Hull husbandry practices and biofouling management of vessels operating in California

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***Abstract*— Commercial shipping has been recognized as the primary vector for the introduction of nonindigenous species (NIS) into coastal environments in California, North America, and across the globe. These shipping-mediated introductions occur primarily through two mechanisms, ballast water and vessel biofouling (i.e. the attachment or association of organisms to a vessel's wetted surfaces). In California, vessel biofouling is believed to be responsible for up to 60% of the 257 nonindigenous species currently established in California's coastal waters. Most vessel operators manage the biofouling on their hulls because of the impact biofouling has on drag, fuel consumption, and operating costs. However, the biofouling associated with a vessel's remaining underwater surfaces, including the "niche areas" that are more susceptible to biofouling because of variable hydrodynamic flow or inadequate antifouling protection (e.g. bilge keels and sea chests), are often undermanaged or unmanaged and may pose a greater risk of species introduction. Biofouling management options vary depending on factors such as vessel type and speed. Because of this, there are many varied biofouling management strategies implemented across the global fleet of vessels. The patterns of these management schemes, along with patterns of voyage characteristics that influence biofouling accumulation, are important tools in assessing risk of species introduction. The California State Lands Commission's Marine Invasive Species Program has been collecting, on an annual basis, detailed information on these management strategies and voyage characteristics from every vessel operating in California since 2008. These data are currently being used to assess the risk of biofouling-mediated species introductions to California and to inform the development of mandatory management requirements to reduce NIS introduction risk to California.**

Keywords—nonindigenous species; invasive species; vector; biofouling; shipping; vessel

I. INTRODUCTION

Nonindigenous species (NIS) are organisms that are introduced, usually by anthropogenic means, to a geographic location where they do not naturally or historically occur. Once established, these NIS can negatively impact their receiving environments in several ways: ecologically through interactions such as competition and predation [1, 2], economically through infrastructure damage or reductions in fishery yields [3, 4], and through human health impacts such as cholera or swimmer's itch [5, 6].

In coastal environments, maritime shipping has been identified as the primary mechanism of introduction (vector), accounting for up to 81% of the established marine and estuarine NIS in California [7], 79.5 % in North America [8], and 74.1% globally [9]. Shipping-mediated species introductions are generally the result of either of two sub-vectors, ballast water and vessel biofouling. Ballast water is taken onboard a vessel for trim and stability purposes, typically as a result of the loading and unloading of cargo or navigating through rough seas. Ballast water is often taken up in one port and discharged in another, thereby transferring an entire community of organisms from the source water to the recipient water [10, 11]. Vessel biofouling, commonly referred to as hull fouling, refers to the attachment or association of organisms to the submerged or wetted surfaces of a vessel, including the hull and the many "niche areas" that are often more susceptible to biofouling accumulation (e.g. sea chests and propellers) due to poor antifouling protection or variable hydrodynamic flow [12]. Vessel biofouling includes organisms that physically attach to these surfaces (e.g. barnacles and mussels) as well as the mobile organisms (e.g. amphipods and crabs) that occupy the three-dimensional spaces created by the attached organisms. Globally, vessel biofouling has been recognized as the most potent individual vector for the introduction of coastal NIS, accounting for up to 42.6% of the currently established coastal NIS worldwide [9]. A similar pattern exists in California, where up to 60% of the currently established marine and estuarine NIS are a result of vessel biofouling [7].

Because of its external nature (i.e. on the outside of the vessel), there is a built-in incentive for vessel operators to minimize the amount of biofouling on a vessel's hull, although not for NIS management purposes. Biofouling on a vessel's hull causes an increase in hydrodynamic drag as the vessel moves through the water, and the amount of the increased drag correlates to the level of biofouling accumulation [13]. This increased drag ultimately results in a reduction in fuel efficiency, meaning a vessel will use more fuel and have higher operating costs with a fouled hull. Because of this biofouling-associated fuel penalty, most vessel owners and operators make it a priority to actively manage the biofouling on their hulls. Biofouling associated with a vessel's many niche areas, however, typically does not impact drag or fuel consumption. As a result, these niche areas are often unmanaged or undermanaged. Because of this drag-influencing dichotomy,

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many vessels sampled for biofouling over the past decade have had low to moderate levels of biofouling associated with their hulls, but elevated abundance, cover, and species diversity associated with their thrusters, bilge keels, rudders, sea chests, and other niche areas [14, 15].

Biofouling management generally falls into two main categories, proactive and reactive. Proactive management involves the use of coatings or other antifouling systems designed to minimize or prevent attachment or association of biofouling, primarily focusing on preventing initial biofouling settling and accumulation. Reactive management measures involve the killing, inactivation, or removal or organisms from vessel surfaces once they have already accumulated. Proactive management is generally more effective and efficient than reactive management; however, most effective biofouling management strategies incorporate both proactive and reactive management into a comprehensive management scheme.

Many of the options for managing biofouling are dependent on the type of vessel (e.g. tank vessel, container vessel) and its operational profile (e.g. traveling speed, port residency time). For example, some antifouling coatings are designed and marketed for vessels traveling at 18 knots, while other coatings may be designed for vessels traveling at 8 knots. Because of the wide variety of vessel types, sizes, routes, and operating profiles, there are many different combinations and styles of biofouling management strategies that are employed on vessels around the world.

In addition to biofouling management practices, a vessel's voyage characteristics can also influence biofouling accumulation. For example, the water flowing past a vessel traveling at slower speeds may not be strong enough to dislodge organisms that are weakly attached. As a result, slow speeds have been linked to increased organism abundance, species diversity, and percentage cover [16, 17]. Other factors affecting the likelihood of biofouling accumulation include, the amount of time a vessel remains stationary at port, lengthy idle periods at anchorage, and visits to tropical ports [18]. In contrast, some vessel activities may function to reduce the accumulation of biofouling on a vessel. For example, freshwater acts as a natural biocide to many marine biofouling organisms, and visiting a freshwater port or transiting through the freshwater Panama Canal can reduce the amount or diversity of organisms associated with a vessel [19, 20]. However, none of these biofouling risk factors occur in isolation, many of them interact with each other to influence biofouling extent on a vessel.

Current efforts to assess the biofouling-mediated risk of species introductions are reliant on sound understanding of the current biofouling management practices and biofouling-influencing voyage characteristics of the vessels that operate in a certain geographic location. Unfortunately, comprehensive assessments of these types of data have been lacking, and this has hampered the ability of resource managers to develop well-informed, science-based strategies for reducing invasion risk. In 2007, the California Legislature recognized the need to gather these types of data to inform the development of management strategies to minimize the biofouling-mediated introduction of NIS into California waters. In adopting California Assembly Bill 740 (Chapter 370, Statutes of 2007), the Legislature required the California State Lands Commission's Marine Invasive Species Program (MISP) to collect detailed information on the biofouling management practices being employed by the fleet arriving to California ports, as well as the voyage characteristics of these vessels in order to properly evaluate the potential risk of species introduction, and to develop a statewide policy to reduce this risk. This study describes the collection and analyses of data relating to the patterns of biofouling management and voyage characteristics from the vessels operating in California during 2008 through 2011, and discusses the many uses for these data and how they are being used to influence policies in California and across the globe.

II. Methods

In adopting Assembly Bill 740 in October 2007, the California Legislature directed the MISP to develop a reporting form to collect data on the biofouling management practices and biofouling-influencing voyage characteristics of the vessels operating in California. In consultation with a stakeholder advisory group, the MISP developed the Hull Husbandry Reporting Form (HHRF; see [21] for description) and adopted the form as a regulatory document to be submitted once per calendar year by each vessel 300 gross registered tons or larger, capable of carrying ballast water, operating within California.

The HHRF consists of eleven questions and is separated into two sections, one section addressing a vessel's hull husbandry practices (e.g. antifouling coating type and most recent dry docking) and the other addressing biofouling-related voyage characteristics (e.g. traveling speed and port residency time). The HHRF is collected annually from each of the approximately 1800 individual vessels operating in California each year, and the data are hand-entered into a purpose-built database. The data entry process is quality controlled to ensure accuracy.

Because these data are intended to be analyzed to better understand the management trends and voyage patterns of the fleet of vessels that operate in California, the data quality is dependent on the completeness of the dataset (i.e. the percentage of vessels submitting the HHRF as required). During 2008, the submission compliance rate for the entire state was 72.8% (Figure 1), but this has been improved upon over the following years through more extensive outreach efforts [21]. Overall, annual compliance rates during 2009-2011 have been at or above 90% (Figure 1).

III. Discussion

The data collected with the HHRF have served many purposes since collection began in 2008. The original intent of the reporting form was to collect data that would fill information gaps that have hindered a proper assessment of potential biofouling-mediated NIS introduction risk to California. Prior to 2008, California's inability to identify how biofouling was being managed across the entire fleet limited the state's ability to determine where the management gaps were, and how management could be improved. Without a

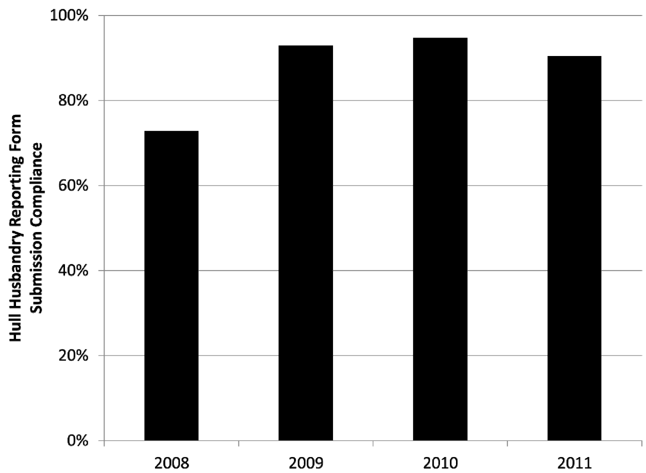

Fig. 1. Percent compliance with annual requirement for vessels to submit the Hull Husbandry Reporting Form to California's Marine Invasive Species Program.

suitable understanding of the biofouling-related voyage characteristics being employed by the vessels operating in California, there was no comprehensive way to evaluate the current risk from this vector. The HHRF data collected annually since 2008 now provide several snapshots of the biofouling management practices and voyage characteristics of the California fleet as a whole and across vessel types. These annual snapshots offer insight into the current level of biofouling management and potential NIS introduction risk. With each additional annual snapshot, the long-term trends become more apparent.

In addition to requiring the MISP to begin collecting biofouling management data via the HHRF in 2007, the California Legislature also included a requirement to use these data to inform the development of biofouling management regulations for vessels operating in California. The patterns associated with ongoing biofouling management have provided a platform for identifying where management can be improved, and areas where existing management practices are sufficient for minimizing the likelihood of successful NIS introduction. The HHRF data have also uncovered patterns associated with certain voyage characteristics that are prevalent enough to warrant more regulatory attention, and others that are relatively conserved across vessel types (e.g. faster traveling speeds of container vessels when compared to tank vessels). Over the past several years, MISP staff has been using these management and voyage patterns along with targeted biofouling research funded by the MISP to inform the development of biofouling management policies, in consultation with a stakeholder advisory group.

These data not only allow for an assessment of overall management trends and risk in order to inform the development of potential policies, but they also provide a mechanism for evaluating the per-vessel risk upon each vessel's arrival to California. By examining the management practices of a single vessel and coupling them with the vessel-specific voyage characteristics reported in the HHRF, MISP staff is able to prioritize boarding for inspection and outreach purposes to ensure compliance with management requirements. With limited available resources, the ability to target vessel inspections based on individual risk improves the effectiveness of the MISP in reducing overall NIS introduction risk to the state, especially because the approximately 1800 individual vessels that operate annually in California account for an average of 10,400 vessel arrivals per year (from 2004-2011; see [21]).

In addition to informing resource managers in California of the biofouling-mediated risk to the state, the HHRF data have also been used to assess management practices and potential species introduction risk to other states from vessels that operate between those states and California (e.g. vessels operating in California and Oregon). In an attempt to assist in filling information gaps in these other jurisdictions, MISP staff has provided HHRF data for the vessels that have operated in California and the state in question. For example, HHRF data associated with vessels operating in California and Oregon were provided to the Oregon Department of Environmental Quality for evaluation in a white paper created in 2011 to assess biofouling-mediated risk for the state of Oregon [22]. Similar data sharing has occurred to assist in risk assessments in Alaska [23] and Washington [24].

Overall, the data collected via the HHRF form the most comprehensive dataset of its kind in the world and will continue to inform the development and revision of statewide policies to reduce NIS introduction risk associated with vessel biofouling. As the annual collection of these data continues, new patterns of biofouling management and voyage trends are likely to emerge. Of particular interest to California's MISP are patterns associated with the recent global economic downturn and continuing rebound, particularly patterns of vessels experiencing long-term layups in certain parts of the world, as discussed by [25]. Continued data collection is also likely to identify how management practices may be changing in response to the changing regulatory environment. Specifically, how the implementation of the International Maritime Organization's recently adopted voluntary biofouling guidelines and the future implementation of California's biofouling management regulations influence management strategies. Future assessments of the changing management practices and voyage characteristics are likely to indicate how effective these new policies are at reducing the successful introduction of NIS to California and across the globe.

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