time in-water surveys made by divers or remotely operated vehicles (ROVs) specific to biosecurity regulations. Divers may exceed ROVs at finding organisms in recesses and other topographically complex areas, and when regulations require confirmation of species identity or viability. In contrast, ROVs may be well suited for regulations that establish upper thresholds on biofouling levels with little concern for organism identity or condition. Several factors will inform how a survey is conducted, including cost, the type of data required by regulations, environmental conditions, safety, and logistics. Survey designs and requirements should be transparent to manage industry's expectations of border procedures, to increase the efficiency with which industry and agencies manage biofouling and potentially align the evaluation of best practices in hull and niche area maintenance across jurisdictions.

Key words: biofouling management, biosecurity, maritime shipping, biological invasions, ROVs, divers, in-water inspections

Introduction

Biofouling is the "unwanted deposition and growth" of organisms that can occur on solid-liquid, solid-gas, and liquid-gas interfaces (Flemming 2002). It is a wide-ranging problem that can have negative consequences from very small to quite large scales, ranging from biofilms on medical devices to large organisms interfering with sensors, dams, and pipelines (Khalanski 1997; Flemming 2002; Voskerician et al. 2003, Delauney et al. 2010). It is also problematic for space exploration (Koenig 1997; McKay 2009; Kim et al. 2013). Given its ubiquity and often unwanted impacts, biofouling is intensively managed across many fields of endeavor, and in some cases there are regulatory frameworks that specify how much biofouling can accumulate before intervention is required (e.g. US Code of Federal Regulations 2014). As a result, biofouling prevention (i.e. antifouling) and biofouling management are broad fields of research and multi-billion-dollar-a-year industries.

One of the most obvious negative consequences of biofouling is its effect on vessel hulls (Townsin

2003). Since the dawn of shipping, the accumulation of organisms on submerged surfaces of vessels has been recognized as a major cause of frictional drag (Dafforn et al. 2011; Schultz et al. 2011), which slows vessels or requires more power to maintain speed. In the modern era, this results in significant increases in fuel costs. An additional unwanted side effect of ship biofouling is the transfer of marine organisms to regions outside of their historical range, which can result in species introductions (Davidson et al. 2016). Introduced biofouling species, in particular, can cause problems because they may foul and thus damage static structures in a recipient region as well as affect environmental, economic, and sociocultural values (e.g. Thresher 1999; Carlton and Eldredge 2009; Fitridge et al. 2012; Fernandes et al. 2016). Management of modern ship biofouling to date has largely involved antifouling coatings and environmental regulations that manage the impact of biocidal compounds on non-target organisms (Clark et al. 1988; IMO 2001; Nehring 2001; Omae 2003). More recently, the management of biofouling translocation on vessels has been considered to reduce marine invasions (IMO 2011). As a result, the landscape for managing and monitoring biofouling of the world's shipping fleet is changing from an industry-driven model focused on voyage efficiency to an industry-plus-biosecurity approach including environmental and broader socioeconomic concerns (Davidson et al. 2016).

Policy frameworks are emerging for maritime shipping at international, national and regional scales to establish limits on biofouling accumulation and transfer to prevent or reduce marine biological invasions (i.e. biosecurity guidelines, e.g. IMO 2011; biosecurity regulations. e.g. New Zealand Government 2014a; California Code of Regulations 2017). Methods to assess compliance must be developed and adopted to assist both regulators and industry. Even in cases where simple documentation of regular maintenance is used as a standard, periodic assessment of ship biofouling should occur for compliance and verification purposes (i.e. to determine the efficacy of maintenance activities). However, to our knowledge, only three regulatory agencies, the Department of Conservation, New Zealand, the Western Australia Department of Primary Industries and Regional Development and the Galapagos Marine Reserve have formally articulated guidelines and protocols to assess compliance with their biofouling regulations (New Zealand Department of Conservation 2017; Government of Western Australia 2017a–c, Guidance Documents 1–3; Zapata Eraso 2015).

This paper discusses the various categories of biofouling regulations in place around the world and the inspection methods and protocols that may be used to assess compliance with thresholds or efficacy of biofouling management plans. We also discuss the use of divers versus remotely operated vehicles (ROVs) for such inspections and some considerations for selection of inspection approach. Our specific focus is on biofouling of commercial ships in marine and estuarine systems and any precedents from prior management frameworks that may inform new biosecurity inspection programs.

Existing and emerging biofouling regulations

Standards addressing biofouling have been in place longer for military ships and other (non-shipping) maritime industries than for commercial shipping, and these rules have been typically motivated by operational or other concerns rather than biosecurity. For example, the US Navy has set standards for the amount of biofouling allowed on vessels to maintain operating and combat efficiency in regard to speed, fuel economy, sensor performance, and corrosion control, with cleaning required when specific types and amounts of biofouling exceed specifications (US Navy 2006). Oil rigs and other industrial facilities (e.g. power plants) in the US that draw surface water for cooling purposes are subject to national requirements that indirectly limit biofouling coverage on intake grates (US Code of Federal Regulations 2014). For these intake structures, biofouling must be removed to comply with flow requirements set by the Environmental Protection Agency's (EPA) National Pollutant Discharge Elimination System (NPDES) permit, this agency's main concern being accidental entrainment death of fishes and other aquatic organisms.

The development of standards aimed at reducing biosecurity risk through controlling biofouling on commercial and recreational vessels is more recent. Currently, these range from very broad voluntary guidelines or best practices to specific mandatory regulations. A full review of these regulations is beyond the scope of this paper. Here we briefly provide some examples that illustrate the breadth of these standards.

Voluntary guidelines and best practices

The International Maritime Organization (IMO) has issued voluntary biofouling management guidelines for biosecurity purposes (commercial vessels, IMO 2011; recreational vessels, IMO 2012). The IMO also governs ship classification and certification, which is arguably the world's largest vessel-monitoring program and includes inspections of vessels in-water and in dry dock, though not explicitly for biofouling purposes. When inspections occur between dry docking periods, classification societies (non-governmental organizations that establish and maintain technical standards for the construction and operation of ships and offshore structures) use commercial divers to evaluate ships' submerged surfaces along with other inspection requirements to determine that ships are seaworthy and to maintain certification to operate (IMO 2011). Technical guidance on best practice for biofouling management was recently released by New Zealand (Georgiades et al. 2018).

Mandatory biofouling management

Several jurisdictions have used the IMO guidelines as a basis for mandatory biofouling management regulations. For example, the US Coast Guard rules require that ship operators "[r]emove biofouling from the vessel's hull, piping and tanks on a regular basis" and that ships maintain a detailed record of biofouling maintenance procedures on board (US Code of Federal Regulations 2012). California state regulations and New Zealand national regulations also require a biofouling management plan, including a biofouling record book, aligning with IMO guidance. Additionally, the state of California requires vessels that have outdated antifouling coatings or long layup periods (durations of time spent at anchor or in single bays) to provide information on hull maintenance practices used to counteract these elevated biofouling risk factors (California Code of Regulations 2017).

Specific thresholds for fouling extent and/or taxa

New Zealand was the first country to propose and enact management regulations that set specific thresholds for biofouling (New Zealand Government 2014a); these rules became mandatory in May 2018. The New Zealand regulations take various risk factors into account, and thus permit varying amounts of biofouling on vessels depending on the duration of a vessel's intended stay in New Zealand. These regulations include specific thresholds for the presence of broad taxonomic groups, and, for vessels intending to stay short-term in New Zealand, sizes of organisms on different hull locations (e.g. < 50 mm length green algae allowed at "wind and waterline" for vessels with short port stays) (New Zealand Government 2014a; Georgiades and Kluza 2017). Western Australia also has mandatory thresholds for biofouling, focusing on the presence of specific taxa listed on its "noxious fish" list (Government of Western Australia 1995, 2014). The definition of "fish" is not limited to finfish and includes invertebrates and macroalgae.

Several jurisdictions aiming to protect high-value marine resources have also set very strict limits, disallowing vessels with any macrofouling. For example, sensitive marine areas in Western Australia are protected by management programs which prohibit the presence of macrofouling on vessels and structures engaged by the extraction industry, for example the Gorgon Project (Wells and Booth 2012). Macrofouling is also prohibited on vessels in the Northwestern Hawaiian Islands (a US National Monument) and the Galapagos Marine Reserve (Papahānoumakuākea Marine National Monument 2009; Zapata Erazo 2015). In Australia's Northern Territory, stringent standards (vessels must arrive "clean") are in place for recreational vessels entering Darwin Harbor from outside Australian waters. The rules, which are a condition of entering the marinas, are enforced by Darwin marinas through an agreement with the government. In-water inspections by divers may be required for vessels depending on length of time since last antifouling, and internal seawater systems may also be required to undergo a decontamination treatment (Northern Territory Government 2016).

Around the world, biofouling management regulations typically apply to commercial vessels only, although New Zealand rules apply to all vessel types (New Zealand Government 2014a), and Australia's Northern Territory and the Galapagos Marine Reserve specifically address recreational vessels, with the goal of preventing invasions and protecting natural resources and socioeconomic assets (e.g. aquaculture) (Northern Territory Government 2016; Zapata Erazo 2015). Within the US, federal regulations, such as the Lacey Act (US Code of Federal Regulations 2004) and many state regulations (e.g. Idaho Code 2008) prohibit the transfer of specific "injurious" or invasive species, but inspections are typically limited to overland movement of recreational watercraft traveling between freshwater systems (McClay et al. 2015).

Most of the new and emerging biosecurity-focused regulations do not cover the ways in which maritime vessels could be inspected to ensure compliance with explicit standards or to assess the efficacy of hull maintenance requirements (New Zealand high value areas, Western Australia and the Galapagos Marine Reserve are exceptions, as discussed below). In contrast, existing regulations and practices that do not consider biosecurity but emphasize efficiency standards tend to follow specific protocols. The US Navy's biofouling assessment is an example of this, with guidance on inspection frequency, a pictorial ranking system for biofouling levels on different ship components, and thresholds that trigger cleaning (US Navy 2006). Commercial ships have widely accepted industry practices and standards with regards to ship inspections for vessel classification and insurance purposes. The National Association of Corrosion Engineers, which is a world authority on industrial standards related to corrosion, has also produced a framework of pictorial-based standards for classifying biofouling on submerged surfaces of ships to promote consistency for underwater inspections (NACE International 2017). Inspections of commercial ships are typically made by divers documenting hull status with still photographs or video, although the use of ROVs is increasing as advancing technology has both improved data collection and reduced costs.

The frequency, methodology, and key drivers of inspections that are currently motivated primarily by operational functionality are not likely to be sufficient to meet biosecurity regulations or goals (Davidson et al. 2016). In areas with species-based standards, images that document the extent of biofouling (percent cover), for example, might not be sufficient to identify listed nuisance species. Certain niche areas, which tend to accumulate biofouling more quickly and heavily than hull surfaces will require greater scrutiny than has previously been the case (Coutts and Taylor 2004; Davidson et al. 2016.) Additionally, the utility of diver- versus ROV- based inspections of submerged surfaces has not been thoroughly evaluated (but see Floerl and Coutts 2011, discussed below). As a result, the lack of standardized methodology and specific protocols for biosecurity-focused biofouling assessment could pose challenges for regulatory agencies and the global shipping industry.

Biofouling inspection protocols for marine biosecurity purposes, including detailed inspection checklists, have been created for specific projects or areas, such as marine seismic surveys (e.g. Woodside Energy 2007), management plans for high value marine areas (e.g. New Zealand Department of Conservation 2017), and biofouling management research (e.g. Lewis 2016), but these have not been broadly adopted. It is likely that more information on biofouling inspections and procedures will become available in the near future in response to implementation of biofouling regulations.

In the subsequent section, we review some details of existing biofouling inspection procedures used by non-shipping industries, the US Navy, and the commercial shipping industry, and discuss the practices and protocols specified by biosecurity regulations. We then consider the advantages and limitations of divers and ROVs for biofouling assessment, and the conditions that may influence their deployment, data quality, and comparability.

Inspections not focused on biosecurity

Non-shipping industry

Inspections of cooling water intake structures in the US focus on complying with performance standards that minimize inadvertent harm to fish and shellfish. For example, biofouling may clog screen openings, which increases intake velocity over acceptable impingement thresholds. There are no published protocols for monitoring biofouling levels, but there are record keeping and reporting requirements. For approved cooling water intake technologies, inspections may consist of remote flow monitoring at intake grates or visual inspection by diver or ROV to ensure that the system continues to operate as designed and permitted (US Code of Federal Regulations 2014).

US Navy

The US Naval Ships Technical Manual (NSTM) provides guidance for biofouling evaluation and control (US Navy 2006). The Navy's primary concern is energy efficiency and vessel readiness, as opposed to biosecurity, and inspections are thus primarily focused on hulls rather than on niche areas. Frequency of inspection, cleaning, or recoating varies with vessel type, intensity and area of operation, as well as the type and age of coatings. High-speed vessels typically deployed on long voyages are more frequently inspected than sedentary ships. As antifouling, foul-release, and anti-corrosion coatings age, inspection and cleaning frequency may increase gradually until recoating is deemed necessary.

When inspections of Navy vessels are conducted, biofouling and coating condition are numerically rated relative to pictorial and descriptive guidance contained in the NSTM. The manual discusses the use of divers only for these inspections, while in other areas of operation, such as salvage, the Navy uses divers and ROVs. Corrective action is mandated when biofouling or coating breakdown exceeds specified trigger points. Action may include cleaning, increasing frequency of inspection (for older coatings especially), or recoating. Inspection and cleaning are also mandated when speed drops more than 1 knot at standard cruising rpm measured at the propeller shaft. Otherwise, light-to-moderate biofouling over 10% or more of a hull's surface may be accepted. A more stringent standard applies to critical surfaces such as propellers, propulsion shafts, masker belts (which reduce noise signature of vessel) and sonar domes. These are inspected and cleaned more frequently than other sections of the ship because of their importance for combat performance. For example, propellers are scrutinized more frequently than other surfaces, particularly before sailing following port-stay or layup.

Although current inspections don't focus on biosecurity, the US Navy does have a biofouling research and development program conducting tests of new procedures and coatings with the goal of incorporating research results with standard operating procedures to enhance both energy efficiency and biosecurity (Haslbeck and Oates 2016).

Commercial and private vessels

Hull inspections, in-water cleanings between dry docking, and recoating of commercial ships' submerged surfaces are routinely carried out to maintain operational function and efficiency. In-water inspections, made by commercial divers, generally occur at the midpoint of dry dock intervals that typically range between 36 and 60 months. Observation of macrofouling would generally prompt maintenance action, although increasing numbers of jurisdictions are prohibiting in-water cleaning, which might result in less frequent cleaning between dry dock periods (Zabin et al. 2017). Video footage of hulls and running gear is collected to assess coating condition and biofouling, and to assess damage and structural integrity. Photos and videos may also be taken in dry dock prior to cleaning. These images and data are being used as biofouling management records, and may supplement biosecurity inspections. Recent and emerging regulations require that dry dock and in-water survey images and reports are included in biofouling record books. However, as biofouling is not a primary focus of these inspections currently (vessel integrity and corrosion are), it is unlikely that these inspections would capture biosecurity risk or document compliance with regulations. For example, niche areas are frequently neglected in the footage, camera resolution may be insufficient for biological determinations (e.g. taxonomic identification), and certain organisms (e.g. mobile crustaceans) may be missed altogether (reviewed in Davidson et al. 2009).

Inspections for biosecurity purposes

Voluntary guidelines and best practices

Currently no protocols have been adopted by entities such as the IMO to determine compliance with voluntary guidelines and best management practices (BMPs), or the efficacy of doing so, and we know of no study that has evaluated the effectiveness of the many recreational boater education and outreach programs that encourage the use of BMPs to reduce biofouling.

Mandatory biofouling management

In 2017, the state of California released regulations aimed at ensuring BMPs for the reduction of biofouling on commercial vessels. While these rules, which came into effect in January 2018, do not include thresholds of acceptable biofouling, the program officers intend to examine vessel hulls and niche areas to determine the efficacy of the state's mandatory biofouling management practices. Specific protocols for inspections and documentation of biofouling have yet to be developed, but regulators intend to primarily use ROVs to make these inspections, based on pilot studies in the state's major ports indicating that ROV footage is adequate to assess biofouling extent (C. Scianni, California State Lands Commission, pers. comm. to CJZ 2018).

Some regulatory bodies mandate biofouling inspections, but do not describe them in any detail. For example, the US EPA requires a comprehensive annual inspection under the Vessel General Permit regulation, which must include "the vessel hull, including niche areas, for biofouling organisms" (US Environmental Protection Agency 2013) but does not say how such inspections are to be made.

Specific thresholds for fouling extent and/or taxa

In New Zealand, vessel biofouling regulations have had a voluntary lead-in period since 2014 and became mandatory in May 2018. However, vessels deemed to have severe fouling may be subject to management action. Vessel operators entering the country can be required to present vessel records, photographs, and receipts for antifouling treatments or inspections as proof of compliance with regulations. The rules state that inspectors may subject any vessel to verification through "inspection of hull, sampling and/or photography", may use "underwater viewing scopes" on recreational vessels, or require an underwater survey from a provider approved by the Ministry of Primary Industries for larger vessels (New Zealand Government 2014b). If vessel owners elect to clean in New Zealand as a way to comply, they must provide photographic evidence that the cleaning matches arrival standards. Since the only approved in-water treatments kill but do not remove biofouling, the photos need to be of sufficient quality to indicate that biofouling organisms are dead (see Morrisey et al. 2015 for a discussion of assessing viability). New Zealand provides guidance documents for biofouling management to meet standards (New Zealand Government 2014b) and for evaluating in-water removal or treatment systems (Morrisey et al. 2015), but as yet have not specified protocols for how inspections to ensure compliance are to be made.

Detailed biosecurity-focused guidelines for biofouling inspections and performance standards are included in a regional coastal plan for the Kermadec and Subantarctic Islands in New Zealand. The plan sets limits on the amount of biofouling allowed on vessels arriving to the islands or operating within nearshore waters (New Zealand Department of Conservation 2017). Inspection, sampling and reporting protocols in the plan are based on recommendations contained in Floerl et al. (2010). The plan includes diagrams of vessel hulls, delineating the hull transects and the appendages and niche areas requiring inspection. It also contains standardized reporting forms, which include vessel particulars, operational history, and biofouling maintenance. Inspection forms include details from the vessel inspection in which inspectors are asked to report biofouling within the inspection transects using standardized Level of Fouling (LoF) ranks (developed by Floerl et al. 2005). The LoF ranks are illustrated with a pictorial guide in the plan. Inspectors are required to photograph transects and may be required to collect specimens, depending on the type of inspection. Specimen collection, preservation, labeling, transporting and identification protocols are also detailed in the plan, as are the qualifications required for inspectors.

In Western Australia, vessels must (a) comply with rules that prohibit specific taxa on a "noxious fish" list or (b) comply with more stringent rules governing vessels associated with the extraction industry that require cleaning prior to entry to sensitive areas (Wells and Booth 2012; Government of Western Australia 2014). For vessels subject to the noxious species prohibition (a), only those identified as high risk are typically subjected to inspection. Western Australia recently adopted three guidance documents that address qualifications for marine biosecurity inspectors, requirements for biofouling inspection reports, and best practices for such inspections (Government of Western Australia 2017a–c, Guidance Documents Attachments 1–3). The inspection reports must contain several components, including vessel particulars, operational history back to the last antifouling coating, biofouling prevention methods employed, and maintenance history, which are used to assess risk and likelihood of the presence of invasive marine species (IMS). Additionally, inspectors must note procedures used for inspection, factors preventing a complete inspection, and environmental conditions, as well as inspection results, such as samples taken, species identified, areas inspected, extent of fouling and confidence level associated with the inspection (Government of Western Australia 2017b, Guidance Document Attachment 2). The inspection itself must include the internal sea water systems and topsides, and either a dry dock or in-water inspection, with a clear indication of what was done, a documented, effective search pattern to ensure good coverage of the vessel, a video of the dive, photos taken *in situ* before samples collected, and the collection of individual IMS encountered. Samples must have a secure chain of custody, with records of where on the vessel they were collected, and must be labelled, coded, preserved and submitted as designated by Fisheries Department protocols (Government of Western Australia 2017c, Guidance Documents, Attachment 3).

In Western Australia, in-water inspections are made by divers, with ROVs used as an initial screening tool (B. Tilley, Department of Primary Industries and Regional Development, WA, pers. comm. to CJZ 2018). Divers attempt to survey the entire vessel, swimming transects over the whole ship, with intervals set based on visibility. However, in many cases, logistical constraints result in inspections being tailored to each vessel and set of circumstances, and divers may focus on niche areas, which are proven to be key areas for biofouling accumulation (B. Tilley, pers. comm. to CJZ 2018). Divers inspect all niche areas, including sea chests, which inspectors can view with a modified CCTV camera (which also provides a chain of custody for evidence gathering), and special attention is paid to anodes, weld lines, dry dock support strips, keel, damaged paint, chains and any other surfaces not coated with antifouling paint (B. Tilley, Department of Fisheries, WA, pers. comm. to CJZ 2018). The inspection is documented with both still shots and video live-streamed to a supervisor who is in communication with the divers. All inspectors must meet standards set forward in the Guidance Document mentioned above.

In Australia's Northern Territory, recreational vessels must arrive "clean" although the extent of allowable fouling is not clearly defined. Written protocols for inspections do not exist. Divers search the vessel's entire underwater surface, looking for biofouling on hull, sea chest, and other sheltered areas, and collect samples of any organism they are unfamiliar with for expert taxonomic identification (M. Simoes, Northern Territory Fisheries, pers. comm. to CJZ 2018). Inspections and treatments for internal seawater systems do not incur a cost to the vessel operator. If a marine pest is found, there are two options for vessel owners: 1) lift and clean vessel at owner's expense or 2) leave Northern Territory waters (M. Simoes, Northern Territory Fisheries, pers. comm. to CJZ 2018).

The Papahānoumakuākea Marine National Monument (PMNM) in Hawaii, USA has one of the strictest biofouling requirements — all vessels must be completely free of any macrofouling. Inspections are made before vessels depart from the main Hawaiian Islands and are a condition of being permitted to enter the Monument. While not part of the agency's written rules, PMNM has a working protocol, which is to survey the entire hull on SCUBA (S. Godwin, National Oceanic and Atmospheric Association, pers. comm. to CJZ 2018). Divers record visual estimates of percent cover of biofouling in each of the following areas: bow, midship, stern, prop and rudder, dry dock support strips and zinc block, and hull above the water line. Specimen collection is made of morphologically distinct species for identification in the laboratory. A small ROV has sometimes been used in place of a diver in cases where vessels that had entered the Monument on an earlier permit (and had been thoroughly inspected by divers) were applying to re-enter within a month (S. Godwin pers. comm. to CJZ 2018). In instances where the ROV found niche areas to be free from fouling, regulators assumed the remainder of the hull was also clean and allowed re-entry.

The Galapagos Marine Reserve also requires inspections of all vessels, including yachts, cruise ships, commercial cargo and fishing vessels arriving into the reserve from ports outside of the Galapagos (Zapata Erazo 2015). Regulations require vessels to clean before arrival and disallow any encrusting organisms. Inspections are mandatory and detailed written protocols include a dockside inspection of the hull above the waterline and in-water visual inspection of the entire hull and niche areas by divers. When divers find encrusting organisms, protocols require that they collect samples representative of all taxa encountered (Zapata Erazo 2015), but the protocols do not indicate how samples are to be identified and biogeographic status determined, nor do they set standards for inspector training and qualifications. Vessels can be turned away if they fail to comply, although it is unclear whether in practice some threshold level, particularly of native species, might be allowable.

Other models for biosecurity inspections

Many of the biofouling regulations discussed above are recent enough that they have not yet been fully implemented. To date, in-water monitoring appears to be limited to (a) all vessels entering the Galapagos Marine Reserve and PMNM (b) high-risk recreational vessels in Australia's Northern Territory (Darwin), (c) vessels deemed high risk in Western Australia or part of the extraction industry in that state, and (d) high-risk vessels or vessels in certain protected waters in New Zealand (e.g. New Zealand Ministry of Primary Industries 2007, New Zealand Department of Conservation 2017). An expansion of ship biofouling monitoring is probable in the coming years as surveys are required to determine whether regulated biofouling standards are being met or whether BMPs are effective at reducing biosecurity risks. This may increase the amount of monitoring that occurs, or change the existing monitoring approach to include data and images that fulfill biosecurity reporting requirements. At the moment, with the exceptions mentioned above, a major gap still exists in how biofouling will be assessed, and in many locations, the capacity to do in-water inspections is lacking.

Several other models exist for inspections that could be used to evaluate biofouling management efficacy. For example, International Paint, a major maritime coatings manufacturer, provides guidelines on how to classify biofouling extent on different areas of the hull during underwater inspections. Thomason (2010) developed a standardized approach to evaluating ship biofouling in dry docks, which has been used to analyze variables associated with biofouling accumulation.

A study commissioned by the New Zealand Ministry for Primary Industries (Lewis 2016) developed standardized reporting forms for evaluating the efficacy of some of the practices for commercial ships recommended by the IMO (which have been adopted by other entities such as New Zealand). Ship information forms include questions on ships particulars, last dry dock date and location, operational history, and ship biofouling management practices. Ship inspection forms ask for estimated extent and severity of various categories of biofouling at forward, midship and aft portions of a ship's port and starboard sides and hull bottom, and include definitions and visual diagrams of various percent cover categories. Additional forms cover sea chest information and biofouling extent on external grates and within sea chests. Photographs are requested of all areas evaluated by the forms. These forms were intended for use in dry dock, but could be models for in-water inspections as well.

In many western states in the US, recreational vessels that are moved on trailers between waterbodies are subject to inspections for specific aquatic invasive biofouling species, namely zebra and quagga mussels (*Dreissena polymorpha* [Pallas, 1771] and *D. rostriformis bugensis* [Andrusov, 1897]). Often watercraft inspectors receive standardized watercraft inspection and decontamination certification training through a sponsor, such as the Pacific States Marine Fisheries Commission. Inspections may be carried out at designated locations along major interstate

Table 1. Considerations for the use of ROV versus diver surveys for biofouling assessment. Costs will also be a major consideration, but are likely to vary widely by location.

Considerations	Inspection-class ROV	Commercial diver
Environmental conditions	• Water turbidity • Current and wind speeds	• Water turbidity • Current and wind speeds • Dangerous marine life • Toxic pollutants
Personnel	• Minimum of two trained staff	• Minimum of three trained staff • Annual recertification process
Safety	• Lockout-tagout of ship	• Lockout-tagout of ship • Emergency plan, including port police & coast guard notification
Logistics	• Power supply (120 VAC) access† • Battery run time† • Tether length limits†	• Bottom time limits • Support boat • Surface interval requirements
Data sampled	• Still photos • Video transects • Live reporting to surface • Specimen collection difficulty*	• Still photos • Video transects • Live reporting to surface • Specimen collection ease • In-person qualitative evaluation

† Depends on ROV power system.
* Specialized 'manipulator arms' or syringes may be used, usually one sample per dive.

highways, or upon entry/exit to parks or waterways (Zook and Phillips 2009). Inspectors typically screen vessels to determine risk status, and thoroughly inspect the high-risk vessels before launching, using a standardized checklist (Zook and Phillips 2012); finding a single live mussel can result in a hold order and required decontamination "hot wash". These protocols may provide a useful template for in-water inspections of small, lightly fouled vessels in good visibility, but are likely impractical for commercial ships in many port settings.

Potential approaches to biofouling assessment

Among the available options for assessing the extent of biofouling on vessels are: 1) archival video footage recorded during hull husbandry inspections; 2) photographs and sampling of hulls in dry dock; 3) inspections made in water by ROVs; 4) inspections made in water by commercial divers. The first two options make use of documents that may already be available as part of a ship's routine maintenance, and as such, these are a component of existing guidelines to maintain a biofouling management record book onboard vessels (IMO 2011; New Zealand Government 2014a, b). However, archival images from underwater and dry dock inspections generally will not capture biofouling extent at the relevant time, prior to entry into port, and are thus unsuitable for real-time assessments. The latter two options will be needed for assessing compliance of vessels that have entered a jurisdiction that is enforcing biofouling standards, or at least sampling a population of arriving vessels to determine whether hull maintenance practices are meeting biofouling standards. Currently, dry-docking or using a small camera manipulated through external gratings in-water may be the only reliable way to inspect a sea chest (e.g. Dacon Inspection Services 2016).

Remotely operated vehicles (ROVs)

ROVs can accomplish tasks ranging from light-duty inspection to construction, maintenance, and salvage at great depth. Some considerations for their use are presented in Table 1. An inspection-class ROV can weigh as little as approximately 8 kg (20 kg with tether, command console, and other components) and may be deployed with relative ease from a pier or a small boat. Reviews of inspection-class ROVs are available (Biofouling Solutions 2017; Capocci et al. 2017), to help determine the most appropriate model for hull surveys. ROVs come in a wide range of prices (authors received quotes between $12,000 and $200,000 USD), and manufacturers tend to have operational and maintenance training available, which are recommended for new operators.

Battery power is a convenient feature of some small ROVs. Others use alternating current from external power, user-supplied small generator, or inverter equipped vehicle. For hull inspections, ROVs able to maintain 3 knots, with power to drag a long tether, able to automatically maintain set depth and heading, and to maneuver incrementally for precise imaging are ideal. In addition to free-flying ability, some may be equipped to "crawl" with wheels or tracks while pinned to a hull-surface by vertical thrust, allowing for stable imagery under trying conditions. However, severe biofouling (high surface relief) can make crawling impossible.

Video transects and still photography can provide percent cover estimates, characterize niche-area biofouling, and provide a limited degree of taxonomic/community detail. Certain niche areas, e.g. sea chests and thrusters, remain difficult to survey adequately using ROVs because of intervening grates, or entrapment risk.

Water turbidity may be the variable most affecting ROV operations and image quality/utility. Visibility of 1 m or less is not unusual for ports, and under these conditions finding and scanning important niche areas is challenging and consistent scans of broader underwater surfaces may not be possible. Although we do not propose visibility criteria for underwater biosecurity survey work, authors' experience suggests operators can find areas of concern on even a lightly fouled vessel in visibilities as low as 0.6 to 1 m, but thorough cover assessments for regulatory purposes under those conditions is problematic. Optional high-definition sonar provides navigational and niche-finding guidance in low visibility.

Regulatory agencies could purchase and operate their own ROVs, or hire an underwater-inspection contractor. A contractor certification process seems likely to be necessary where inspections could have enforcement ramifications. Frequent hull-inspections might be better served by an in-house ROV capability, whereas rare inspections might not warrant it. Further technological developments could potentially overcome some of the current limitations of ROVs, including improvements to endoscopes, arms and multiple collection containers, ability to crawl and fly, to shoot still footage when needed, and to operate using low visibility imaging systems. Ongoing incorporation of drone and web interface technologies suggests continued gains in convenience and versatility.

Divers

The alternative option for real-time *in situ* assessments of ship biofouling is to use divers. Divers are commonly employed to examine ships and underwater port structures for a variety of reasons, so many of the logistical considerations for diver surveys are already well known by industry. For biofouling inspections, diving with air supplied by surface support or SCUBA equipment can be used. Divers on surface support can stay in the water for longer, but must remain tethered to the surface (which may have implications for accessing parts of larger vessels) and have a higher technical equipment requirement than those on SCUBA.

Dive surveys have significant logistical implications (Table 1), especially related to human health and safety. These are largely known from a long history of port diving. Personnel must be properly trained and maintain certification and insurance status. Scientific diving and commercial diving — which require different levels of training and certification — are both available for ship biofouling surveys although it is possible that inspections would fall outside the remit of scientific diving if monitoring became routine and scientific data collection was no longer considered the primary goal. Commercial diving is more appropriate after protocols have been developed, the dive operations become routine and image- or metric-based (e.g. percent cover), and standards have been set for biosecurity inspectors. In general, health and safety regulations may be more stringent for dive operations than for ROVs, stipulating, for example, that dives be made within a set distance of a hyperbaric treatment chamber, an emergency oxygen kit be onsite, and that divers not fly for 24 hours after diving, which may affect costs.

Divers on SCUBA typically work in buddy pairs, with a third diver as an emergency support/back-up, as well as boat crew. Commercial divers on surface air typically require more surface support, with a tender and crew. Subsequent limitations to dive operations are related to safe operating conditions. Ports and more specifically live vessels require detailed risk-management procedures even when operating systems of surveyed vessels are shut down. Port environments are often turbid, which further increases the level of risk and may be contaminated with chemical pollutants from port operations as well as land-based run off. Surveys by divers, particularly of large vessels, may be more time consuming than those done by ROVs and divers are also limited in underwater time by air supply, cold, fatigue, and other health and safety considerations, such as predatory megafauna.

Divers can collect both written and photographic data, but their major advantage over ROVs is the ability to collect biological samples, provide better qualitative evaluations of ships' submerged surfaces under a range of circumstances, including from many niche areas, and provide real-time communication of observations. The divers' peripheral vision, touch and ability to maneuver into position to observe biofouling organisms in places that cannot be easily accessed may enhance their inspection quality relative to video captured using an ROV. Notes and photographs can be used to describe the pattern and extent of biofouling, estimate percent cover of both general hull surfaces and niche areas, and provide a basic description of taxonomic and community detail. Taxonomic analysis of any samples collected allows exact identification of specimens, and subsequent analysis of their biogeographic status.

Comparing ROVs and divers

We only found one published field trial directly comparing biofouling data collected by divers and ROVs. Floerl and Coutts (2011) assessed the ability of divers and ROVs to examine the same four vessels in terms of their ability to 1) inspect all hull and niche areas; 2) provide clear imagery of biofouling; 3) collect samples of biofouling. Two types of ROVs were used, one that had crawler capacity, and one that was free-flying. To replicate the variability of field conditions, two of the vessels were inspected in a protected harbor setting and two at a moorage two miles offshore. ROVs provided higher quality video footage than divers, with the crawler ROV able to do this better than the free-flying ROV under the open-ocean conditions. Individual taxa, including mimics of target species, could be detected from ROV video footage. However, divers were better able to access complex niche areas than ROVs, to provide higher quality still photography, to detect mimics of target species, and to collect samples.

Anecdotally, commercial divers trained to recognize invasive marine species over several years have been able to detect 3 mm Asian green mussels (*Perna viridis* [Linnaeus, 1758]) in amongst heavy biofouling (Anonymous Reviewer, pers. comm. 2018); a task that likely would only be possible by ROV equipped with the best available technology (including crawling and high definition camera). This suggests that jurisdictions requiring 1) detection and collection of certain taxa (i.e. from a list of IMS) and/or 2) species identification (rather than broad taxonomic groups); and/or 3) a high level of certainty in inspection findings, should use divers. Floerl and Coutts (2011) found that costs for divers were higher, in some cases nearly twice as high, than the ROVs, but this is expected to vary greatly with location (including whether there are commercial divers or ROVs available locally) and survey specifics (e.g. vessel size and complexity, whether it is at berth, mooring or anchor, and environmental and safety conditions).

Further comparative studies are needed to adequately assess the effectiveness of ROVs versus divers. ROV technology is constantly evolving, and some of the limitations listed above may be overcome in time. Currently, the main advantages of ROVs include the reduced safety and logistical considerations, while the higher data precision (including the potential to collect biological samples) may justify the additional considerations of using divers (Table 1).

Discussion

New and emerging regulations on vessel biofouling vary widely and may require different approaches to determine compliance. It is notable, thus far, that issues of compliance monitoring, including inspection protocols, have frequently not been a part of regulatory or guideline text for biofouling management, even in cases with specific rules on allowable types and amounts of biofouling (e.g. New Zealand Government 2014b). While military and commercial vessels have a longer history of being surveyed for biofouling, it is unlikely that these inspections, which are typically focused on operational functionality, will be useful in terms of documenting compliance with biosecurity regulations. Rather, the new rules will eventually require purpose-designed surveys made by divers or ROVs, focusing on the specific requirements of each jurisdiction's biosecurity regulations or evaluating whether best management practices are meeting or exceeding biofouling thresholds. Protocols for biofouling inspections focused on biosecurity have been developed for several jurisdictions and/or specific projects or locales. These protocols have many similar components, typically guided by biofouling research and/or working knowledge of biofouling accumulation on ships. To the extent possible, given that different jurisdictions are guided by different legislative powers, these could be used to form the basis of a standardized approach to such inspections, which would be useful to both regulatory agencies and industry. Studies that measure the effectiveness of various protocols in detecting marine taxa or accurately characterizing cover are also needed to assist agencies with setting standards and protocols.

Ideally, regulators would select divers or ROVs based on specific data needs (Figure 1, far left panel). Divers appear to provide better data when regulations require identifications to the species or genus level for jurisdictions that prohibit particular species. Divers may also be better than ROVs at finding organisms in recesses and other topographically complex areas (niche areas), which is a pressing motivation for bio-

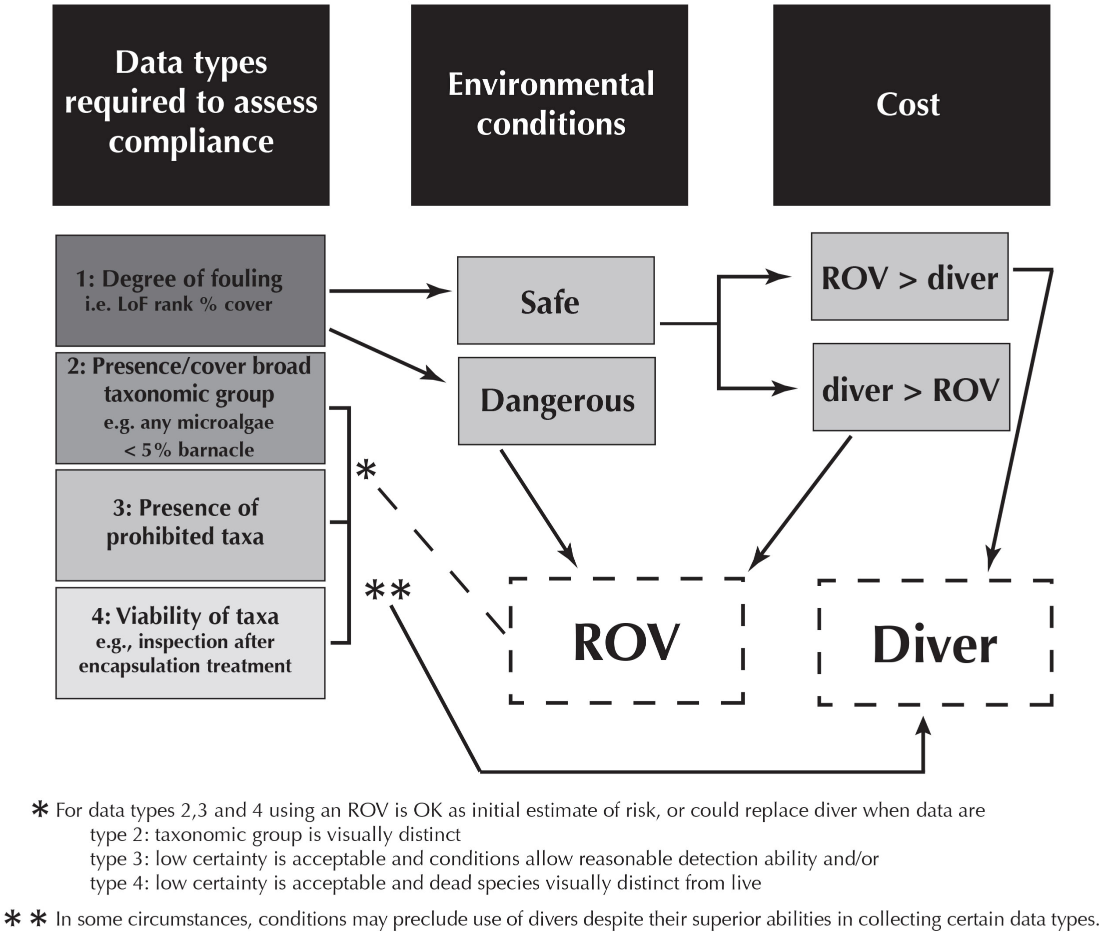

Figure 1. Schematic of some of the considerations for the selection of divers or ROVs for assessing compliance with biofouling regulations. Data needs might drive the selection of divers versus ROVs under ideal conditions (e.g. solid line from data types 2–4), but other considerations such as environmental conditions, diver safety and costs are also important. Acceptable levels of certainty in the data collected will be weighed against these factors. For example, if high certainty is required divers might be selected over ROVs for data types 2–4 even when using divers is more expensive.

security-based biofouling standards (Davidson et al. 2016). Divers are also likely needed in situations where regulations require an assessment of species viability or differentiation between size classes (see Morrisey et al. 2015, Table 8–2). For example, divers may be needed to evaluate requirements that specify organism-size-based percent cover (e.g. New Zealand standards for cover of algae based on thallus length) and require proof that biofouling species are no longer viable following approved treatment methods. On the other hand, ROVs can be used to meet regulations that specify threshold levels of total biofouling cover, or of broad taxonomic groups, or target taxa that are larger and readily identifiable by video footage in the field.

The relative effectiveness of either method will vary with conditions: ROVs operate best in good to moderate visibility, while divers may be better than ROVs at operating under low visibility conditions and when a ship is heavily fouled. Regulators in California expect that ROVs will be able to collect sufficient data for California's in-water assessments, based on pilot studies in the ports of San Francisco and Los Angeles (C. Scianni, pers. comm. to CJZ 2018). In contrast, regulators in Western Australia say typical turbid conditions there preclude good data collection by ROVs (R. Adams, B. Tilley, pers. comm. to CJZ 2018). Management agencies need to be aware of limitations of either approach, and be willing to balance levels of uncertainty in the data with other critical concerns (Figure 1). Further comparative studies of divers and ROVs could help quantify these levels of uncertainty.

In reality, environmental conditions, particularly those that affect safety, and cost will dictate how inspections are undertaken (Figure 1, second and third panels). ROVs are the only realistic choice for in-water inspections when conditions are too dangerous for divers and haul-out or quarantine are unfeasible. Some ports (or terminals at a minimum) in high flow and turbidity environments may never have conditions amenable to surveys by either method. Initial proof-of-concept research has been carried out on the use of sonar to detect levels and broad classes of biofouling in low visibility conditions. Under highly controlled conditions differences in surface topography less than 1 cm could be detected, but further testing is needed to determine if this would be an efficient tool (J. McDonald, Department of Fisheries, Western Australia, pers. comm. to CJZ 2018). The US Naval Research Laboratory is evaluating novel methods of biofouling measurement including variable fluorescence imaging, optical and acoustic imaging, electrochemical sensors, electrical impedance, and biomolecular detection (First et al. 2014; M. First, US Naval Research Laboratory, pers. comm. to ICD 2018).

Cost considerations will drive the extent to which compliance is monitored and the logistical approaches that regulatory agencies take, although this will vary by location and evolve over time, particularly as demand for in-water inspections rises as a result of new regulations (McClay et al. 2015). Some of the current costs of inspections by either divers or ROVs include travel and shipping of equipment. Training and equipping local commercial dive companies or agency staff could help reduce dive costs. Initial monitoring for biofouling standards is likely to occur at focal ports (such as ports of first arrival for overseas vessels) to build capacity while managing costs. To reduce the costs associated with diving, agencies might take a hybrid approach as Western Australia and PMNM are doing, using ROVs for initial screening, with follow up by divers when ROVs find something potentially important that cannot be resolved with imaging or without collection. ROVs also might be used to make an initial determination of degree of fouling, with divers carrying out surveys on heavily fouled vessels. Such an approach can make use of the best qualities of each survey method, saving time and costs associated with dive inspections.

Overall, increasing attention to vector management has influenced maritime shipping in recent decades and the trajectory suggests that biofouling should be managed according to industry needs *and* biosecurity concerns, rather than just the former. As a result, research will be needed to determine if biofouling management practices are minimizing the transfer of biofouling on ships and continuous monitoring or risk-based evaluations will be required for jurisdictions with mandatory biofouling standards. The ultimate goal is to reduce the rate of ship-mediated marine invasions around the world by ensuring very low levels of biofouling are in flux. Such an outcome will rely on differential policy-making across many jurisdictions, that endeavor to align as possible, and the monitoring decisions that convert policy into practice.

Acknowledgements

This work was funded by the US Maritime Administration through the Maritime Environmental Resource Center, Maryland USA. This manuscript was greatly improved with the assistance of four anonymous reviewers. We thank our colleagues at various regulatory agencies for their patience in explaining the details of regulations and approaches to compliance, Lina Ceballos for assisting with translation of the Galapagos Marine Reserve inspection regulations, and Blu Forman for figure preparation.

References

Biofouling Solutions (2017) Evaluation of remotely operated vehicles for aquatic biosecurity surveillance for department of agriculture and water resources. Report reference BFS1483; version 3.0, 79 pp

California Code of Regulations (2017) Title 2, Division 3, Chapter 1, Article 4.8 – Biofouling Management to minimize the transfer of nonindigenous species from vessels arriving at California Ports. California State Lands Commission, Sacramento, California, 24 pp

Capocci R, Dooly G, Omerdić E, Coleman J, Newe T, Daniel T (2017) Inspection-class remotely operated vehicles—a review. *Journal of Marine Science and Engineering* 5: 1–32, https://doi.org/10.3390/jmse5010013

Carlton JT, Eldredge LG (2009) Marine bioinvasions of Hawaii: the introduced and cryptogenic marine and estuarine animals and plants of the Hawaiian Archipelago. Bishop Museum Bulletin in Cultural and Environmental Studies 4, Bishop Museum Press, Honolulu, 203 pp

Clark EA, Sterritt RM, Lester JN (1988) The fate of tributyltin in the aquatic environment. *Environmental Science & Technology* 22: 600–604, https://doi.org/10.1021/es00171a001

Coutts ADM, Taylor MD (2004) A preliminary investigation of biosecurity risks associated with biofouling on merchant vessels in New Zealand. *New Zealand Journal of Marine and Freshwater Research* 38: 215–229, https://doi.org/10.1080/00288330.2004.9517232

Dacon Inspection Services (2016) http://www.dacon-inspection.com/services/inspection-services/advanced-ndt/sea-chest-inspection (accessed 01 Mar 2018)

Dafforn KA, Lewis JA, Johnston EL (2011) Antifouling strategies: History and regulation, ecological impacts and mitigation. *Marine Pollution Bulletin* 62: 453–465, https://doi.org/10.1016/j.marpolbul.2011.01.012

Davidson IC, Brown CW, Sytsma MD, Ruiz GM (2009) The role of containerships as transfer mechanisms of marine biofouling species. *Biofouling* 25: 645–655, https://doi.org/10.1080/08927010903046268

Davidson IC, Scianni C, Hewitt C, Everett R, Holm E, Tamburri M, Ruiz G (2016) Mini-review: Assessing the drivers of ship biofouling management – aligning industry and biosecurity goals. *Biofouling* 32: 411–428, https://doi.org/10.1080/08927014.2016.1149572

Delauney L, Compere C, Lehaitre M (2010) Biofouling protection for marine environmental sensors. *Ocean Science* 6: 503–511, https://doi.org/10.5194/os-6-503-2010

Fernandes JA, Santos L, Vance T, Fileman T, Smith D, Bishop JDD, Viard F, Queiros AM, Merino G, Buisman E, Austen MC (2016) Costs and benefits to European shipping of ballast-water and hull-fouling treatment: impacts of native and non-indigenous species. *Marine Policy* 64: 148–155, https://doi.org/10.1016/j.marpol.2015.11.015

First MR, Policastro SA, Strom MJ, Riley SC, Robbins-Wamsley SH, Drake LA (2014) 3D imaging provides a high-resolution, volumetric approach for analyzing biofouling. *Biofouling* 30: 685–693, https://doi.org/10.1080/08927014.2014.904293

Fitridge I, Dempster T, Guenther J, de Nys R (2012) The impact and control of biofouling in marine aquaculture: a review. *Biofouling* 28: 649–669, https://doi.org/10.1080/08927014.2012.700478

Flemming H-C (2002) Biofouling in water systems—cases, causes and countermeasures. *Applied Microbiology and Biotechnology* 59: 629–640, https://doi.org/10.1007/s00253-002-1066-9

Floerl O, Coutts A (2011) Feasibility of using remotely-operated vehicles (ROVs) for vessel biofouling inspections. Report prepared for Western Australia Department of Fisheries, National Institute of Water & Atmospheric Research Ltd, 52 pp

Floerl O, Inglis GJ, Haydon B (2005) A risk-based predictive tool to prevent accidental introduction of non-indigenous marine species. *Environmental Management* 35: 765–778, https://doi.org/10.1007/s00267-004-0193-8

Floerl O, Wilkens S, Inglis G (2010) Development of a template for vessel hull inspections and assessment of biosecurity risks to the Kermadec and sub-Antarctic Islands regions. Prepared for the Department of Conservation, 110 pp

Georgiades E, Kluza D (2017) Evidence-based decision making to underpin the thresholds in New Zealand's CRMS: biofouling on vessels arriving to New Zealand. *Marine Science and Technology Journal* 51: 76–88, https://doi.org/10.4031/MTSJ.51.2.5

Georgiades E, Growcott A, Kluza D (2018) Technical guidance on biofouling management for vessels arriving to New Zealand. Ministry for Primary Industries, Wellington, ISBN No: 978-1-77665-793-3, 16 pp

Government of Western Australia (1995) Fish resources management regulations 1995. Perth: Government of Western Australia, Department of Fisheries, 331 pp

Government of Western Australia (2014) Biofouling biosecurity policy 5th May 2014. Perth: Government of Western Australia, Department of Fisheries, 8 pp

Government of Western Australia (2017a) Guidance Statement, Attachment 1. Criteria for suitably qualified invasive marine pest experts, Version 1.0 July 2017, 6 pp

Government of Western Australia (2017b) Guidance Statement, Attachment 2. Invasive marine species inspection report requirements, Version 1.0 July 2017, 6 pp

Government of Western Australia (2017c) Guidance Statement, Attachment 3. Best practice guidelines for invasive marine species inspections, Verson 1.0 July 2017, 5 pp

Haslbeck E, Oates E (2016) Biofouling remediation equals higher speed, lower drag. The Navy's Energy and Environmental Magazine, Currents spring 2016: 24–29

Idaho Code (2008) Idaho State Legislature. Title 22, Agriculture and Horticulture. Chapter 19, The Idaho Invasive Species Act of 2008: 1062–1067

IMO (2001) International convention on the control of harmful antifouling systems on ships. London: International Maritime Organization, 45 pp

IMO (2011) Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species. Marine Environment Protection Committee, International Maritime Organization, Annex 26, Resolution MEPC.207 (62), London, 25 pp

IMO (2012) Guidance for minimizing the transfer of invasive aquatic species as biofouling (hull fouling) for recreational craft. Marine Environment Protection Committee, International Maritime Organization, London, MEPC.1/Circ.792 Annex, 7 pp

Khalanski M (1997) Industrial and ecological consequences of the introduction of new species in continental aquatic ecosystems: The zebra mussel and other invasive species. *Bulletin Francais de la Peche et de la Pisiculture* 344: 385–404, https://doi.org/10.1051/kmae:1997037

Kim W, Tengra FK, Young Z, Shong J, Marchand N, Chan HK, Pangule RC, Parra M, Dordick JS, Plawsky JL, Collins CH (2013) Spaceflight promotes biofilm formation by *Pseudomonas aeruginosa*. *PLoS ONE* 8: e62437, https://doi.org/10.1371/journal.pone.0062437

Koenig DW (1997) Microbiology of the space shuttle water system. *Water Science and Technology* 35: 59–64, https://doi.org/10.2166/wst.1997.0710

Lewis JA (2016) Project 16214 Assessment of preventative biofouling management measures. MPI Technical Paper No. 2016/69. Report prepared for Biosecurity Science, Food Science and Risk Assessment Directorate, Ministry for Primary Industries, Wellington, 125 pp

McClay T, Zabin C, Davidson I, Young R (2015) Vessel biofouling prevention and management options report. Final report to the US Coast Guard, 55 pp

McKay CP (2009) Biologically reversible exploration. *Science* 323: 718 , https://doi.org/10.1126/science.1167987

Morrisey D, Inglis G, Tait L, Woods C, Lewis J, Georgiades E (2015) Procedures for evaluating in-water systems to remove or treat vessel biofouling. MPI Technical Paper No: 2015/39. Prepared for Ministry of Primary Industries, 103 pp

Nehring S (2001) After the TBT era: Alternative antifouling paints and their ecological risks. *Senckenbergiana Maritima* 31: 341–351, https://doi.org/10.1007/BF03043043

New Zealand Department of Conservation (2017) Regional Coastal Plan: Kermadec and Subantarctic Islands, Operative 15 September 2017, 156 pp

New Zealand Government (2014a) Craft risk management standard: biofouling on vessels arriving to New Zealand, Ministry of Primary Industries, Wellington, 9 pp

New Zealand Government (2014b) Guidance document: Craft risk management standard: biofouling on vessels arriving to New Zealand, Ministry of Primary Industries, Wellington, 31 pp

New Zealand Ministry for Primary Industries (2007) Requirements for vessel arriving in New Zealand, 16 pp

NACE International (2017) Pictorial standard for underwater evaluation of fouling degree on ship hulls. SP21421-2017. NACE International, National Association of Corrosion Engineers, Houston, Texas, USA, 20 pp.

Northern Territory Government (2016) https://nt.gov.au/marine/for-all-harbour-and-boat-users/hull-pest-inspections-for-visiting-boats (Accessed 03 Jan 2017)

Omae I (2003) Organotin antifouling paints and their alternatives. *Applied Organometallic Chemistry* 17: 81–105 https://doi.org/10.1002/aoc.396

Papahānoumakuākea Marine National Monument (2009) Marine Alien Species Inspection Standards for Maritime Vessels, Papahānoumakuākea Marine National Monument, National BMP-001, 2009, 1 p

Schultz MP, Bendick JA, Holm ER, Hertel WM (2011) Economic impact of biofouling on a naval surface ship. *Biofouling* 27: 87–98, https://doi.org/10.1080/08927014.2010.542809

Thomason JC (2010) Biofouling and shipping: data-mining the world's largest antifouling archive. In: Durr S, Thomason JC (eds), Biofouling, Blackwell, Oxford, pp 207–216

Townsin RL (2003) The ship hull biofouling penalty. *Biofouling* 19: 9–15, https://doi.org/10.1080/0892701031000088535

Thresher RE (1999) Diversity, impacts and options for managing invasive marine species in Australian waters. *Australian Journal of Environmental Management* 6: 137–148, https://doi.org/10.1080/14486563.1999.10648462

US Code of Federal Regulations (2004) US Fish and Wildlife Service, 18 CFR 42–43, 16 CFR 3371–3378 Lacey Act, Chapters 3 and 53, 42. Importation or shipment of injurious mammals, birds, fish (including mollusks and crustacea), amphibia, and reptiles, amended 2004, 11 pp

US Code of Federal Regulations (2012) US Coast Guard, 33 CFR, Chapter 1, Subchapter 0, Subpart D, Section 151.2050, Additional requirements – nonindigenous species reduction practices, pp 273–274

US Code of Federal Regulations (2014) Part II US Environmental Protection Agency, 40 CFR Parts 122 and 125. National Pollutant Discharge Elimination System – Final Regulations to Establish Requirements for Cooling Water Intake Structures at Existing Facilities and Amend Requirements at Phase I Facilities; Final Rule, Volume 79, No 158, August 15 2014, 141 pp

US Environmental Protection Agency (2013) Vessel General Permit for Discharges Incidental to the Operation of Vessels (VGP), Section 4.1.3, Final 2013. US Environmental Protection Agency, 194 pp

US Navy (2006) Naval Ships' Technical Manual, Chapter 081, Revision 5, Waterborne Underwater Hull Cleaning of Navy Ships 01 Oct 2006, 68 pp

Voskerician G, Shive MS, Shawgo RS, von Recum H, Anderson JM, Cima MJ, Langer R (2003) Biocompatibility and biofouling of MEMS drug delivery devices. *Biomaterials* 24: 1959–1967, https://doi.org/10.1016/S0142-9612(02)00565-3

Wells F, Booth G (2012) Setting a new benchmark in managing biofouling on vessels in a sensitive marine environment. Proceedings of the SPE/APPEA International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production. Perth, Australia, September 11–13 2012. Society of Petroleum Engineers, 11 pp, https://doi.org/10.2118/156749-MS

Woodside Energy Ltd (2007) Non-indigenous marine species management plan: Maxima 3D Marine Seismic Survey, Scott Reef, Perth, 56 pp

Zabin C, Davidson I, Ruiz G (2017) In-water vessel cleaning: current and emerging technologies, associated risks, and management options for Hawaii. Final report to the Hawaii State Department of Land and Natural Resources, Division of Aquatic Resources, 64 pp

Zapata Erazo C (2015) Procedimiento 07: Inspeccion de cascos de embarcaciones Manual de procedimientos para inspectores y technicos de la agencia de regulación y control de la bioseguridad y cuarentena para Galápagos, Agencia de Regulación y Control de la Bioseguridad y Cuarentena para Galápagos (ABG), Puerto Ayora, Santa Cruz, Islas Galápagos, Ecuador, pp 1–10

Zook W, Phillips S (2009) A survey of watercraft interception programs for Dreissenid mussels in the Western United States: results of an on-line survey completed in February 2009, produced for the Western Regional Panel of the National Aquatic Nuisance Species Task Force, Pacific Marine Fisheries Commission, 69 pp

Zook W, Phillips S (2012) Uniform minimum protocols and standards for watercraft interception programs for Dreissenid mussels in the Western United States (UMPS II): an updated version of the original 2009 document, Pacific Marine Fisheries Commission, 77 pp