Geographic Limitations and Regional Differences in Ships' Ballast Water Management to Reduce Marine Invasions in the Contiguous United States

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Marine species are in constant motion in the ballast water and on the hulls of the ships that ply the world's oceans; ships serve as a major vector for biological invasions. Despite federal and state regulations that require ballast water exchange (BWE), particular trade routes impose geographic and temporal constraints on compliance, limiting whether a ship can conduct BWE at the required distance (≥200 nautical miles) from shore to minimize transfers of coastal organisms. Ships moving across the Americas are largely unable to conduct open-ocean BWE, but instead often conduct exchanges inside coastal waters. Overall, strong differences exist in volumes, geographic sources, and the use of BWE for ballast water discharge among the three major coasts of the contiguous United States. Such patterns suggest important geographic differences in invasion opportunities and also argue for more effective alternative ballast water treatments that can be applied more evenly.

Keywords: ballast water, shipping, nonnative species, marine invasions, propagule supply

Commercial shipping is the primary means by which goods are moved across the globe, and ships connect ports and coastal systems from all corners of the planet in a complex network (Drake JM and Lodge 2004, Kaluza et al. 2010). Shipping is also widely recognized as a dominant invasion pathway by which nonnative species are introduced to marine ecosystems around the world (Carlton and Geller 1993, Fofonoff et al. 2003, Hewitt et al. 2009). Either by ballast water transport and discharge or the biofouling of ships' hulls and interstices, a diverse biota, ranging from macrofauna to bacteria and viruses, is in constant motion (Ruiz et al. 2000, Drake LA et al. 2002).

A key factor in the successful establishment and spread of nonnative species is propagule pressure (NRC 2011). The probability of invasion (establishment) is strongly influenced by the frequency, magnitude, and quality of nonnative propagules (viable organisms) delivered, including organisms at various life stages, such as larvae, juveniles, adults, eggs, cysts, and those in resting stages (Lonsdale 1999, Endresen et al. 2004, Miller et al. 2007, Johnston et al. 2009, Miller and Ruiz 2009). In general, the likelihood of invasion will increase with an increasing propagule supply (see NRC 2011 for a review). However, even when controlling for propagule supply, invasion probability is expected to exhibit considerable variation among species, source and recipient environments, routes, time periods, and a multitude of other factors (Smith et al. 1999, Ruiz et al. 2000, NRC 2011).

Understanding the spatial patterns of propagule supply associated with ships' ballast water is especially challenging, because vessels have a global reach and do not operate evenly across geographic locations, as has been illustrated by previous studies (Carlton et al. 1995, Smith et al. 1999). Ships inadvertently entrain coastal marine communities and disperse propagules differentially from their ballast water. *Ballast water* is water, including the associated biota and sediments, that is pumped or gravitated into the ballast tanks or cargo holds of ships to stabilize them and to provide proper trim when the vessel is partially loaded or empty of cargo. Ballasting and deballasting is especially necessary as ships load and offload cargo in port to compensate for changes in weight distribution, but ballast operations also occur in

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reaction to weather, sea state, and navigation requirements (NRC 1996).

To simply estimate the cumulative ballast water volume delivered to a port or geographic region, it is not sufficient to know the frequency of ship arrivals, because not all vessels discharge ballast and because significant variation exists in discharge volumes among vessel types (e.g., container ships, bulk carriers, tankers, and passenger vessels) and geographic locations (Verling et al. 2005, Falkner et al. 2009). Although ballast water flux estimates have improved greatly in recent years (see the next section), this variable alone is unlikely to be a good proxy for propagule supply, because the diversity, density, and quality of the organisms varies greatly among vessels (NRC 2011).

In the early 1990s, open-ocean ballast water exchange (BWE) was introduced to reduce transfers of viable biota and ballast-mediated invasions (NRC 1996). For the United States, BWE was first implemented in the Great Lakes and became mandatory throughout the country only in 2004; it was focused on vessel arrivals from outside of the United States and Canada. This study presents the most comprehensive nationwide analysis of ballast water delivery to date and the first since BWE became mandatory.

Despite the lack of quantitative estimates of ballast water propagule supply delivered to most regions, because of insufficient biological sampling and high uncertainty among vessels (NRC 2011), a dramatic shift has occurred in the nature of ballast water discharged in the United States. Since 2004, vessels arriving to US waters from outside of (the United States and Canada) have been required to treat their ballast water before discharge. At present, by far the most widely implemented treatment used in the United States is open-ocean BWE (box 1).

BWE can have variable performance, but experimental studies suggest that it may routinely remove 88%–99% of the original water and its associated coastal organisms (Ruiz and Reid 2007, Bailey et al. 2011). Therefore, widespread implementation of BWE across the United States represents a substantial reduction in propagule pressure relative to unmanaged or untreated ballast water.

To date, there has not been a national-scale analysis to evaluate the extent of BWE or gaps in its implementation. Using extensive and detailed data on ballast water delivery and management, we provide a comprehensive synthesis of overseas ballast water flux to the contiguous United States following promulgation of federal ballast water management regulations, specifically, between 1 January 2005 and 31 December 2007. We further evaluate striking geographic differences in ballast water-delivery and management patterns across the contiguous United States and discuss implications for the current strategies and policies to reduce the likelihood of invasion.

Quantification of ships' ballast water management and discharge

Since July 1999, the National Ballast Information Clearinghouse (NBIC) and the US Coast Guard have implemented and operated a nationwide program to measure ballast water management and delivery patterns of commercial vessels that arrive to the United States from outside the US or Canadian exclusive economic zone (EEZ). As directed by US federal regulation, all vessels equipped with ballast water tanks and bound for ports or places in the United States are required to submit the Ballast Water Reporting Form to the NBIC 24 hours in advance of arrival to a US port or place of destination (USDHS 2010). There are two classifications of arrivals to the United States: *overseas arrivals* (i.e., vessels that transited outside the US or Canadian EEZ prior to arriving at a US port) and *coastwise arrivals* (those that have not transited outside these EEZs prior to arriving at a US port). In July 2004, expanded ballast water management requirements mandated overseas arrivals to implement at least one of the following ballast water-management practices: (a) Perform complete open-ocean BWE on all tanks containing ballast water before the tanks are discharged into US waters. (b) Retain ballast water onboard the vessel while in US waters. (c) Prior to the vessel's entering US waters, use an alternative, environmentally sound, ballast water treatment method that has been approved by the US Coast Guard.

Currently, no alternative methods of ballast water treatment have been officially approved by the US Coast Guard, so ballast water management for overseas arrivals to the East, Gulf, and West Coasts consists of either open-ocean exchange or ballast water retention (USDHS 2010). Nevertheless, if a vessel operator deems open-ocean exchange too

Box 1. Ballast water operations and open-ocean exchange.

Open-ocean *ballast water exchange* (BWE) is the replacement of port or coastal ballast water, and the biota that it contains, with open-ocean water, which may contain pelagic organisms. The goal of BWE is to reduce the number of viable coastal organisms moved directly among coastal systems. Ideally, when BWE is conducted properly (≥200 nautical miles from any landmass), only pelagic water and its associated biota are discharged in ports, which creates a habitat mismatch (especially as it relates to salinity, temperature, and other water-quality measures), which is meant to minimize the probability of an incursion by nonnative species. Ships replace coastal water either by emptying the tank at sea and refilling it (the *empty–refill* method) or by pumping open-ocean water into the bottom of the tank while allowing the port water to overflow at the top (the *flow-through* method). Both methods can be carried out while the ship is underway, but in some cases, the process can take a day or more to complete.

dangerous because of weather or sea conditions, mandatory exchange is exempted (only 1.4%, 1.6%, and 1.6% of overseas arrivals to the East, Gulf, and West Coasts, respectively, reported safety as a reason for not conducting BWE during the 2005–2007 period). Likewise, ships are not required to significantly deviate or delay from a scheduled route to perform open-ocean exchange and may receive permission directly from the US Coast Guard to discharge the minimum volume of unexchanged ballast water necessary to perform operations (the number of such cases was not available for this analysis).

Although coastwise arrivals (i.e., transits that remain inside the US and Canadian EEZs) are also required to report their ballast activities, our analyses were restricted to overseas arrivals. The mean annual overseas reporting compliance rate across the three coasts for this time period was estimated to be 81.5% (with a standard error of 0.84%) when the number of qualifying Ballast Water Reporting Forms reported to the NBIC was compared with the corresponding, but independent and mandatory, Electronic Notices of Arrival reported to the US Coast Guard's National Vessel Movement Center (*https://enoad.nvmc.uscg.gov*). *Coasts* were defined as the regions encompassing the ports and places of destination for overseas arrivals in the following way: The East Coast was defined as the area from the Maine–New Brunswick border to Cape Canaveral, Florida; the Gulf of Mexico was defined as all ports south of Cape Canaveral to Brownsville, Texas; and the West Coast was defined as the area between San Diego, California, to the Washington–British Columbia border. The East and Gulf Coast definitions include Cape Canaveral as the biogeographic break point (Barry et al. 2008). Arrivals to Alaska, Hawaii or Guam, and US protectorates in the Caribbean, as well as arrivals to the Great Lakes and other inland waterways, were excluded from the present analyses.

The Ballast Water Reporting Forms yield information on ship identity, ship type, gross tonnage, ballast water capacity, and total amount of ballast water onboard. In addition, they contain route information including the arrival port, the last port of call, and the next port of call. The Ballast Water Reporting Forms also include the geographic source locations of ballast water; the ballast water volumes and dates; and the corresponding locations, volumes, and dates of discharge for all ballast water dispersed to the United States. If BWE was conducted, the geographic end point of the exchange is required. Although the Ballast Water Reporting Forms consist of self-reported data, they are but one part of the US Coast Guard's required documentation and are subject to inspection and enforcement action. Using these data, all overseas ship arrivals were categorized as *dishcargers* (those that discharged their ballast water) or *nondischargers* (those that had not). The dischargers were further subdivided by management status into *dischargers with no exchange* (those that did not conduct BWE or any other approved alternative treatment) and *discharges with exchange* (those that did conduct BWE). The nondischargers were grouped as vessels that had ballast water onboard and vessels that reported no ballast water onboard. The dischargers with exchange were divided on of the basis of whether the ballast water exchange took place at least 200 nautical miles (NM) from a landmass (open-ocean exchange), as is required by federal regulation, or less than 200 NM from a landmass (coastal exchange).

The data were queried from the National Ballast Information Clearinghouse database (*http://invasions.si.edu/nbic*). Map layers were created in ArcGis (Esri, Redlands, California). Our statistical analyses were performed using SAS (SAS Institute Inc., Cary, North Carolina).

Ship arrivals and ballast water delivery volumes by port

A disparity was evident between the frequency of ship arrivals and the volumes of ballast water discharged when individual ports of the United States were compared (figure 1a, 1b). When examined at the port level, the locations of frequent arrival were not necessarily the locations that received the most ballast water discharge. For example, Miami and Port Everglades, Florida; New York; and Los Angeles and Long Beach, California, were among the busiest ports, as measured by arrival frequency, but they received far less ballast water discharge than many other ports with fewer arrivals. In contrast, several ports in the Pacific Northwest region (e.g., Portland and Kalama, Oregon; Tacoma and Seattle, Washington) received larger volumes of ballast water discharge than would be expected on of the basis of arrival frequency. On the Gulf Coast, arrival frequency and ballast discharge tended to be more closely correlated than elsewhere (figure 1). Although there was a positive correlation between the number of overseas arrivals and the volume of overseas discharge among ports, this often explains little variation, and the relationships are uneven among the coasts, and therefore, the number of ship arrivals is generally not a good predictor of the amount of ballast discharge (figure 1).

Ship arrivals and ballast water delivery volumes by coast

During the three-year period between 1 January 2005 and 31 December 2007, the NBIC received reports from 104,787 overseas arrivals to destinations on the East (45.3%), Gulf (33.4%), and West (21.2%) Coasts. The national average annual percentage of ships reporting ballast water discharge was 23.9% (with a standard error of 2.0%); however, the percentages varied among the coasts. The overwhelming majority of overseas arrivals to these coasts reported no ballast water discharge; they either retained their ballast water or were not carrying ballast upon arrival (table 1).

On an annual basis, the mean number of arrivals discharging unexchanged ballast water differed significantly among coasts, but the number of arrivals discharging only exchanged ballast water was not significantly different (figure 2a). On the Gulf and West Coasts, the number of arrivals

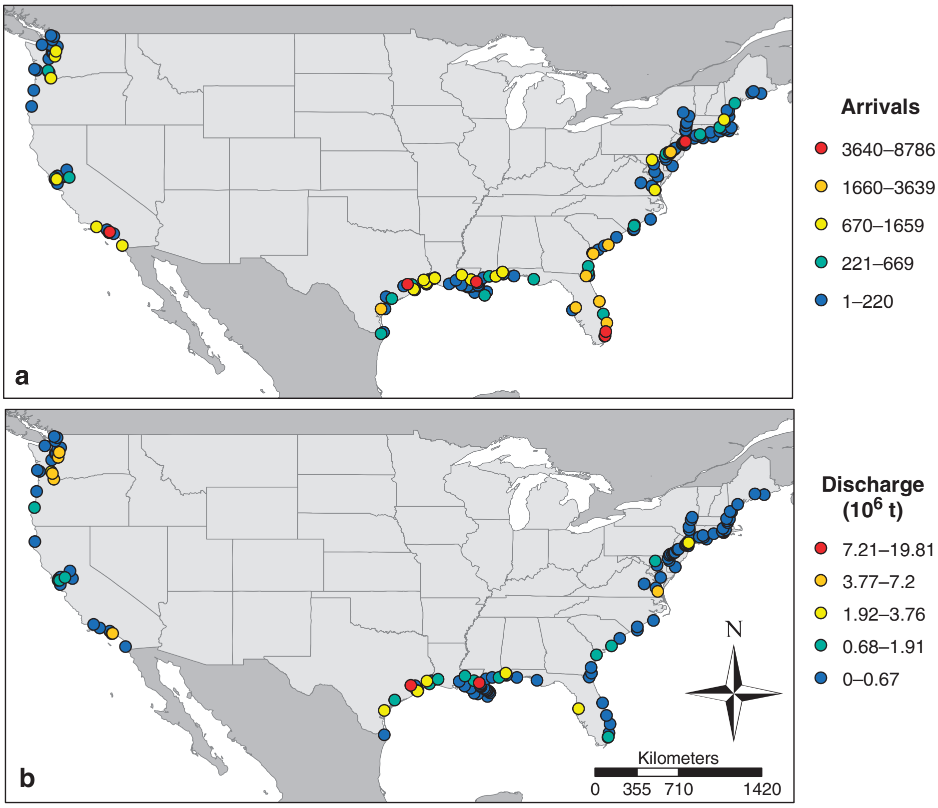

Figure 1. (a) Total number and locations of overseas arrivals. (b) Overseas ballast water discharge volumes (10^6 metric tons [t]) and locations on the East, West, and Gulf Coasts of the United States reported to the National Ballast Information Clearinghouse from 1 January 2005 to 31 December 2007. The correlation between log(number of arrivals + 0.1) and log(amount of discharge + 0.1) for ports on each coast were as follows: East Coast, $r^2 = .148$, n = 99; Gulf Coast, $r^2 = .814$, n = 61; West Coast, $r^2 = .345$, n = 46.

Table 1. Mean annual percentage and standard errors of arrivals according to the vessels' reported ballast water discharge status and total overseas arrivals to the East, Gulf, and West Coasts from 1 January 2005 to 31 December 2007.

	No ballast on board		Retained ballast water		Discharged ballast water		
Coast	Mean annual percentage	Standard error	Mean annual percentage	Standard error	Mean annual percentage	Standard error	Total number
East	16.0	0.7	62.1	3.1	21.8	0.9	47,486
Gulf	27.9	0.6	43.5	0.7	28.6	3.3	35,044
West	9.1	0.4	70.0	1.4	20.8	0.4	22,257
Total	18.6	0.1	57.6	0.2	23.9	2.0	104,787

discharging only exchanged ballast water was significantly higher than that of arrivals discharging unexchanged ballast water; in contrast with the East Coast, where there was no clear difference between the frequencies of dischargers by discharge type (figure 2a).

When ballast water discharge volumes were compared among coasts, the Gulf Coast received the greatest reported ballast water discharge (58.8×10^6 metric tons [t]) between January 2005 and December 2007, regardless of their management status. During this same period, the West Coast received 44.5×10^6 t, and the East coast received 22.2×10^6 t of discharge. Only 4.7% of overseas ballast water was discharged without exchange on the West Coast (2.1×10^6 t) compared with 23.0% on the East Coast (5.1×10^6 t) and 21.0% on the Gulf Coast (12.3×10^6 t). When annual ballast water discharge volumes were compared statistically, all three coasts were shown to have received more exchanged than unexchanged ballast water, but the proportion of unexchanged to exchanged volumes on the West Coast was less than that on the Gulf or East Coast (figure 2b).

Geographic sources of ballast water

When global sources of ballast water were mapped for each of the three US coasts, the delivery patterns differed markedly. The spatial patterns of ballast water source and delivery indicated that although all three coasts received some ballast water from nearly every corner of the globe, the major sources differed strongly among the coasts (figure 3a–3c). The East Coast received its greatest volumes of ballast water from northwestern Europe, the Mediterranean region, the Caribbean, and Central and South America (primarily Venezuela), as well as the Far East (China, Japan, and the Korean peninsula) (figure 3a). The Gulf Coast received the majority of its ballast water from Mexico, Central and South America (Venezuela and Colombia), the Caribbean, northwestern Europe, and to a lesser extent, the Mediterranean region, with little from Asia (figure 3b). The West Coast received the overwhelming majority of its ballast water from Asia, with lesser amounts from Mexico, Central America, and the Hawaiian Islands, and nearly none from northwestern Europe, the Mediterranean region, South America, or the Caribbean (figure 3c).

Shipping routes and patterns of ballast water exchange

Overseas arrivals to the United States can be divided into two major categories on the basis of whether their direction of transit is primarily along the east–west axis, categorized

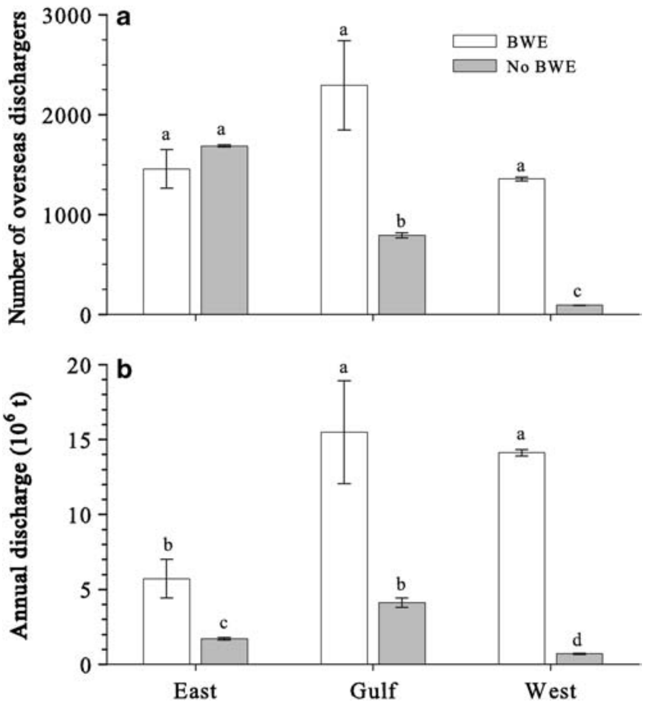

Figure 2. (a) Mean annual number of overseas arrivals discharging ballast water and (b) the mean annual discharge as a function of the management status (i.e., ballast water exchange [BWE] or no BWE), to the three US coasts reported to the National Ballast Information Clearinghouse from 1 January 2005 to 31 December 2007. There were significant differences in the numbers of arrivals discharging exchanged and unexchanged ballast water, but these were dependent on the coast ($F(2,12) = 96.11$, $p < .001$). Discharge volume as a function of management status was dependent on the coast, and there was a significant difference among the coasts ($F(2,12) = 28.45$, $p < .001$). Significant differences (at $\alpha = .05$) based on Tukey's pairwise comparisons of arrivals and discharge volume (log transformed) are denoted by letters. The error bars represent the standard error. Abbreviation: t, metric tons.

here as *transoceanic* arrivals, or along the north–south axis, as *Pan-American* arrivals. Clearly, these categories reflect general differences in trade routes; they also roughly divide the ship transits according to the length of the voyage and the maximum distances from landmasses. For example, transoceanic voyages from Asia to the West Coast or from the Mediterranean to the East Coast usually have ample time and achieve sufficient distance from landmasses to complete open-ocean BWE. In contrast, many ships transiting from Mexico, Central and South America, or parts of the Caribbean neither have sufficient time nor can achieve sufficient distance (i.e., ≥200 NM from shore) to perform open-ocean BWE.

When we considered only exchanged ballast water, there were strong differences in the location of BWE between the two transit types. For the transoceanic transits, 91% of ballast water by volume underwent BWE in waters at least 200 NM from land. Conversely, only 24% of ballast water discharged by the Pan-American transit vessels was exchanged at least 200 NM from land. All other exchanged discharge volumes were exchanged in coastal waters (figure 4a, 4b). Therefore, the amount of improperly managed ballast water (i.e., coastal BWE) was much more extensive for the Pan-American than for the transoceanic transits.

When the total (exchanged + unexchanged) ballast water discharge volumes from the transoceanic and Pan-American voyages were compared, the proportions and volumes of discharged water that either underwent no exchange or underwent coastal BWE were markedly higher for the Pan-American transits (figure 5). For the Pan-American transits, 29.7% of the total volume was unexchanged and 53.5% underwent improper coastal BWE, whereas only 6.9% of the total transoceanic discharge volume was unexchanged, and 8.3% underwent coastal BWE. These differences were most pronounced for the Gulf Coast, where the total volume of unexchanged or improperly exchanged ballast water discharge from the Pan-American transits exceeded the volume of discharge from the transoceanic arrivals, the majority of which underwent open-ocean BWE (figure 5).

Although ship-mediated invasions depend on vessel arrivals, the number of arrivals to a region is not, by itself, a good predictor of ballast water delivery or invasion opportunity, because not all arriving ships discharge ballast water. Other investigators have previously shown that the number of ship arrivals is not a good proxy for ballast water discharge, and, furthermore, that the volume of ballast water is not necessarily a good predictor of ballast water-mediated invasion because of the complex nature of the invasions (e.g., Carlton et al. 1995, Smith et al. 1999, NRC 2011).

Despite federal and state ballast water management regulations, significant amounts of ballast water are still being dispersed to US coastal systems without management and without proper treatment. It is clear that open-ocean BWE was applied much more extensively, both volumetrically and proportionally, on the West Coast than on either the East or the Gulf Coast. Therefore, whatever the protective effects of open-ocean BWE are, they were conferred differentially across the coasts.

For discharging vessels, the opportunity for proper BWE (i.e., ≥200 NM from any landmass) is clearly dependent on the relative positions of ballast water sources and discharge locations. Our results demonstrate that the proper application of open-ocean BWE is directly dependent on voyage type—that is, whether ships move across longitudes (transoceanic transits) or across latitudes (Pan-American transits)—and that the volumes of improperly and unexchanged ballast water delivered to the West and East Coasts were approximately equal and relatively small in volume (about 1–1.5 million t per year) for each voyage type but that coastally exchanged and unexchanged ballast water delivered to the Gulf Coast by Pan-American arrivals (about 10.6 million t per year) far exceeded the volume discharged

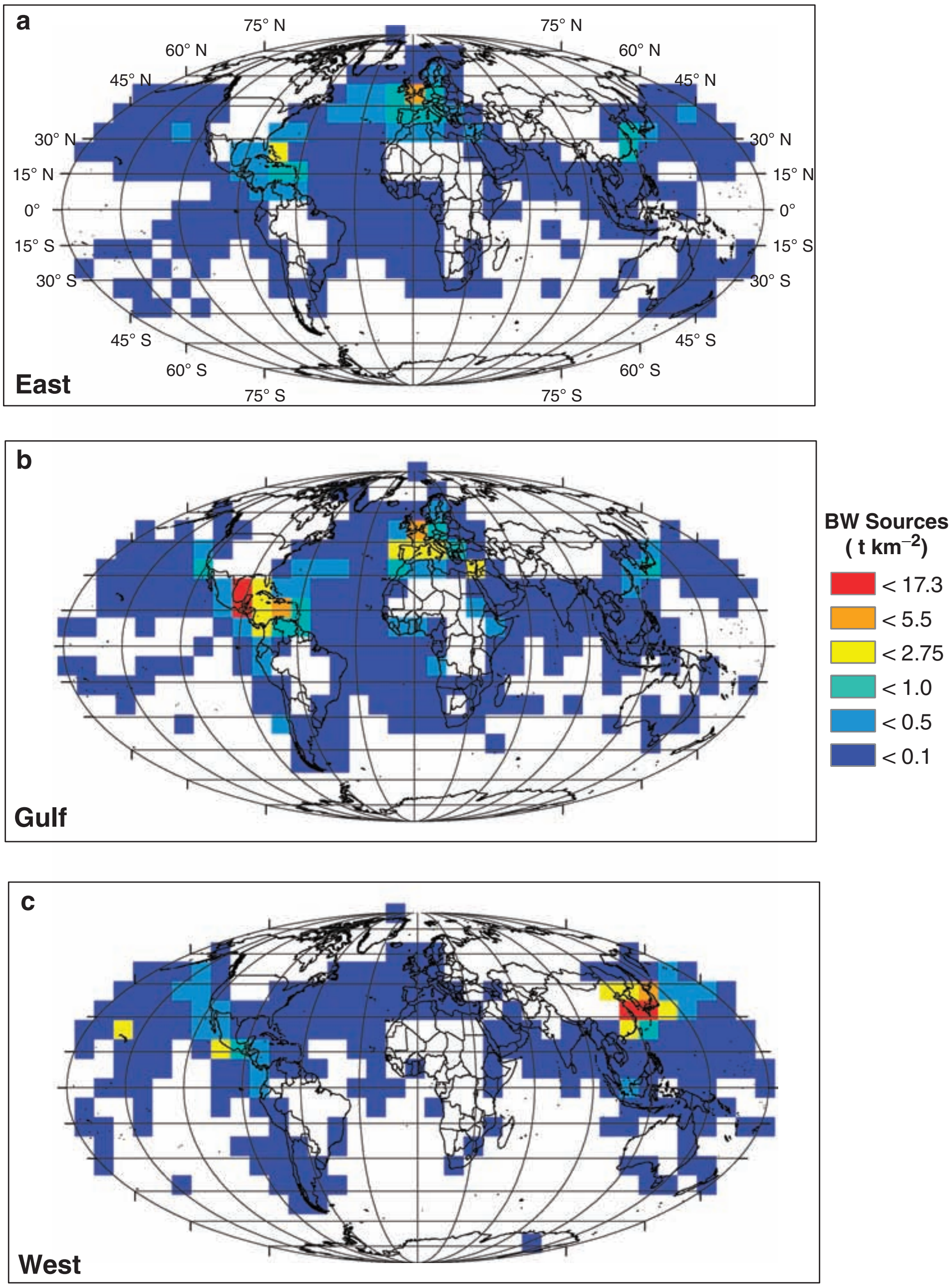

Figure 3. Global distributions of original sources prior to any type of ballast water exchange (BWE) and relative volumes of overseas ballast water discharged in the United States, reported to the National Ballast Information Clearinghouse from 1 January 2005 to 31 December 2007. (a) East Coast, (b) Gulf Coast, and (c) West Coast. Abbreviation: t km^{-2}, metric tons per square kilometer.

by transoceanic voyages. Open-ocean BWE was extensive among the transoceanic transits to all three coasts; however, the extent of coastal BWE that was conducted in lieu of open-ocean BWE, especially by Pan-American-transit vessels, was great. This pattern highlights the geographic constraints of open-ocean BWE as a comprehensive treatment for reducing the introduction of viable coastal biota to US waters.

Although open-ocean BWE has been tested experimentally and shown to reduce the densities of coastal biota substantially (e.g., Ruiz and Reid 2007, Bailey et al. 2011), there is little or no experimental data on the influence of coastal BWE on the density and viability of discharged organisms. It is probably reasonable to assume that coastal BWE is sometimes less effective than open-ocean BWE, but how the efficacy changes with the distance from shore has not been characterized. The distribution of coastal biota will no doubt vary, depending on physical and chemical oceanographic characteristics (e.g., prevailing currents or the presence of a coastal shelf). Therefore, coastal exchanges may actually reduce the number of coastal organisms transferred, thereby reducing the propagule supply at discharge, but regardless of density reductions, a replenishment of ballast tanks with “fresh” coastal organisms may enhance the physiological condition and survival of the biota that are ultimately discharged. Clearly, in many instances, open-ocean BWE will be impossible without significant course deviation or delay, so if BWE remains a mandated method of ballast water management, further investigations that characterize the effectiveness of coastal exchange for reducing the transfers and inoculations of viable coastal biota will be required to more fully understand the effectiveness of BWE as a treatment method for reducing coastal invasions.

Conclusions

The magnitude and geographic diversity of ballast water delivery reflects the opportunity for species transfers (invasion opportunities), but they cannot be used to estimate the likelihood of invasion, because invasion depends greatly on the characteristics of the biota and environmental matching, and on inoculation dynamics. Only with extensive and detailed in-tank plankton-concentration measures can ballast water–mediated propagule introductions be truly quantified. Furthermore, only when ballast water tank analyses are coupled

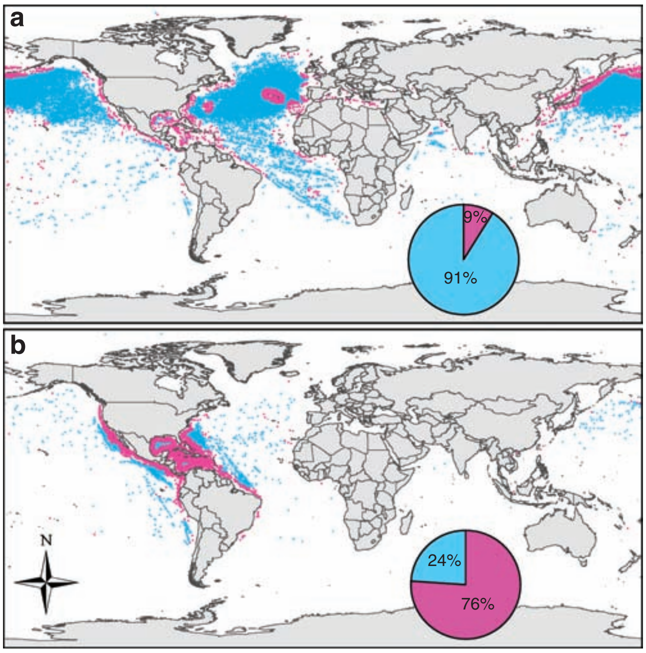

Figure 4. Reported endpoint locations of ballast water exchange (BWE) for ballast water from (a) transoceanic and (b) Pan-American sources. Open-ocean BWE, located at least 200 nautical miles (NM) from shore are depicted in cyan, and coastal BWE, those less than 200 NM from shore, are depicted in magenta. The pie charts indicate the corresponding BWE volumes as a function of type (open-ocean vs. coastal BWE). The data were reported to the National Ballast Information Clearinghouse from 1 January 2005 to 31 December 2007.

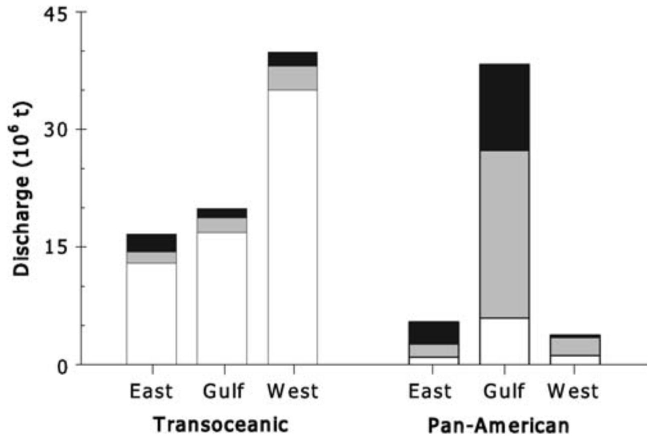

Figure 5. Overseas ballast water discharge volumes delivered to the East, Gulf, and West Coasts of the United States by transoceanic and Pan-American transits (reported to the National Ballast Information Clearinghouse from 1 January 2005 to 31 December 2007). Ballast water that underwent open-ocean ballast water exchange (BWE; white), coastal BWE (gray), or no BWE (black) are illustrated. Abbreviation: t, metric tons.

with corresponding field-based monitoring can invasion risk be accurately estimated. In the absence of such biological data, the direct quantification of ballast water flux and diversity simply provides a picture of differential opportunity for ballast-mediated introductions among regions of the coastal United States. The observed patterns indicate that the likelihood and nature of species transfers to US coasts differ substantially among those coasts. The differences are attributable to unique trade patterns and markets, the relative locations of ballast water sources, and perhaps most importantly, the behavior of ships in terms of the extent and location of BWE.

The inability of many vessels to fully conduct BWE in the open ocean is a significant shortcoming of BWE as a ubiquitous prevention measure for reducing the introduction of nonnative species. Geographic and temporal constraints reduce the opportunity and ability of many commercial vessels to impose maximum protection against invasive species. On the basis of ballast water volume alone, Pan-American voyages appear to undermine the potential for BWE to minimize invasive species transfers to the United States, especially along the Gulf of Mexico coast, because the majority of ballast water discharged is either unmanaged or has been exchanged in coastal waters.

To address untreated ballast water discharges to the United States, the development of alternative onboard ballast water–treatment systems is now urgently needed. Properly designed onboard treatment systems will minimize the introduction of viable organisms outside their native ranges and will enable vessels to operate worldwide without fear of unintended environmental consequences (but see Minton et al. 2005). In recent years, the International Maritime Organization (IMO 2004) and, more recently, the US Coast Guard (USDHS 2009) have proposed global discharge standards that define the maximum allowable concentration of viable biota that may be discharged in ballast water. Although such standards have yet to be fully adopted, they have motivated the development and testing of potential alternative treatment technologies (Dobroski et al. 2009, Lloyd's Register 2010). The development and proper use of onboard ballast water treatment technologies represent essential steps toward greater environmental protection the world over.

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