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# Biological Invasions in Coastal Marine Ecosystems: How Changes in Trade Are Linked to Ballast Water Delivery of Nonindigenous Species

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Biological Invasions in Coastal Marine Ecosystems:

How Changes in Trade Are Linked to Ballast Water Delivery of Nonindigenous Species

by

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Abstract

Globalization has escalated transfers of nonindigenous species (NIS) across natural dispersal barriers. The resulting biological invasions have become a leading global mechanism of ecological change. NIS are often transported between coastal marine ecosystems in the ballast water of commercial ships, and patterns of NIS introduction and establishment can be linked to global trade dynamics. Here I examined drivers of trade and ballast water across spatial and temporal extents of invasion. The analyses incorporated a variety of datasets on trade, industries, and ship behavior to identify fluctuations in globally transported commodities that lead to changes in maritime shipping patterns and frequency. Importantly, I estimated quantitative relationships between trade exports and ballast water imports. Changes in the number and proportion of vessel arrivals that discharged ballast water, and the frequency of discharge, drove fluxes in ballast water volume. In San Francisco Bay, California, the annual tonnage of the top 11 export commodities by vessel type predicted total bay-wide overseas ballast water discharge ($R^2$ = 0.92), largely driven by exports of dry bulk goods to Asia and petroleum to western Central America. Across the West, Gulf, and East Coasts of the United States, a four-fold increase in exports of petroleum, coal, and liquefied natural gas explained a more than three-fold increase in ballast water delivery by vessel type ($R^2$ = 0.97), linking the coastal US with trade partners in Asia, Europe, and North and South America. In coastal Alaska, the annual number of tank and bulk vessels that discharged ballast water predicted annual statewide ballast water volume by each vessel type ($R^2$ = 0.70, $R^2$ = 0.94, respectively), driven by oil exports to the US West Coast and mining and timber exports to Asia. These relationships clarify the influence of trade on ballast water and invasion dynamics to support hindcasts and forecasts of NIS introductions. Additionally, I created an adaptable risk-based screening protocol of ballast water delivery. An application of this tool to a dataset of vessel arrivals on the Oregon coast and lower Columbia River identified high priority vessels for inspection within the range of resources available to managers. This study as a whole is a step forward in understanding invasion patterns, NIS risk to coastal ecosystems, and the sustainability of current drivers of global maritime shipping.

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# Introduction

Biological invasions by nonindigenous species (NIS) result from the movement of organisms beyond natural dispersal limits. Species are limited in their natural dispersal by physical and biological barriers, e.g., land masses, oceans, competition from other species (Vermeij 1991). Humans have overcome geographic barriers and introduced species into novel environments across space and time (Ojaveer et al. 2018). The rate and scale of NIS introductions seen in modern times has become possible with the advent of human transportation systems and networks, vastly increasing the abundance, density, and variety of species transferred around the globe (Hulme 2009). Moreover, humans facilitate invasions by altering the environment and reducing biological barriers. For example, development and infrastructure cause disturbance, alter native species population levels, and appear to facilitate NIS invasions (Dafforn 2017; Padilla and Williams 2004).

The patterns, processes, and ecological impacts of biological invasions have been increasingly studied in the past 60 years since the publication of Charles Elton's book *The ecology of invasions by animals and plants* in 1958 (Richardson 2011). In the process of a successful invasion, NIS must pass through stages of transport, introduction, establishment, and spread, facing barriers at each step (Blackburn et al. 2011). Predicting invasion success remains a difficult task since it depends on a combination of species-specific attributes and characteristics of the recipient environment (Papacostas et al. 2017; Catford et al. 2011), though some patterns have emerged. Native species richness and functional diversity are thought to increase resistance to invasion on small scales

(Stachowicz 1999), cross-latitudinal studies indicate that biotic resistance decreases from tropical to temperate zones while abiotic pressures increase (Freestone et al. 2013), and time since introduction is a strong predictor of NIS range size (Byers et al. 2015).

Successful biological invasions are a leading cause of ecological change on a global scale (Pyšek and Richardson 2010). NIS impacts have been documented across biomes, including terrestrial agriculture (Paini et al. 2016) and forests (McKenzie et al. 2005), freshwater aquatic ecosystems (Gallardo et al. 2016), and the marine environment (Molnar et al. 2008). Invasions can cause direct biotic impacts by reducing the abundance of native species through competition and predation, ultimately affecting the functionality of food webs (Gallardo et al. 2016). Indirect effects on native species genetics are possible with hybridization and introgression with NIS (Mooney and Cleland 2001). With time, invasive species can modify habitat structure and disturbance regimes, as well as other abiotic characteristics of the introduced environment (Strayer et al. 2006). Ecosystem services to society can be negatively altered, such as food provisioning, water quality, shoreline protection, and tourism (Katsanevakis et al. 2014).

Globalization has led to increasing NIS transfers by a variety of pathways and vectors, resulting in rising impacts and damages (Hulme 2009; Chapman et al. 2017). Recent total annual costs from invasive species have been estimated at $120 billion in the United States (Pimentel et al. 2005), £1.7 billion in Great Britain (Williams et al. 2010), and $13.6 billion in Australia (Hoffmann and Broadhurst 2016). Growing ecological, economic, and social costs of biological invasions have garnered international attention and calls for prevention, control, and research (Pagad et al. 2015). As a result, comprehensive approaches to biosecurity and NIS management have been developed across ecosystems and pathways (Meyerson and Reaser 2002; Jarrad et al. 2011) (Figure 1).

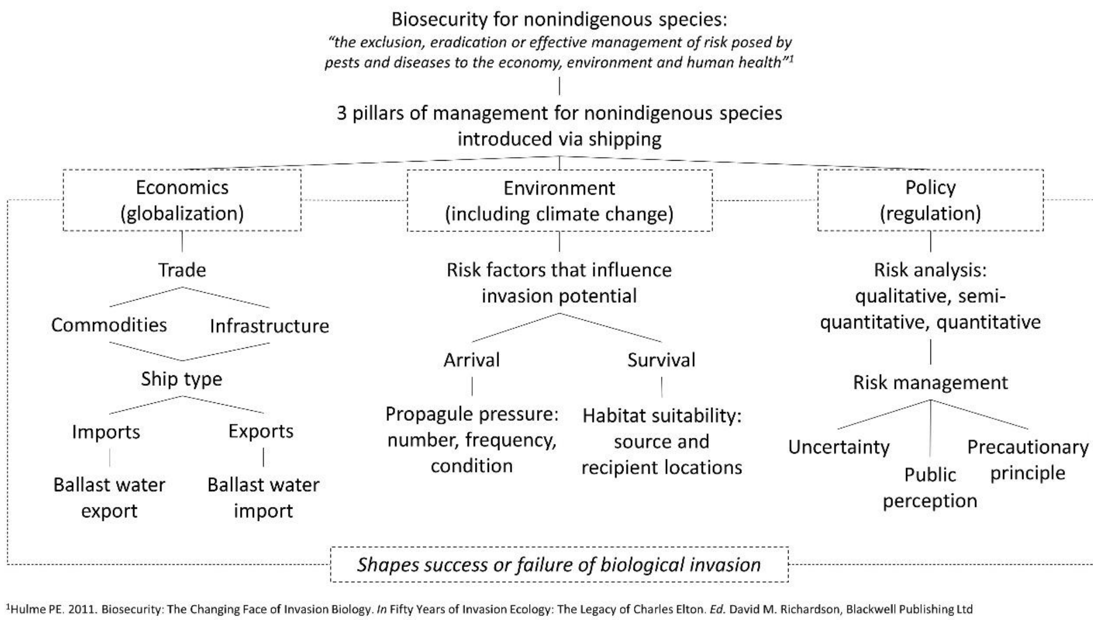


**Figure 1. Pillars of biosecurity management for nonindigenous species**
Each pillar independently influences the likelihood of success or failure of biological invasion and jointly contributes to biosecurity measures that aim to prevent or minimize NIS introductions and establishment.

In the marine environment, maritime shipping is the leading vector to introduce NIS, primarily from ballast and biofouling (Ruiz et al. 1997; Bailey et al. 2020). The mode of NIS introductions to coastal ecosystems has progressed through time from wooden sailing ships to steel-hulled, engine-powered ships and present day large-capacity commercial vessels (Ojaveer et al. 2018). Modern ships connect far-reaching ports in a matter of days, enhancing the speed and frequency of viable NIS deliveries and increasing the likelihood that organisms survive the journey to establish upon release (Hulme 2009; Wonham et al. 2013).

The direction and magnitude of maritime shipping is driven by trade dynamics, as ships transport goods between port systems globally (Seebens et al. 2016). Consequently, NIS introductions are linked to fluxes in trade patterns and the movement of unique trade commodities (Carney et al. 2017). Continued growth and expansion of maritime shipping and coastal infrastructure is anticipated to increase risk of invasions in marine ecosystems, since there appears to be no saturation in the accumulation of NIS worldwide (Seebens et al. 2017; Sardain et al. 2019). Furthermore, development of new trade routes (e.g., China's Belt and Road Initiative, the Arctic's Northwest Passage and Northern Sea Route) and shifting trade patterns (e.g., expansion of the Panama Canal) will expose coastal areas to novel NIS (Miller and Ruiz 2014; Muirhead et al. 2015; Liu et al. 2019). Successful colonization by introduced species is dependent on environmental match between trade partners (Keller et al. 2011), and climate change is anticipated to increase opportunity in high latitude ecosystems (Mahanes and Sorte 2019).

Ballast water from ships has been studied as a dominant vector of NIS for at least thirty years and is the subject of biosecurity measures internationally and in the United States (Bailey 2015). Ships take on seawater as ballast to maintain stability when cargo loads are reduced or absent, entraining aquatic organisms in the process. Ballast water and biota are moved between ports similarly to, and often in the opposite direction of, cargo deliveries from a ship. The result is a network of organism transfers between port systems that result in NIS introductions and establishment (Seebens et al. 2016).

Ballasting behavior varies by ship type, since some vessels carry cargo on nearly every voyage and/or require relatively low volumes of ballast water for operation (e.g., container and passenger ships), in contrast to vessels that carry bulk goods in one direction and ballast water on return (e.g., tankers and bulk carriers) (Verling et al. 2005; Minton et al. 2015). A greater proportion of tanker and bulk carrier arrivals discharge ballast water than other ship types, and their average discharge volumes are higher (Davidson et al. 2018). As a result of these differences in vessel behavior, ports that export bulk goods receive relatively large volumes of ballast water.

To reduce the likelihood of introducing NIS to coastal ecosystems, ships manage ballast water prior to discharge. Ballast water exchange was adopted as a management tool internationally and in the United States in the 1990s, wherein vessels replace coastal water in mid-ocean by emptying and refilling or allowing water to flow through ballast tanks (Verna and Harris 2016). The aims of ballast water exchange are to reduce the number and density of organisms, deliver an osmotic shock to remaining coastal organisms to inhibit survival, and discharge lower-risk open-ocean species in arrival ports. This practice is estimated to be 90% effective, in that it is expected to reduce the concentration of coastal zooplankton by an order of magnitude (Minton et al. 2005). Mid-ocean exchange remains the leading mechanism of ballast water management, though development of economically and technologically feasible onboard treatment systems began in the early 2000s and is increasing rapidly. Ballast water treatment systems must meet an established threshold of organism densities of different size classes, and often use a combination of filtration and chemical means to reach specific (required) discharge standards (Verna and Harris 2016). Many treatment systems have now been approved for use in the United States, but installation and operation remain ongoing challenges. Ballast water treatment systems are expected to reduce invasion opportunity below that of ballast water exchange, but their effects on actual invasion rates through time are unknown (Minton et al. 2005). Nevertheless, the transition from exchange to treatment marks a shift toward quantitative standards of NIS introduction risk.

To effectively manage risk of biological invasions, it is useful to identify factors that will influence the likelihood and consequence of NIS introduction and establishment across space and time (Gibbs and Browman 2015). In the coastal United States, the location, timing, and source of marine invasions have been driven by trade dynamics. For instance, the US Pacific Coast receives large volumes of trade originating from western Pacific ports, also the source location of many introduced species (Ruiz et al. 2000). The greatest number of initial (new) marine invasions to the US has occurred on the Pacific Coast, followed by the Atlantic and Gulf Coasts. The greatest number of secondary invasions (from one coast to another) has occurred on the Gulf Coast, indicating opportunities for stepping stone invasions from other invaded coastlines (Ruiz et al. 2000). As trade patterns shift, the likelihood of NIS introductions from ballast water, and the risk of invasions, will also shift. The US Gulf Coast, though historically relatively uninvaded, received over half of the total volume of ballast water nationwide in 2013 (Ruiz et al. 2015) and the annual volume increased through 2018 as a result of growing US energy exports (Chapter 2). Detecting these patterns is useful for biosecurity management and survey efforts that aim to measure temporal invasion rates. Given lag times in NIS establishment and discoveries, it may be years before the outcome of trade shifts are apparent (Crooks 2005).

The quantitative relationships between trade and ballast water delivery have been a missing link in invasion dynamics, though some studies have characterized the influence of individual commodities on shipping and ballast water (Carney et al. 2017; Holzer et al. 2017). Here, research gaps are filled by gathering comprehensive trade and ballast water datasets to identify fluctuations in globally transported commodities that lead to changes in maritime shipping patterns and frequency. This work is possible due to the robust National Ballast Information Clearinghouse that captures data from commercial vessel arrivals to ports in the United States (National Ballast Information Clearinghouse 2019). Although such detailed ballast water datasets are often not available in other countries, the findings described here illustrate that trade can be used as a robust proxy for ballast water and indicate that natural resource extraction is a major driver of bulk shipping traffic. Furthermore, the approach to risk-screening of ballast water developed here can broadly enable managers to appropriately allocate resources and choose best management practices based on information available at the time.

This dissertation spans multiple aspects of a complex and broad body of literature on biological invasions while examining maritime shipping and trade dynamics (Figure 2). The research focuses on the transport and introduction stages of invasion, as that is where preventative management is recognized to be most valuable and cost-effective (Epanchin-Niell 2017). The results can be used to identify potential hotspots of NIS introductions within the context of human activity and environmental change.

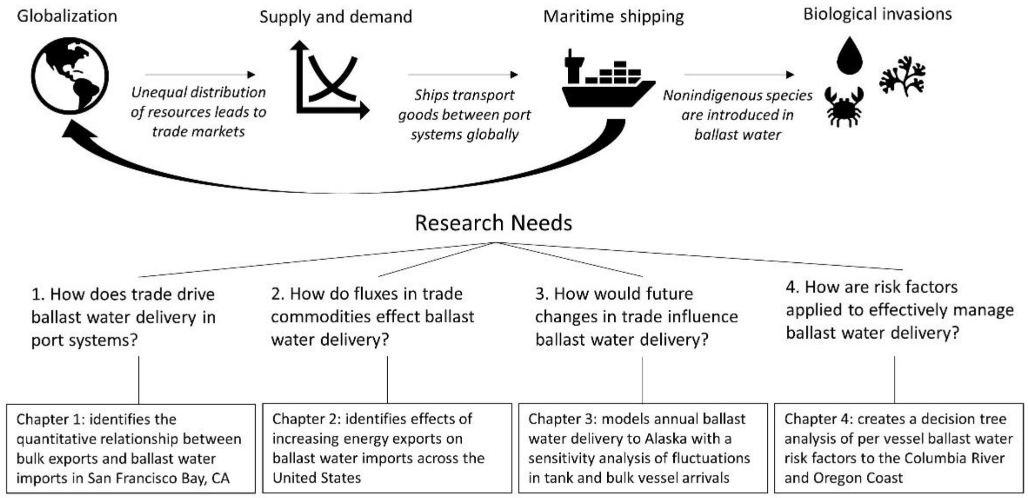


**Figure 2. Conceptual diagram of research gaps**

Globalization and trade have led to increased introductions of NIS from the ballast water of ships, resulting in biological invasions globally. The chapters in this dissertation address research needs related to the influence of trade on maritime shipping patterns and vessel ballasting behavior.

My research questions are:

1. How does trade influence ballast water delivery?
2. How do changes in trade commodities affect spatial and temporal patterns of ballast water dynamics?
3. How can we manage ballast water or trade to limit NIS introductions?

This research aims to address current gaps by defining relationships between trade and ballast water dynamics. Chapter 1 presents a robust multivariate linear model of overseas bulk commodities exports and ballast water imports across all ports in highly invaded San Francisco Bay, California, indicating that trade data can provide a reliable proxy of ballast water volume and source. Chapter 2 uniquely combines datasets on exports of oil, coal, and liquefied natural gas from the coastal United States to explain temporal growth in ballast water imports across all coasts, adding a new dimension to the sustainability challenge of global energy demand. Chapter 3 models statewide ballast water delivery to the sparsely invaded coastline of Alaska and provides a sensitivity analysis of ballast water discharge volume given fluctuations in the number of discharging vessels. Chapter 4 develops a semi-quantitative risk assessment of ballast water discharge to moderately invaded coastal Oregon and introduces a novel decision tree to aid decision makers with limited program resources for management.

In its totality, my dissertation adds to the body of literature on invasion dynamics by uniquely identifying how trade influences ballast water delivery of NIS across space and time. First, I examine a broad list of trade commodities to ascertain drivers of vessel behavior with implications for invasion dynamics at regional, statewide, and national scales. Second, I provide a critical and novel proxy for ballast water discharge volume that is widely applicable. Third, I use known risk factors of NIS introductions to inform management priorities and action. This research can inform future work on invasion dynamics influenced by shipping, the sustainability of natural resource extraction and global movement of commodities, and the location and prioritization of NIS survey efforts.

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Chapter 1

# Trade exports predict regional ballast water discharge by ships

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## Abstract

Biological invasions often result from transfers of organisms during various trade activities. In coastal ecosystems, commercial ships are a dominant source of species transfers globally, and ships' ballast water (BW) is a major focus of biosecurity management and policy to reduce invasions. While trade drives shipping patterns, diverse vessel types and behaviors exist such that the quantitative relationship between trade and BW dynamics is still poorly resolved, limiting both science and management. Here we estimated the relationship between tonnage of overseas exports and BW discharge volume for San Francisco Bay, California, by explicitly considering BW practices by vessel type. Using extensive datasets on shipborne exports and BW discharge, we (a) evaluated spatial and temporal patterns across nearly 20 different ports in this estuary from 2006-2014 and (b) developed a predictive model to estimate overseas BW discharge volume from foreign export tonnage for the whole estuary. Although vessel arrivals in San Francisco Bay remained nearly constant from 2006-2014, associated tonnage of exported commodities more than doubled and BW discharge more than tripled. Increased BW volume resulted from increased frequency and per capita discharge of bulk carriers from Asia and tankers from western Central America and Hawaii, reflecting likely shifts in direction of commodity movement (i.e., trade). The top 11 export commodities (59%

of total export tonnage) were transported on bulk carriers or tankers. We developed a multivariate linear model where annual tonnage of these top 11 export commodities by vessel type were predictors of total bay-wide overseas BW discharge (adjusted $R^2$ = 0.92), having the potential to estimate past or future BW delivery in San Francisco Bay. Tonnage of bulk exports provides valuable insights into BW flux and invasion dynamics, since most BW discharge to ports is driven by trade of bulk commodities and the associated behavior of bulk and tank ships. BW discharge data are not available for many global regions and time periods, whereas trade data are widely available and can provide a reliable proxy estimate of BW volume and geographic source, which are critical to evaluate invasion risk.

## Introduction

Biological invasions by nonindigenous species (NIS) are a leading cause of ecological change and economic impact (Mack 2000, Pysek & Richardson 2010), and no global region is immune to invasions. In marine ecosystems, coastal bays and estuaries are hotspots for invasions as centers of human populations, creating focal points for the transfer of organisms via trade (Ruiz et al. 2000). Over the past century, the growth and expansion of transportation, commerce, and accompanying development in coastal areas have increased the risk of invasion (Hulme 2009, Dafforn et al. 2015), with the degree of international trade a key measure of a country’s NIS abundance (Westphal et al. 2008).

Although global trade includes several mechanisms or vectors that transfer coastal organisms among geographic regions, commercial ships connect ports throughout the world and are a dominant source of invasions resulting from vast numbers of organisms moved by ballast water and hull biofouling (Ruiz et al. 2011, Bailey et al. 2020). Ballast water (BW) is used to maintain vessel stability, draft, and trim. Water taken on in one port or location entrains a diverse community of organisms that are discharged at subsequent ports of call, creating a large-scale transfer of organisms that can colonize new bioregions. A large ship can transfer more than 50,000 metric tons of coastal water across oceans in 8-10 days, and the United States alone receives over 180 million metric tons of BW from overseas vessels each year (NBIC 2016). Most of this BW is delivered by bulk and tank cargo vessels, which transport bulk dry and liquid commodities, respectively. These vessel types deliver bulk commodities in one direction and return without cargo in the opposite directly, carrying BW to maintain stability. As a result, bulk commodity vessels often contribute the majority of BW to ports compared to other vessel types, such as containerships or cruise ships that carry cargo on each voyage (Verling et al. 2005, Minton et al. 2015, Davidson et al. 2018). Due to such differences in vessel operations among ship types, total vessel arrivals are often not a good proxy for BW deliveries in space or time, whereas the volume of BW received at a port may often be linked intrinsically to the volume of commercial bulk exports, such as oil, grain, or coal (Carney et al. 2017).

Although not a precise predictor, greater volumes of BW discharge are expected to result in greater propagule supply and likelihood of introducing NIS (Minton et al. 2005, NRC 2011). As a result, changes in the scale and direction of trade can have direct consequences on the transport and introduction of NIS across space and time, and such changes are linked directly to the flux of commodities among ports. Furthermore, both frequency and magnitude of organism transfers, or propagule pressure, are expected generally to increase invasion likelihood (NRC 2011, Simberloff 2009). However, maritime trading partners do not all present equal probability of invasions. Ports located in environmentally similar regions are often prone to successful exchange of species, for example the western United States and China (Meyerson & Mooney 2007). Assessments of vector strength, trade partners, and environmental match are effective means to evaluate potential changes in NIS risk (Gibbs & Browman 2015).

While multiple countries require vessels to report data on volume and source of BW discharges, most countries still do not have access to such data (e.g., Zhang et al. 2017). Even where present, these data sets began in the late 1990s. Thus, comprehensive data is rare for most countries and ports around the world and is truly limited to the past few decades even when available. This paucity of BW data in most global regions in space or time limits understanding of quantitative relationships between shipping and invasions that are desired in both invasion science and management.

To date, few studies have used trade data to evaluate its quantitative relationship with BW delivery and the possible application of predicting changes in BW discharge volumes over time (Carney et al. 2017, Holzer et al. 2017). Here, we combine extensive data on vessel arrivals, BW discharge volume, and cargo import/export data to evaluate the relationship between trade and BW delivery over nine years in San Francisco Bay, California, a highly invaded estuary with diverse commercial shipping. Our approach explicitly considers differences in the operational profile of different vessel types, with respect to BW and cargo, and measured changes in BW discharge frequency, volume, and source region as key variables in invasion dynamics. This approach has potential broad application to predict BW delivery in diverse regions or time periods where trade data are available.

## Materials and methods

### *Study site*

San Francisco Bay is a large estuary located in central coastal California, USA, that has at least 20 commercial shipping ports frequented by foreign and domestic vessel traffic, ranging from San Francisco and Oakland in the lower bay to Sacramento and Stockton in the upper estuary (Fig. 1.1).

The area is home to roughly 7.5 million people with a diverse range of aquatic habitats and associated biota (Cloern & Jassby 2012). The estuary receives freshwater input from the Sacramento and San Joaquin Rivers, which transport runoff from 40% of California's surface area (Nichols et al. 1986), though the volume of freshwater input varies annually and water is often diverted or dammed before reaching the estuary (Cohen & Carlton 1998). The upper reaches of the estuary, including Suisun Bay and eastward, are low salinity, nutrient rich, turbid waters. The lower bay is also rich in nutrients but conversely is a high salinity, high productivity area with large tidal influences (Cloern & Jassby 2012).

*Vessel traffic and ballast water delivery data*

To examine BW discharge and vessel arrival patterns to San Francisco Bay over time, we extracted data from the National Ballast Information Clearinghouse (NBIC) (http://invasions.si.edu/nbic/) for a nine year period from 2006 through 2014. Following 2004, nearly every commercial vessel operating in U.S. waters was required to submit a Ballast Water Management Reporting Form to the NBIC at each arrival, and the NBIC estimates that compliance with the reporting requirements is approximately 94% nationwide. The data collected on these forms includes BW source and discharge locations and volumes, arrival locations, vessel types, and presence/absence of BW management. We characterized BW that was sourced and vessels that arrived from beyond the 200 nautical mile exclusive economic zone (EEZ) as overseas, and BW that was sourced and vessel that transited solely within the EEZ as coastwise.

While we examined all commercial vessels, we focused particular attention on bulk and tank vessels arriving from overseas, since these vessel types were expected to deliver most of the BW. For these two vessel types, we examined the distribution of arrivals and BW discharge among San Francisco Bay dominant arrival ports, which differ in salinity characteristics, including: Alameda, Antioch, Benicia, Carquinez, Concord, Crockett, Martinez, Oakland, Pittsburg, Redwood City, Richmond, Rodeo, Sacramento, San Francisco, San Rafael, Stockton, and Suisun Bay. Further, we identified dominant overseas source bioregions for bulk and tank vessel traffic to San Francisco Bay. For bulk carriers, these bioregions were EAS-1 through EAS-VIII and NWP-1 through NWP-5, and included the countries of China, Indonesia, Japan, North Korea, South Korea, Thailand, Taiwan, Vietnam, Malaysia, Singapore, and Philippines. For tankers, the following bioregions were dominant overseas sources: NEP-VI through NEP-IX and SEP-H along the west coast of Central America (Fig. 1.1) (Kelleher et al. 1995).

*Trade data*

To examine spatial and temporal trade patterns to ports in San Francisco Bay, we extracted data from USA Trade Online, a publicly available online database provided by the U.S. Census Bureau (https://usatrade.census.gov/), over the same nine year period. The database provided annual and monthly measures of import and export commodities for the ports of Alameda, Carquinez Strait, Crockett, Martinez, Oakland, Redwood City, Richmond, Sacramento, San Francisco, and Stockton, however data for Sacramento was not available after 2010. Commodity data were categorized using the Harmonized Commodity Description and Coding Systems (HS codes) introduced in 1988. These classification codes consist of a series of two-digit chapters (e.g., 27: Mineral Fuels, Mineral Oils and Products of their Distillation; Bituminous Substances; Mineral Waxes) containing four- and six-digit subcategories with increasing resolution (e.g., 271019 Petroleum oils and oils from bituminous minerals, not containing biodiesel, not crude, not waste oils). Based on the spatial heterogeneity in arrivals and discharge by vessel type, we identified the commodities (six-digit codes) associated with bulk and tank vessels in each port.

*Analyses*

We assessed the contribution of various vessel types to arrivals and BW discharge over the nine-year period to San Francisco Bay. For bulk and tank vessels, we estimated the total BW discharge volume, frequency of discharge, and per capita discharge per year. In addition, we identified the relative contribution of discharge by bulk and tank vessels according to both BW source and discharge port in San Francisco Bay.

Using a combination of data from the NBIC and USA Trade Online, we developed a linear model for San Francisco Bay that estimates the relationship between the tonnage of exports transported by bulk and tank vessels and the total volume of overseas BW discharge. Since the slope of the model reflects this relationship within the range of trade tonnage received during our study period, we limit inferences drawn from the results to that range. Trade statistics were unavailable for some ports for which BW data were available (Benicia, Concord, Pittsburg, Rodeo, and Suisun Bay).

## Results

### *Arrivals and BW discharge by ship type*

From 2006 through 2014, San Francisco Bay received a reported 33,558 arrivals and 55,584,402 $m^3$ of BW. The number of annual arrivals remained consistent through time (3,729 ± 141, mean ± standard deviation) and was dominated by coastwise vessels (79%). Container, tank, and bulk vessels were the primary types to call on ports in San Francisco Bay. In sharp contrast, the volume of BW discharge increased 84% over the nine-year period. While coastwise BW discharge declined slightly, the volume of overseas BW more than tripled by 2014 (Fig. 1.2). Bulk and tank vessels discharged most BW, and these two vessel types accounted for 87% of the total volume and 91% of the overseas volume.

The growth in reported BW discharge from overseas sources was driven specifically by bulk and tank vessels. While the number of overseas bulk and tank vessel arrivals fluctuated little during our study period (Fig. 1.3A), the cumulative annual volume of overseas BW discharged by each vessel type increased over five-fold over the nine years (Fig. 1.3B). This temporal growth was the combined result of a dramatic increase in the number and proportion of discharging vessels (Fig. 1.3C) and a rise in the mean volume per vessel discharge (Fig. 1.3D).

*BW source regions and recipient ports*

Ballast water from bioregions of eastern Asia adjacent to Japan, China, and South Korea accounted for 70% of all overseas bulk carrier discharge (Fig. 1.1A). The observed overall increase in BW discharge by bulk carriers in San Francisco Bay (Fig. 1.3B) was driven largely by a growing contribution of vessels from Asia, and primarily China (Appendix A Sup. Fig. 1A). While the contribution of bulk carrier arrivals from Asia fluctuated between 62-76% of total arrivals (across all regions), the frequency of discharging vessels increased three-fold from Asia across the nine years, accounting for 80-90% of all discharge events by bulk carriers from 2008-2013 (Table 1.1A), and the percent of discharging vessels was much higher than that of other source regions.

In contrast, the Pacific coast of Central America was the dominant source region of overseas BW discharge for tankers (Fig. 1.1B), representing 53% of total volume discharged to San Francisco Bay by overseas tank vessels from 2006 through 2014. The annual discharge volume from this source region grew more than four-fold over the nine years, with most coming from Mexico (Appendix A Sup. Fig. 1B). The increasing contribution of BW from Central America was driven by both an increase of vessel arrivals and percent discharging from this region (Table 1.1). Hawaii was also a major cumulative source region for BW discharge by tankers arriving to San Francisco Bay across years (Fig. 1.1B), but the relative contribution to annual arrivals and BW discharge was smaller than Central America and declined over time (Appendix A Sup. Table 1).

It is noteworthy that the overseas arrivals and BW discharge in San Francisco Bay differ among specific ports and show a broader regional pattern with respect to the estuary's salinity gradient (Fig. 1.4). Bulk vessels tended to call on ports in the upper estuary such as Benicia, Pittsburg, Stockton, and Sacramento where bulk exports of rice to Japan, coal to Mexico, and iron ore to China were most common. This low salinity area received two-third of overseas bulk carrier BW discharged in San Francisco Bay (Fig. 1.4B). Conversely, tankers frequently called on ports in the lower bay such as Richmond and San Francisco where exports of oil to Central America were common. This high salinity area received two-thirds of the Bay's overseas BW discharged from tankers (Fig. 1.4B).

*Relationship of change in trade to BW discharge volume*

The change in overseas BW discharge by bulk and tank vessels was directly related to (and driven by) increased export of bulk commodities. Overall, there were nearly 4,500 6-digit export commodities from ports within San Francisco Bay, and total tonnage of these exports increased annually and more than doubled from 2006 through 2014. The top eleven commodities by tonnage were bulk commodities, transported by bulk or tank vessels, and accounted for 59% of total shipping exports. More specifically, eight of these eleven commodities were transported by bulk carriers (e.g., waste products, petroleum coke, coal, rice) and three were transported by tankers (petroleum oils) (Fig. 1.5).

There was a strong relationship between foreign exports and overseas BW discharge volume among years, for bulk and tank vessels, both alone and together. The relationship between the tonnage of the top eight export commodities from bulk carriers ($10^6$ kg) and the volume of overseas BW ($10^3$ $m^3$) discharged by bulk carriers in San Francisco Bay can be described by

$y = -1{,}250 + 0.5022x$, $R^2 = 0.86$.

The relationship between the tonnage of the top three export commodities from tankers ($10^6$ kg) and the volume of overseas BW ($10^3$ $m^3$) discharged by tankers can be described by

$y = -717.98 + 0.5820x$, $R^2 = 0.87$.

A multivariate linear model of the relationship between the annual tonnage of the top eleven export commodities and the total annual overseas BW discharge volume received throughout San Francisco Bay can be described by

$y = -2{,}002.38 + 0.6212x_1 + 0.5324x_2$, where

y is the annual volume of overseas BW discharge ($10^3$ $m^3$),

$x_1$ = annual tonnage of exports transported by tankers ($10^6$ kg),

$x_2$ = annual tonnage of exports transported by bulk carriers ($10^6$ kg),

and an adjusted $R^2 = 0.92$.

## Discussion

### *Predicting BW discharge from trade*

This study elucidates the quantitative effects of trade exports on BW discharge characteristics, including volume and source region. It is generally understood that trade drives shipping and BW delivery, affecting invasion dynamics on a global scale (Bailey et al. 2020, Hulme 2009, Kaluza et al. 2010, Sardain et al. 2019, Seebens et al. 2013, Ruiz et al. 2000). Fluctuations in commodity supply, product demand, and emergence of new trade routes and partners all affect the number, tempo, and type of vessel calls at a port. Yet, how exactly this converts to BW delivery has been more elusive, since (a) most vessels do not discharge BW upon arrival (Miller et al. 2011, Minton et al. 2015) and (b) BW discharge varies by both vessel type and specific export commodity. As a result, the number of vessel arrivals alone is a poor proxy for BW discharge volume and organism transfer, as our data and other studies show (Fig. 1.3; Davidson et al. 2018, Miller et al. 2011, Minton et al. 2015, Verling et al. 2005). Several past studies have adopted coarse estimates of BW by vessel types, using an average value sometimes adjusted for vessel size, but this approach largely ignores the high level of variation and directionality of BW versus cargo transfers within vessel type. Here, we explicitly evaluated selective commodity exports, focusing on bulk dry and liquid cargo associated with larger discharge volumes from bulk and tank vessels (compared to other vessel types), to develop a model that explains > 90% of temporal variation in overseas BW discharge volume across all ships and ports in San Francisco Bay.

Using detailed knowledge of transportation logistics for specific cargos and ship types, our approach provides a predictive model for BW discharge volume that may be applicable broadly to other locations or time periods. We suggest the general approach is likely to be robust, representing an improvement of past methods for estimation, because it relies on a mechanistic understanding of BW transfer associated with specific cargo and vessel types. Importantly, this approach also is accessible in most regions. Given that BW discharge data are only available recently (and for a very limited number of countries), whereas trade and ship arrival data exist commonly with broad spatial and temporal coverage, such a modelling approach has considerable appeal and potential as a general tool for both backcasting and forecasting BW delivery as well as considering implications for invasion dynamics. Furthermore, this approach may be useful for assessing biosecurity threats under shifts in trade patterns and partners that affect vessel behavior, cargo types, and connectivity between source/recipient ports.

However, we recognize that our analysis currently evaluates only a short snapshot of time and is limited to one major port system. We are encouraged by the strong relationship between trade of bulk commodities and total BW discharge volume, creating new opportunities to clarify the historical record for San Francisco Bay such as effects of changing trade on BW quantity and source regions as well as associated invasion patterns. The response of invasions to shifts in trade and BW delivery remains a key knowledge gap, for both invasion science and management, which is impeded by limited data on BW history and propagule delivery (NRC 2011, Ruiz et al. 2013). The utility of our model to help in these respects requires further testing and validation, both across time within San Francisco Bay and in other regions.

This general approach expands upon previous work on the relationship of BW discharge associated with particular bulk cargo. Several studies highlight the dominant contribution of bulk carrier and tanker vessels to total BW discharge volume at ports around the world (Carlton et al. 1995, Cope et al. 2015, David et al. 2012, Miller et al. 2011, Minton et al. 2015, Verna et al. 2016). Temporal measures of the relationship between bulk cargo and BW quantities focus primarily on single commodities and ship type. For example, coal exports by bulk carriers explains most of the variation in overseas BW delivery in Chesapeake Bay, driving a surge in both BW volume and propagule supply between 2005 and 2013 (Carney et al. 2017). Similarly, projections of liquefied natural gas exports from the United States anticipate substantially greater BW discharge from tankers, primarily along the U.S. Gulf Coast (Holzer et al. 2017). Here, we apply a similar approach to a broad list of bulk commodities, across multiple types of bulk and tank vessels, allowing us to explain the large temporal changes in BW discharge observed for San Francisco Bay over nine years.

*Source region and recipient port*

Our analysis shows how expanding bulk exports resulted in a surge in overseas BW flux from particular geographic source regions, arriving to different portions of San Francisco Bay. Each source and arrival port has consequences for associated biota and invasion opportunities. The location of a trade partner obviously affects the biological composition of BW discharge. BW delivery from China and Mexico expanded greatly during our study, driving a 3-fold increase in total discharge to San Francisco Bay. Although it is generally expected that increasing propagule supply increases the likelihood of new invasions (NRC 2011, Simberloff 2009), environmental conditions also affect the outcome (Seebens et al. 2016). Although we did not evaluate environmental match directly, it appears that China may be a more potent source for new invasions than Central America, based on the many successful past invasions from this region (Cohen & Carlton 1995, Winder et al. 2011). Moreover, BW discharge from bulk carriers occurred in the upper reaches of the estuary (Fig. 1.4) where salinities are reduced, and we note that many of the past invasions from Asia were in low salinity habitats. This suggests that both climate and salinity provide a good match for colonization of species arriving with BW from Asia, and the increase in BW may represent an elevated chance of new invasions associated with bulk carriers.

The increase in BW discharge and source regions reflect the underlying shifts in trade exports per port in San Francisco Bay, where more exports increased the volume and frequency of discharge events. For example, in the port of Stockton, a change from importing to exporting commodities caused a temporal shift in the proportion of bulk carriers that discharged BW. Arrivals to Stockton fell from 2006 through 2009 as bulk imports of Portland cement from China (distributed to western U.S. states) declined. Arrivals then rebounded and grew through 2014, coinciding with a spike in exports of iron ore and coal to China and Mexico. Meanwhile, from 2006 to 2014 the proportion of vessels that discharged BW increased annually from 8% to 70%. When bulk carriers imported commodities, they discharged little BW. As bulk exports grew and became the driver of vessel arrivals, the port received a 20-fold increase in BW volume.

In contrast to bulk carriers, the surge in BW from tankers reflected a shift in trade dynamics with Central America and, to a lesser extent, Hawaii. The proportion of overseas tankers that discharged BW sourced in Mexico peaked from 2010 – 2012, coinciding with a peak in exports of oil commodities from the Bay to that country. Oil exports to Mexico then declined in 2013 and 2014 as exports of coal skyrocketed (transported by bulk rather than tank vessels). At the same time, more tanker BW began to arrive from Central America because of increased oil exports, particularly to Guatemala and El Salvador. Tanker BW discharge from Hawaii rose concurrently. Overall, the proportion of discharging overseas tankers grew annually over the nine years (Table 1.1), though sourced from varying coastal ecosystems.

The type of vessel used to transport commodities also influences the location of discharge, reflecting specialization of ports and associated infrastructure. With the combined shipping pressure of bulk and tank vessels in ports throughout San Francisco Bay, most of the area routinely received BW. However, a clear distinction emerged between upper estuary (low salinity) bulk carrier discharge and lower bay (high salinity) tanker discharge (Fig. 1.4). For example, the high salinity port of Richmond has terminals capable of handling both dry and liquid bulk cargo, but three oil commodities accounted for most (68%) of total exports and two-thirds of the BW received there was discharged by overseas tankers.

*Invasion response to trade shifts*

Trade statistics can provide considerable insight into vessel movement patterns and the associated flux of BW as a leading source of coastal species transfer and invasions. Our study expands upon previous exploration of the trade-BW relationship to provide estimates of BW flux at higher resolution and accuracy, using operational profiles of different vessels types according to cargo type and direction of trade. Our approach also allows some comparison of environmental match between source and recipient regions as a coarse proxy of relative similarity and perhaps invasion opportunity. While these are important variables, which contribute to invasion outcomes, they are not sufficient to characterize the associated propagule supply characteristics and invasion probability.

In general, the 3-fold increase in annual overseas BW discharge observed in San Francisco Bay is likely to have increased total propagule delivery from overseas sources, although organism concentrations are notoriously variable in space and time, differing among source regions, voyage conditions, seasons, and years (Briski et al. 2013, Carney et al. 2017, Smith 1999, Verling et al. 2005). We further expect the increase in BW from China in particular to result in increased probability of invasions to San Francisco Bay from this region based on past invasion history associated with this trade (as noted earlier). However, the relationship between propagule supply and invasion outcome is still poorly resolved, with high uncertainty of expected responses (NRC 2011, Wonham et al. 2013), driven partly by limited available data to adequately characterize the number of species as well as frequency and concentrations delivered through time.

It is noteworthy that nearly all (> 98%) of overseas BW discharged to San Francisco Bay in our study was reported to be treated with either exchange (flushing of tanks) in open ocean or a treatment technology required to reduce the concentration of coastal organisms (NRC 2011). This has likely reduced the propagule supply of coastal biota arriving in BW compared to historical BW discharge from Asia and elsewhere (but see Carney et al. 2017). If this is indeed the case, the residual risk of colonization is uncertain, as we have entered a new era where concentrations of organisms in BW are below historical conditions. Today, the extent to which concentrations of coastal organisms are below a critical threshold for successful invasions remains a major question in invasion ecology and management (Ruiz and Carlton 2003, NRC 2011).

There is typically a lag time from species arrival to population growth and detection (Bailey et al. 2020, Crooks 2005, Sakai et al. 2001). Moreover, the ability to estimate changes in invasion rate with statistical confidence are especially challenging, given that most of the available data are limited to occurrence records instead of repeated measures that aim to detect change in San Francisco Bay and elsewhere (Costello et al. 2007, Costello & Solow 2003, Solow & Costello 2004, Ruiz et al. 2011). Thus, evaluation of the full effect of changes in vessel behavior documented here will require both time and detailed analyses.

*Conclusions*

Shipping is a major driver of biological invasions. Globalization, emerging transport networks, and increased connectivity have led to invasions in marine, freshwater, and terrestrial biomes alike (Hulme 2009). Furthermore, there appears to be no saturation in global invasions despite heightened awareness and management efforts (Seebens et al. 2017). Fluctuations in supply and demand of traded commodities influences the magnitude and direction of NIS transfers, as well as the construction and location of facilities that are designed to manage imports and exports (Bulleri & Chapman 2010, Ruiz et al. 2015). The latter affect the environmental conditions of the recipient communities, which in turn can determine habitat suitability and opportunity for colonization.

This study quantifies how the direction, magnitude, and location of trade drives overseas BW discharge by ships in San Francisco Bay. We developed a predictive model for BW discharge using trade export data by focusing on bulk commodities associated with bulk carriers and tankers. Our approach has the potential for broad application since such trade data are available in space and time around the world. Moreover, this approach provides a key measure of BW flux to support biosecurity management in many global regions where comprehensive data on BW discharge is lacking. Further measures, such as in situ sampling and NIS surveillance, are still required and critical to evaluate the propagule supply associated with BW flux as well as invasion consequences.

Tables

**Table 1.1. Vessel arrivals and ballast water discharge**

The proportion of vessel arrivals and ballast water discharge to San Francisco Bay from (A) overseas bulk carriers from Asia and remaining bioregions, and (B) overseas tankers from Central America and remaining bioregions. Total number of vessels (n) shown for percent discharging vessels.

| (A) Overseas Bulkers | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|---|---|
| Asia Source Region*<br>% Discharging (n) | 23%<br>(145) | 32%<br>(117) | 64%<br>(124) | 76%<br>(123) | 78%<br>(123) | 70%<br>(136) | 73%<br>(143) | 75%<br>(146) | 69%<br>(153) |
| Other Source Regions<br>% Discharging (n) | 33%<br>(89) | 28%<br>(74) | 24%<br>(58) | 26%<br>(39) | 25%<br>(40) | 41%<br>(56) | 28%<br>(53) | 39%<br>(70) | 55%<br>(92) |
| Contributions from Asia | | | | | | | | | |
| % Total arrivals | 62% | 61% | 68% | 76% | 75% | 71% | 73% | 68% | 62% |
| % Dischargers | 53% | 64% | 85% | 90% | 91% | 81% | 87% | 80% | 68% |

*Asia bioregions: EAS-1 through EAS-VIII, NWP-1 through NWP-5

| (B) Overseas Tankers | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Central America Source Region*<br>% Discharging (n) | 20%<br>(45) | 29%<br>(42) | 43%<br>(90) | 35%<br>(71) | 43%<br>(95) | 46%<br>(108) | 49%<br>(131) | 60%<br>(88) | 63%<br>(101) |
| Other Source Regions<br>% Discharging (n) | 11%<br>(198) | 11%<br>(201) | 12%<br>(193) | 15%<br>(182) | 16%<br>(129) | 18%<br>(114) | 16%<br>(136) | 33%<br>(157) | 47%<br>(144) |
| Contributions from Central America | | | | | | | | | |
| % Total arrivals | 19% | 17% | 32% | 28% | 42% | 49% | 49% | 36% | 41% |
| % Dischargers | 29% | 35% | 63% | 48% | 67% | 71% | 74% | 50% | 48% |

*Central America bioregions: NEP-VI through NEP-IX, SEP-H

Figures

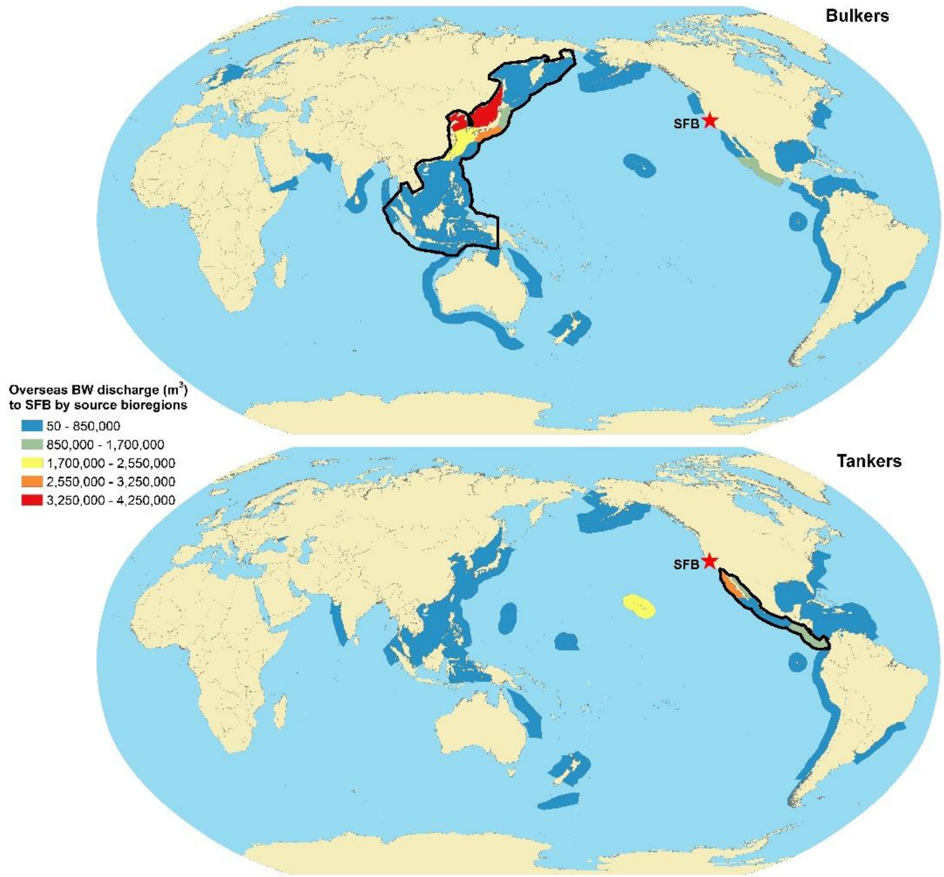


**Figure 1.1. Bulker and tanker ballast water source bioregions**
Total overseas ballast water discharged in San Francisco Bay by source bioregions, from 2006 through 2014, by bulk carriers (upper) and tankers (lower). Cumulative discharge volume ($m^3$) per source bioregion is indicated by color. Bioregions outlined in black on each map represent those considered Asia and western Central America (upper and lower, respectively) and shown in Table 1.1.

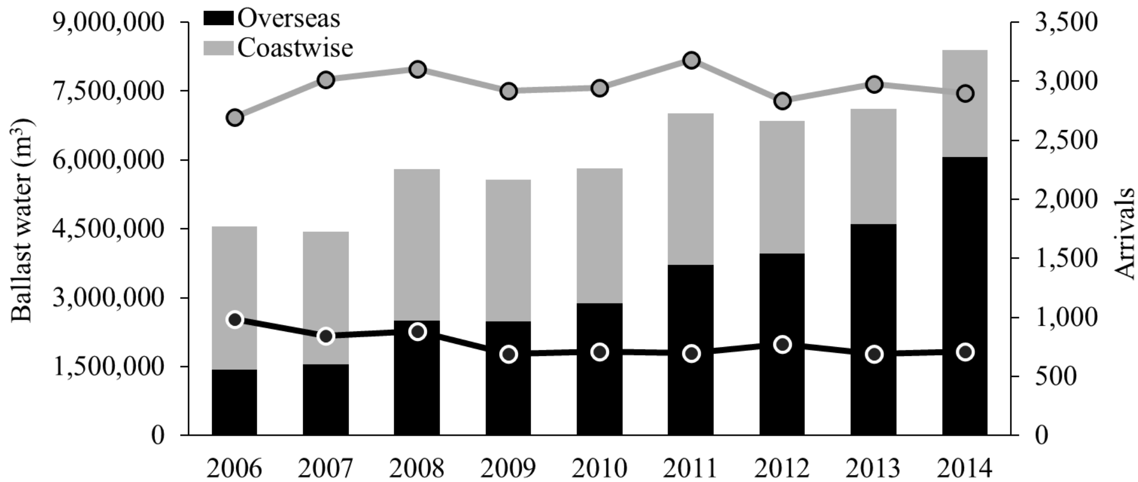


**Figure 1.2. Annual arrivals and ballast water**
Annual contributions of overseas and coastwise ballast water discharge (bars) and arrivals (lines) to San Francisco Bay by commercial vessels.

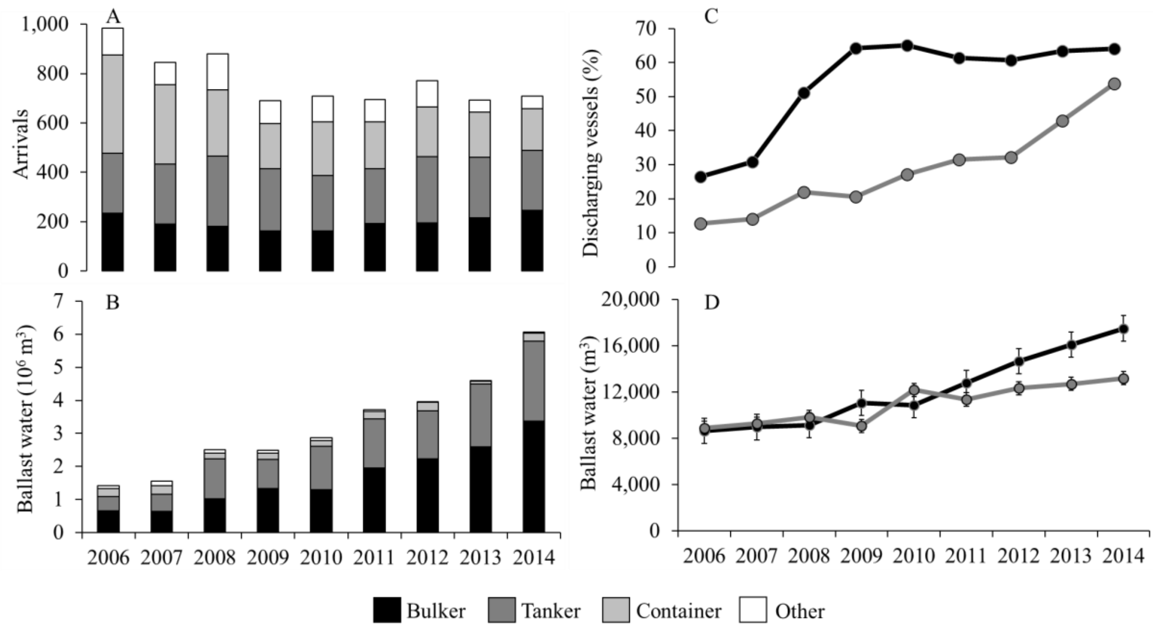


**Figure 1.3. Annual variation by vessel type**
Annual variation by vessel type for overseas (A) arrivals, (B) ballast water discharge, (C) percentage discharging arrivals, and (D) mean discharge volume of those vessels reporting discharge to San Francisco Bay. Error bars in panel (D) represent standard error. Panels (C) and (D) show growth in bulkers and tankers only.

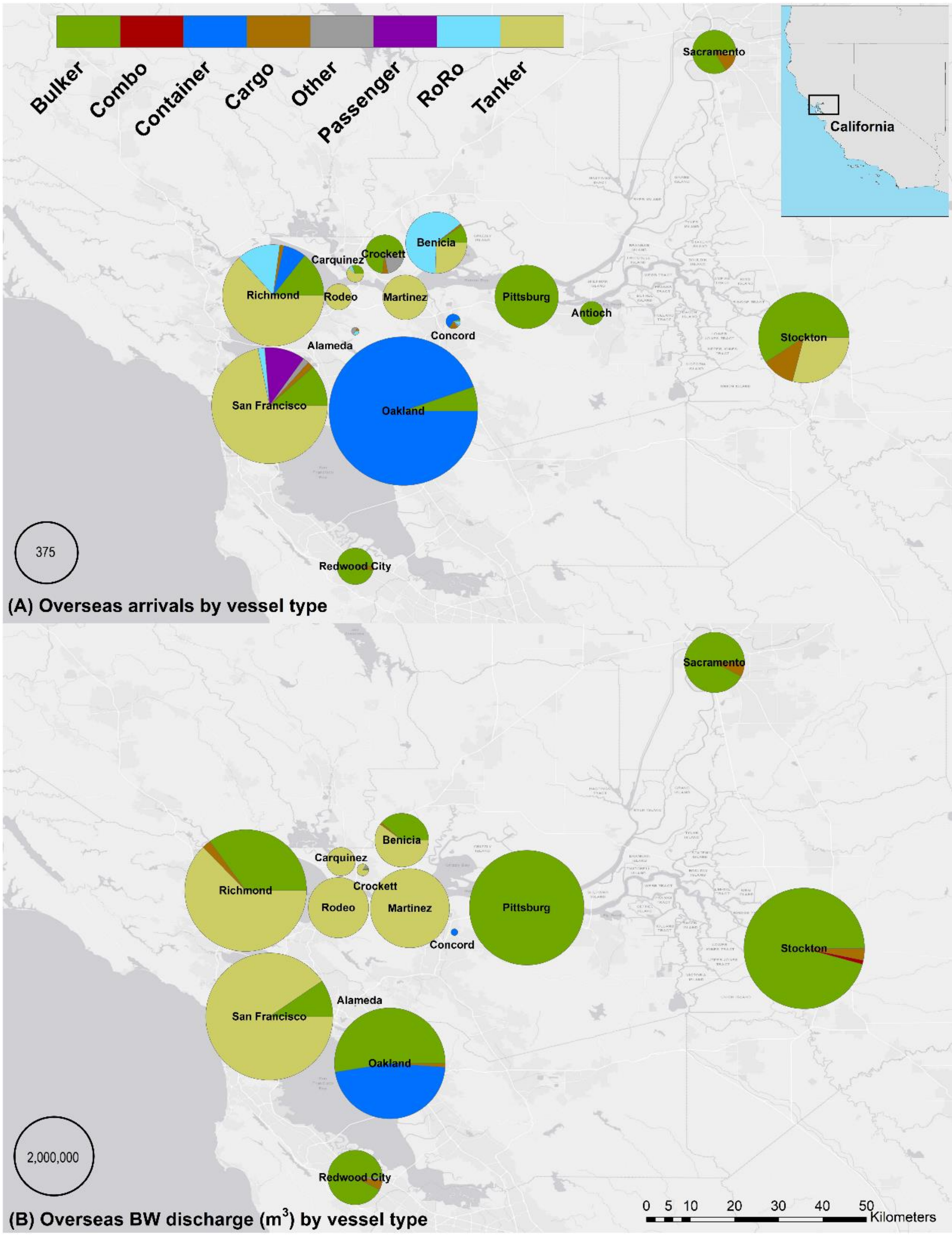


**Figure 1.4. Spatial variation by vessel type**

The relative contribution of vessel type to (A) total overseas vessel arrivals and (B) overseas ballast water discharge to ports within San Francisco Bay from 2006 through 2014. Scale is shown in bottom left of each figure for arrivals (A) and discharge (B).

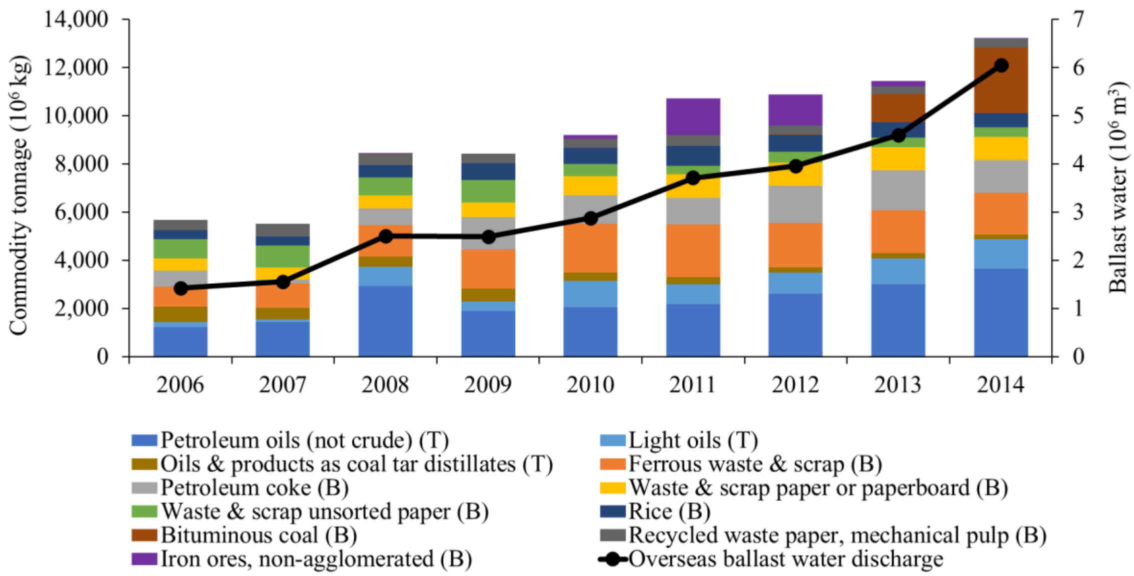


**Figure 1.5. Annual tonnage of top export commodities**
The annual tonnage (bars) of the top eleven commodities exported from San Francisco Bay and the annual volume (line) of overseas ballast water discharge. The type of vessel that exported each commodity is noted as bulk carrier (B) or tanker (T). These top 11 commodities comprised 59% of the total export tonnage.

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# Chapter 2
# Expanding US energy exports fuel opportunity for marine biological invasions

## Abstract

Variability in maritime trade influences the location and magnitude of coastal biological invasions from the ballast water of ships. Here we identify a previously unexplored driver of increasing ballast water imports to the United States from 2005-2018, representing a 422% growth in shipborne exports of oil, coal, and liquefied natural gas, particularly from the Gulf Coast. Across all coasts, we found 97% of the variability in ballast water imports among years was explained by the tonnage of energy exports. Tank and bulk ships transported energy goods globally, greatly expanding the vector strength and species source pool. This study finds that energy trade dynamics drive changes in ballast water delivery and highlights an additional sustainability challenge of growing global energy demand beyond climate change. We use our findings to assess the dynamic effects of global energy supply and demand on regional ship behavior and invasion opportunity.

## Introduction

The supply and production of energy resources varies around the world, thus, to meet demand of growing economies and populations, raw and finished energy goods are traded internationally via maritime shipping. In 2018, an estimated 1.9 billion tons of crude oil, 1.2 billion tons of coal, and 318 million tons of liquefied natural gas (LNG) were in world maritime trade, comprising nearly a third (31.5%) of goods loaded globally not considering refined petroleum products[1]. Moreover, global energy consumption is projected to rise nearly 50% by 2050, driven primarily by countries within Asia[2]. While access to modern energy is valuable to improving quality of life, there are trade-offs associated with rapid energy expansion that challenge the sustainability of natural resources[3]. Efforts to address energy sustainability have often focused on the supply (e.g., exploration, production, refinement) and demand (e.g., consumption) of fossil fuels to mitigate climate change[4,5]. Here we address a new dimension of energy sustainability focused on the behavior and effects of maritime shipping, the link between supply and demand.

Maritime shipping is the world's primary vector to introduce estuarine and marine nonindigenous species (NIS), including over 350 coastal NIS in North America from 1981-2010[6]. Ship types influence the source and magnitude of NIS introductions differently given operating profiles, configuration, and cargo[7]. Ships that specialize in carrying dry and liquid bulk goods, such as coal, petroleum, and LNG, typically transit with cargo in one direction and carry ballast water on the return voyage. The uptake and discharge of seawater as ballast provides ships stability as needed but also collects (samples) and releases entire planktonic communities between ports. The number and frequency of ships that discharge ballast water across space or time positively influences the likelihood of NIS introduction and establishment[8]. As a result, biological invasion risk is projected to increase as the magnitude of global maritime shipping grows, driven by socioeconomic factors.[9]

Over the past four decades, trade of energy goods in the United States has undergone a transition from net imports to net exports, altering maritime shipping dynamics in coastal ports[10]. By 2018, a recent production boom from shale formations led the United States to be the world's leading producer of oil and natural gas[11]. Increasing tonnage of petroleum, coal, and LNG were exported from coastal US ports to countries around the world on bulk and tank ships, even goods destined to countries on the same continent[12].

Here we thoroughly examined fluxes in the scale and directionality of maritime trade of energy goods as a driver of biological invasion opportunity. In this analysis, we (1) explored the relative proportions of total national and regional exports across time from the United States; (2) uniquely integrated comprehensive trade datasets across three energy sectors (petroleum, coal, and LNG, hereafter referred to as energy); (3) assessed the influence of energy exports on shipping behavior; and (4) modeled the relationship between energy exports and ballast water imports across space and time, and by ship type. Our results reveal an unintended consequence of rising global energy demand and underscore the need to integrate associated maritime shipping and invasion dynamics into sustainability goals.

## Methods

### *Total export data*

We obtained data on total United States exports from USA Trade Online, a database provided by the United States Census Bureau[13]. USA Trade Online reports imports and exports of goods classified by the hierarchical Harmonized System (HS) codes, where 22 sections contain 2-digit chapter codes that classify goods broadly, then 4-digit heading codes and 6-digit subheading codes that classify goods with increasing specificity. For example, Section 2 Vegetable Products contains Chapter 10 Cereals that contains Heading 1004 Oats. We extracted data on the annual kilograms of 4-digit goods that were exported from port districts on the West, Gulf, and East Coasts from 2005 through 2018. We used the 2-digit chapters to broadly group goods as Agriculture, Energy, Mineral, or Other. Agriculture goods included HS chapters 1 – 15 (sections 1, 2, and 3), Energy goods included HS chapter 27 (section 5), Mineral goods included HS chapters 25 and 26 (section 5), and remaining chapters (and sections) were Other goods. We categorized 242 4-digit export goods in this way, representing 97.5% of the total export tonnage, and goods that were at least 0.02% of total export tonnage. Furthermore, we identified the type of vessel that transported each 4-digit good (e.g., tank, bulk, container ship).

*Energy data*

We obtained data on United States exports of petroleum and coal from the Energy Information Administration (EIA). We used data from the EIA because it is comprehensive and provides detailed information on current and projected trade of energy goods. We note that energy tonnage in data collected from the EIA does not fully match the annual tonnage in the “energy” category of total exports from USA Trade Online. We suspect this discrepancy to be the combined result of multiple factors, including variability in reported export location (e.g., port vs. port district); the primary source of data for each database; density conversion factors for some petroleum products; variability in revisions made to each database by their hosts; and variability in product name/identification. We used data from the EIA to analyze specific energy exports and data from USA Trade Online to summarize relative exports only.

The EIA reports petroleum export data at the spatial level of Petroleum Administration for Defense Districts (PADDs)[14]. The United States is divided into seven PADDs, where PADDs 1-5 encompass the 50 states and District of Columbia, and PADDs 6 and 7 contain US territories. Our dataset included exports from PADDs 1, 3, and 5, representing the East Coast, Gulf Coast, and West Coast (including Alaska and Hawaii) (see Figure 2.2). For these PADDs, we extracted data on barrels of crude oil and refined petroleum that were exported annually from 2005 through 2017 and monthly for 2018. There were 28 distinct petroleum goods (crude oil and 27 refined products). We converted volumes of each petroleum good to tonnages using densities (metric tons/barrel) obtained from the United States Environmental Protection Agency[15]. We then aggregated refined petroleum goods into seven categories based on their end use. The fuels category contained 17 products (e.g., motor gasoline, diesel, propane, kerosene) and the fuel additives category contained five products (e.g., motor gasoline blending components, oxygenates). Lubricants, waxes, petroleum coke, asphalt, and miscellaneous were individual categories of refined petroleum. Crude oil was a unique category.

The EIA reports coal exports from individual terminals throughout the United States[16]. We identified export terminals located on the West, Gulf, and East Coasts and excluded exports from all other locations including the Great Lakes, interior (landlocked) terminals, and US territories to spatially align with locations of petroleum exports. We extracted annual data on short tons of coal exported from 2005 through 2018, converted to metric tons, and summed the export tonnages from ports within each coast. The coal dataset included metallurgical coal (used for steel production), steam coal (used for electricity generation), and coke.

We obtained data on United States exports of liquefied natural gas (LNG) from the Office of Fossil Energy (OFE)[17]. The OFE reports daily vessel-specific LNG exports from all coastal export terminals in operation. During our study period, operational terminals were located in Kenai, Alaska (West Coast), Sabine, Louisiana (Gulf Coast), Corpus Christi, Texas (Gulf Coast), and Cove Point, Maryland (East Coast). We extracted data on cubic feet of LNG exports in annual reports from 2008 through 2018 (LNG exports did not occur during 2005-2007) and converted these volumes to tonnage (48.7 million cubic feet = 1 metric ton LNG). We cross-checked export data obtained from the OFE against shipborne LNG export data available from the EIA. Total annual export quantities matched across datasets; we chose to use the dataset from OFE due to its increased resolution of export location (terminal).

*Ballast water data*

We obtained data on ballast water delivery to the United States from the National Ballast Information Clearinghouse (NBIC)[18]. Commercial vessels are required to report ballast water source, management, and delivery locations and volumes (cubic meters) to the NBIC upon entering US ports on a standardized Ballast Water Management Reporting Form. We extracted vessel-specific arrival and ballast water delivery data from

2005 through 2018 for the West, Gulf, and East Coasts. We used data only for vessels that arrived and ballast water that was sourced from beyond the US exclusive economic zone.

*Analysis*

All analyses were conducted in R[19]. For data collected from the EIA, we compiled a list of Series IDs that identified each good from each export location (PADD or terminal) and a separate list of Series IDs that identified each good to its trade destination. We then used the R package "EIAdata" to import data for analysis[20]. For the destinations of coal exports, we used data provided by the United States Department of Commerce, Bureau of the Census, 'Monthly Report EM 545' compiled by the EIA in a quarterly spreadsheet available on their website.

We summarized the total annual tonnage of energy (metric tons of petroleum, coal, and LNG) exported from each coastal region (West, Gulf, East) and the annual tonnage of ballast water that was imported to each coastal region. We then modeled the relationship between annual energy exports and annual ballast water imports using multiple linear regression with categorical and continuous variables. Further, we modeled the relationship between annual energy exports and annual ballast water imports for the two dominant vessel types (bulkers and tankers) using multiple linear regression.

## Results

### *Total exports*

The United States exported a multitude of goods that we have summarized into Agriculture (e.g., corn, soybean, wheat), Energy (e.g., oil, coal, natural gas), Mineral (e.g., metal ores, sulfur, clays, sand, gravel), and Other (e.g., wood, paper, waste). From 2005-2018, the United States increasingly exported Agriculture, Energy, and Other goods from coastal ports, though the rate of change in Energy exports was greatest. Exports of Energy surpassed all other goods in 2009 and accounted for more than 50% of national export tonnage by 2018 (Figure 2.1a). The growth in national Energy exports relative to other goods was driven largely by a dramatic surge from the Gulf Coast, where Energy was one-third of exports in 2005 and two-thirds in 2018, even while exports of Agriculture and Other goods also rose. On the West Coast, Energy was a growing proportion of exports but remained smaller than Agriculture and Other goods. Energy was a leading export from the East Coast in most years, alongside Other goods (Figure 2.1b-d).

### *Energy boom*

Energy tonnage exported from the coastal United States rose annually from 85 million metric tons (MMT) in 2005 to over 444 MMT in 2018 (Figure 2.2). Petroleum exports grew the most during this period (470%) after remaining relatively stable since the early 1980s (Appendix B Supplemental Figure 1). Coal exports fluctuated over time, falling from a 2012 peak of 107 MMT through 2016 before returning to near peak levels by 2018. Relatively small amounts of LNG (< 6 MMT) were exported through 2015, after which exports grew nearly 500% in three years and accounted for 5% of total energy tonnage in 2018.

Energy exports from each coast varied and grew asymmetrically in type and magnitude over the 14-year period from 2005-2018 (Figure 2.2). On the West Coast, energy exports were predominantly petroleum fuels, steam coal, and petroleum coke. By 2018, annual coal exports from the West Coast had risen from 0.5 MMT to nearly 10 MMT and petroleum exports exceeded 22 MMT, more than doubling the tonnage of energy exported since 2005. The Gulf Coast experienced the largest growth in energy exports of nearly 600% and was the leading region to export crude oil, refined petroleum, and LNG. Exports of petroleum from the Gulf Coast increased annually to more than 291 MMT in 2018 while LNG exports began in 2016. The East Coast led the nation annually in coal exports, dominated by metallurgical and steam coal. Energy exports from the East Coast more than tripled from 2005 after coal rebounded and LNG shipments began in 2018.

*Ship behavior*

Ship specialization of cargo exports drove trends in spatial and temporal ballast water delivery across the United States. Bulk carriers (bulkers) exported three coal products and petroleum coke, while tankers exported a variety of bulk liquid goods such as refined petroleum (including fuels), crude oil, and LNG (Appendix B Supplemental Figure 2). As a result, most ballast water imports on the West and East coasts where coal and petroleum coke exports were common were delivered by bulkers (77% and 75%, respectively), and tankers imported most ballast water on the Gulf Coast (54%) due to increasing petroleum exports.

As energy exports grew nationally, the volume of bulker and tanker ballast water imports rose 230% and more than 1000%, respectively, from 2005-2018. This flux in ballast water volume was driven by a growing proportion of vessels that discharged on each coast, rather than an increasing number of vessel arrivals (Figure 2.3, Figure 2.4). On the West Coast, where agriculture and other bulk commodities were commonly exported in addition to energy, ballast water imports nearly doubled, and the proportion of discharging bulkers remained greater than 50% and was as high as 80%. Ballast water imports to the Gulf Coast increased over 8-fold as the proportion of discharging tankers rose from 14%-65%; the number of arrivals increased by just 42%. East Coast ballast water imports increased 9-fold, though the annual proportion of discharging bulkers fluctuated with the trend in coal exports.

*Relationship between energy exports and ballast water imports*

There was a strong relationship between fluxes in energy exports and ballast water imports across the coastal United States from 2005-2018 (multiple linear regression, $F_{3, 38} = 378.9$, adjusted $R^2 = 0.97$, Figure 2.4). The relationship between ballast water imports and energy exports was dependent on ship type ($F_{3, 24} = 175.8$, adjusted $R^2 = 0.95$), as bulkers imported 87% more ballast water per ton of energy exported than tankers (Appendix B Supplemental Figure 3). Nationally, bulkers imported more ballast water than tankers annually from 2005-2016. Nevertheless, tankers exported greater tonnage of energy than bulkers in 2009, corresponding with a decrease in coal exports from the Gulf and East Coasts, and annually from 2014-2018. Tanker energy exports grew roughly 30% in both 2017 and 2018 as petroleum exports boomed on the Gulf Coast, leading to an increase in ballast water imports in those years.

*Invasion opportunity*

The magnitude of ballast water imports was driven by ship type and the destinations of cargo. Bulkers exported coal to Canada, the Netherlands (for distribution to other European countries), Brazil, the United Kingdom, South Korea, and India. Most petroleum was exported by tankers to Mexico and Canada. When LNG exports began in earnest in 2016, primary tanker destinations were South Korea, Mexico, Japan, and China (Appendix B Supplemental Figure 4). From 2005-2018, energy exports from the United States grew more than 400% to 13 countries and 1,000% to seven countries (Figure 2.5). The largest increase in energy exports was to Taiwan (> 21,000%) primarily from petroleum.

The proportion of ballast water imports that was reported to have undergone management to reduce the concentration of coastal organisms varied by ship type and coast (Appendix B Supplemental Figure 5). Bulkers tended to have high and steady rates of ballast water management across all coasts (ranging from 89.7 ± 1.2% in 2005 to 94.9 ± 1.1% in 2018, mean ± standard error). Conversely, tankers reported managing less than 50% of ballast water in 2005 on the West and Gulf Coasts. Under changing regulations, the management rates of tankers improved to greater than 90% by 2018 on all coasts. Management rates were generally lower on the Gulf Coast than the West and East Coasts for both vessel types. Most ballast water imports were managed with mid-ocean ballast water exchange, with a lesser but growing volume managed with onboard treatment systems (1% in 2014 – 25% in 2018).

## Discussion

Our findings indicate that the sustainability of present-day energy demand can be linked to the behavior and dynamics of bulk and tank ships engaged in international trade. The growing usage of energy across a variety of sectors (e.g., industry, transportation, electricity production) has often been associated with global sustainability challenges, particularly air pollution and climate change[21]. Maritime shipping presents a sustainability and regulatory challenge beyond vessel emissions ($CO_2$, $SO_X$, $NO_X$) to invasive species[22]. Here we show that growth in tonnage of energy exports drives the flux and magnitude of ballast water delivery to a remarkably strong degree, which was previously unappreciated, and in turn is likely a key variable in dynamics of biological invasions.

### *Energy trade dynamics*

Demand for energy comes as the world is increasing its capacity and usage of electricity and transportation alongside other investments in economic development[23]. As energy consumption accelerates, geography and distribution of resources have led to greater energy transport on ships, linking supply and demand[24]. As a result, energy globalization, though variable, has grown over time as countries develop new trade partners[25]. A variety of factors, such as policies, price, and technology, interact to create dynamic markets for energy trade.

In the era since coal production spurred the Industrial Revolution in the 18th century[26], demand for modern energy has at various times been a driver or a passenger of global events. Variability in supply and demand has in turn driven fluctuations in shipping behavior. In the United States, steam coal exports from the East Coast rebounded in 2017 and 2018 in part to meet India's growing electricity demand from coal-fired power plants and due to the shutdown of nuclear-powered plants in Europe. Exports of metallurgical coal from the United States increased in 2017 when a tropical cyclone disrupted supply that typically originated in Australia. The global pandemic beginning in late 2019 brought a sharp decline in energy demand that affected price and production around the world[27].

The energy industry is shaped by policy and action at various levels. In the 1970s, global events induced two energy crises in the United States that resulted in national oil shortages, high prices, and a ban on crude oil exports. In response, experts called for greater reliance on domestic coal and encouraged stockpiling, among other measures, to boost energy independence from global supply shortages[28,29]. During the following decades, while demand grew but domestic oil production declined, the United States became the top oil-importing nation in the world[30]. The tide turned in the late 2000s when hydraulic fracturing and horizontal drilling technologies led to a boom in unconventional oil and gas extraction and production[10]. US refineries, long accustomed to processing imported heavy crude oil, adopted technologies to process newly available domestic light oil. By 2011, the United States had become a net exporter of refined petroleum products[30]. The crude oil export ban from the 1970s was lifted in December 2015 and exports increased annually through 2019. Meanwhile, in 2016, the US became a net exporter of LNG and since then new LNG export terminals came online on the Gulf and East Coasts to increase capacity. In 2018, the United States had the largest ever annual growth in oil and gas production of any country in the world[11]. Additionally, the United States has the largest coal reserves in the world and has remained a net exporter through time despite fluctuations in global demand[31]. In 2019, as energy production increased and imports declined, the United States became a total net exporter of energy for the first time in 67 years.

*Maritime shipping*

Fluctuations in global energy supply and demand directly influenced regional maritime shipping dynamics in the United States. Growing energy exports led to an increasing proportion of arriving ships that discharged ballast water on each coast, positively influencing the opportunity for biological invasions. A combination of ship type and export commodity affected the magnitude and location of ballast water imports. Bulkers imported more ballast water than tankers in most years and disproportionately more per ton of energy exported. However, the nearly six-fold rise in petroleum and LNG exports from the Gulf Coast led to the largest growth in ballast water imports to that coast over time from tankers.

More ship arrivals and ballast water imports are expected to result in an increased likelihood of invasions, since the number and frequency of viable organism introductions, or propagule pressure, increases the probability of NIS introduction and establishment [8,32]. The assemblages of species in ballast water are determined by the source pool of the trade partner. Countries that imported coal and petroleum coke, often in Asia and Europe, were key source locations of biota delivered by bulkers. Likewise, the destinations of petroleum exports by tankers, often Canada and Mexico, increasingly connected those regions with the Gulf Coast. Greater connectivity with a variety of trade partners can increase propagule pressure and broaden the species source pool.

Energy is anticipated to continue to play a role in shipping dynamics in the United States. For instance, several additional LNG export terminals are under construction, approved, or proposed, largely on the Gulf Coast[33,34]. This region has historically had fewer primary invasions compared to the West and East Coasts[35], but the exaggerated propagule pressure documented here will likely influence future invasion dynamics. Risk of ballast-borne invasions throughout the United States will continue to remain unevenly distributed, with hotspots emerging at locations where the volume and frequency of imports are greatest. Current energy export terminals and new coastal or offshore infrastructure can serve as monitoring sites for detecting existing and novel invasions, such as ports on the Texas coast.

*Future sustainability*

Rising energy use has been driven by economic growth and this trend looks to continue into the future[36]. In recent years, the demand for relatively cheap and available fossil fuels in developing nations such as China and India has skyrocketed with potential for additional growth[37]. The LNG sector is expected to expand from regional markets to globally integrated trade with rising demand and short-term transactions, potentially leading to tanker shipments that are sensitive to global fluctuations in supply and demand. China's Belt and Road Initiative to boost trade between Asia, Africa, and Europe, already recognized as a pathway for terrestrial invasions, will include a Maritime Silk Road with dozens of proposed new ports and increased oil and gas supply throughout the region[38,39].

Ensuring people's access to energy is distinctly recognized by Goal 7 of the United Nation's 2030 Sustainable Development Agenda[40]. In addition to improving social well-being and opportunity, energy is fundamental to the achievement of many other global sustainability goals, such as no poverty (Goal 2), good health (Goal 3), quality education (Goal 4), clean water and sanitation (Goal 6), and economic growth (Goal 8)[3]. To meet this goal amidst the growing consumption of fossil fuels, the world aims to improve energy sustainability with efficiencies and transition to renewable sources. Efforts to reach climate goals, such as those set forth in the Paris Agreement, may eventually shift trade patterns or even reduce the volume of shipping with changes in dominant energy sources (e.g., reduction in coal)[41]. Marine pollution regulations set forth by the International Maritime Organization to limit sulfur in ships' fuel will influence refinery practices beginning in January 2020[42]. In the future, cleaner energy sources and new technologies may boost the sustainability of energy production and storage[43]. While the proportion of modern, renewable energy has grown modestly in recent years, future policy and consumer demand will continue to change the landscape of energy supply[2].

The future sustainability of energy markets and maritime shipping will undoubtedly be shaped by anticipated and unanticipated events. As seen here, the direction and magnitude of maritime shipping is derived from global drivers of economic growth and trade between countries. Since shipping is the leading mechanism to introduce NIS to coastal marine environments, this pattern underscores the influence of global socioeconomics on ecological processes and the human-mediated nature of biological invasions. Given that there does not yet appear to be saturation in global invasions[44], as the shipping network grows our methods can be applied more broadly or to other regions experiencing fluxes in bulk maritime trade. Exploring the global drivers of regional changes in shipping behavior can aid local prioritization of early detection and rapid response initiatives for biological invasions.

*Recommendations*

Coordinated, preventative approaches are critical to the sustainable management of leading vectors of NIS. Decades of effort to curb the introduction of species in ballast water led to the International Maritime Organization's (IMO) Ballast Water Management Convention that entered into force in 2017. The Convention requires vessels engaged in international trade to use ballast water treatment systems (BWTS) to meet organism concentration limits upon discharge. Since the Convention is phased in over multiple years, some vessels are currently operating these systems while others prepare for installation. The United States is similarly phasing in requirements for vessels to operate BWTS prior to discharge in US waters. In the meantime, vessels engage in ballast water exchange, a practice to flush water and organisms entrained in coastal ports beyond 200 nautical miles from shore. BWTS are expected to reduce the concentration of organisms in ballast water more than ballast water exchange[45]. Our results underpin the urgency for the global fleet to install and operate BWTS. Furthermore, it is imperative to understand the efficacy of BWTS under different coastal conditions (e.g., salinity, turbidity, organism concentrations) and growing ballast water volumes. Despite international attention to ballast water management, increased volume and frequency of ballast water delivery may offset the benefits of reduced organism concentrations achieved by mid-ocean exchange or onboard treatment systems[46].

Fouling on ship hulls, niche areas, and other underwater surfaces is also a dominant mechanism of NIS introductions from ships. Longer port calls allow more time for organisms to accumulate in source locations and release in introduced locations[7]. In 2018, the global median number of days in port for dry bulk carriers was nearly 3 times that of container ships, and a third greater for liquid bulk carriers[1]. The impact of energy exports on the number, frequency, and port residence times of bulker and tanker arrivals is an area for further study in the United States and elsewhere, as residence times vary by location depending on the number of arrivals and the efficiency (turnaround time) of the port.

Global sustainability challenges are often related. As indicated here, natural resource extraction and economic growth directly impact opportunity for biological invasions that cause lasting impacts to the health and resiliency of native ecosystems. Examining synergies between sustainability challenges highlights opportunities for integrated management, linking disciplines and avoiding policy silos[47]. The result is a more comprehensive and efficient approach to solving global challenges[48].

Figures

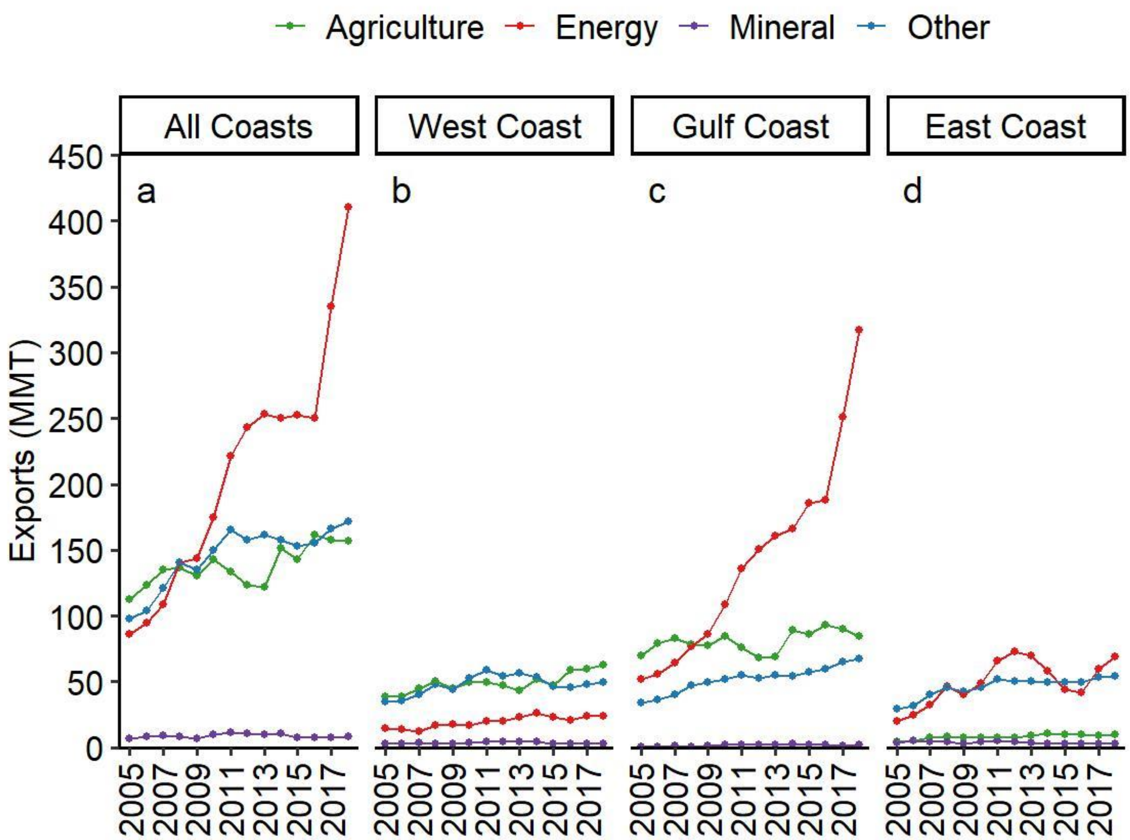


**Figure 2.1. Total exports from the coastal United States**
Values represent the annual tonnage of shipborne exports (million metric tons) aggregated by type of goods. Panel a represents the sum of panels b-d; panels b-d represent exports from each coast.

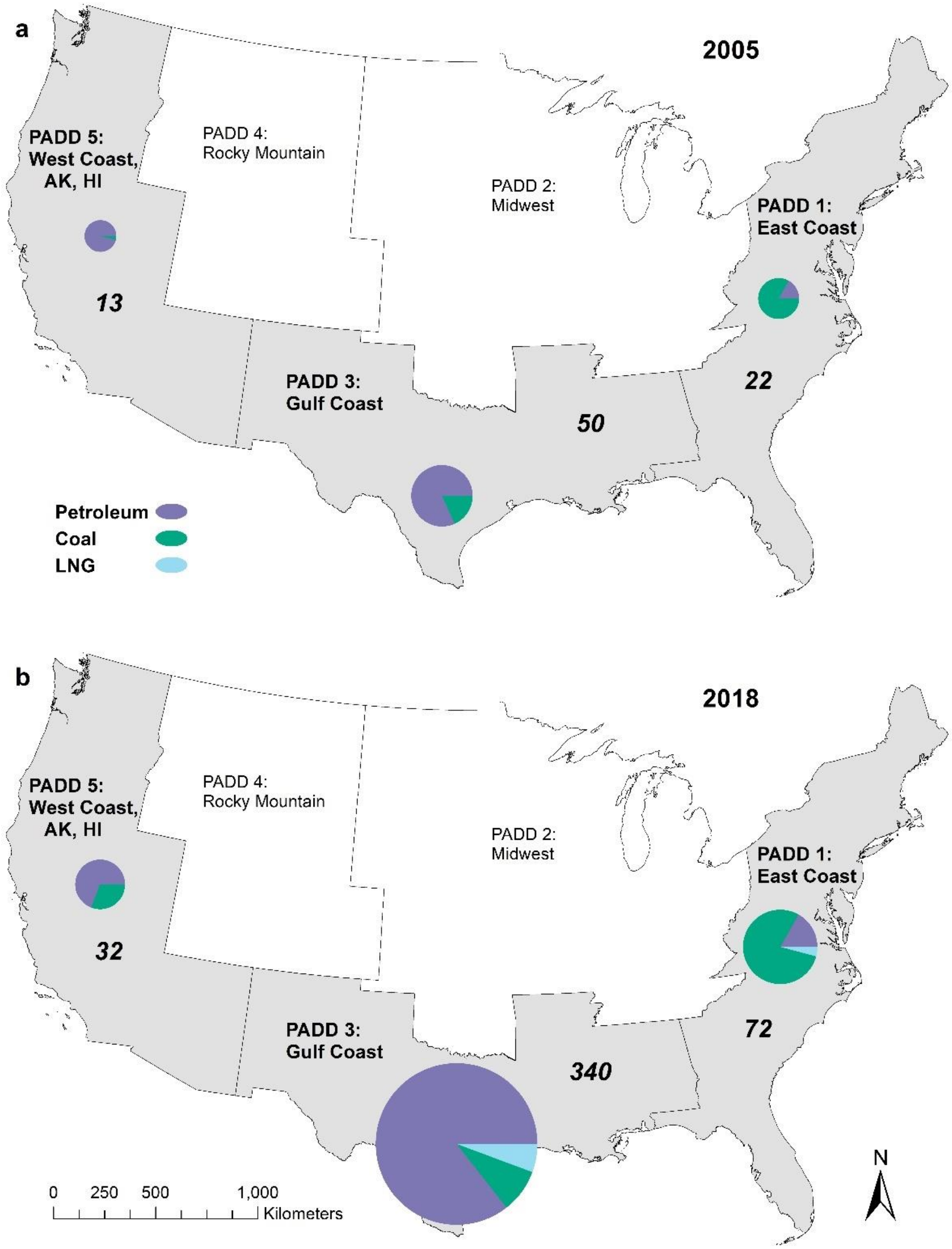


**Figure 2.2. Spatial and temporal energy exports**

Tonnage of energy exports from the coastal United States in 2005 (a) and 2018 (b). Pie charts and values indicate million metric tons of total shipborne energy exports from each region. Regions are denoted by Petroleum Administration for Defense Districts (PADDs 1 – 5).

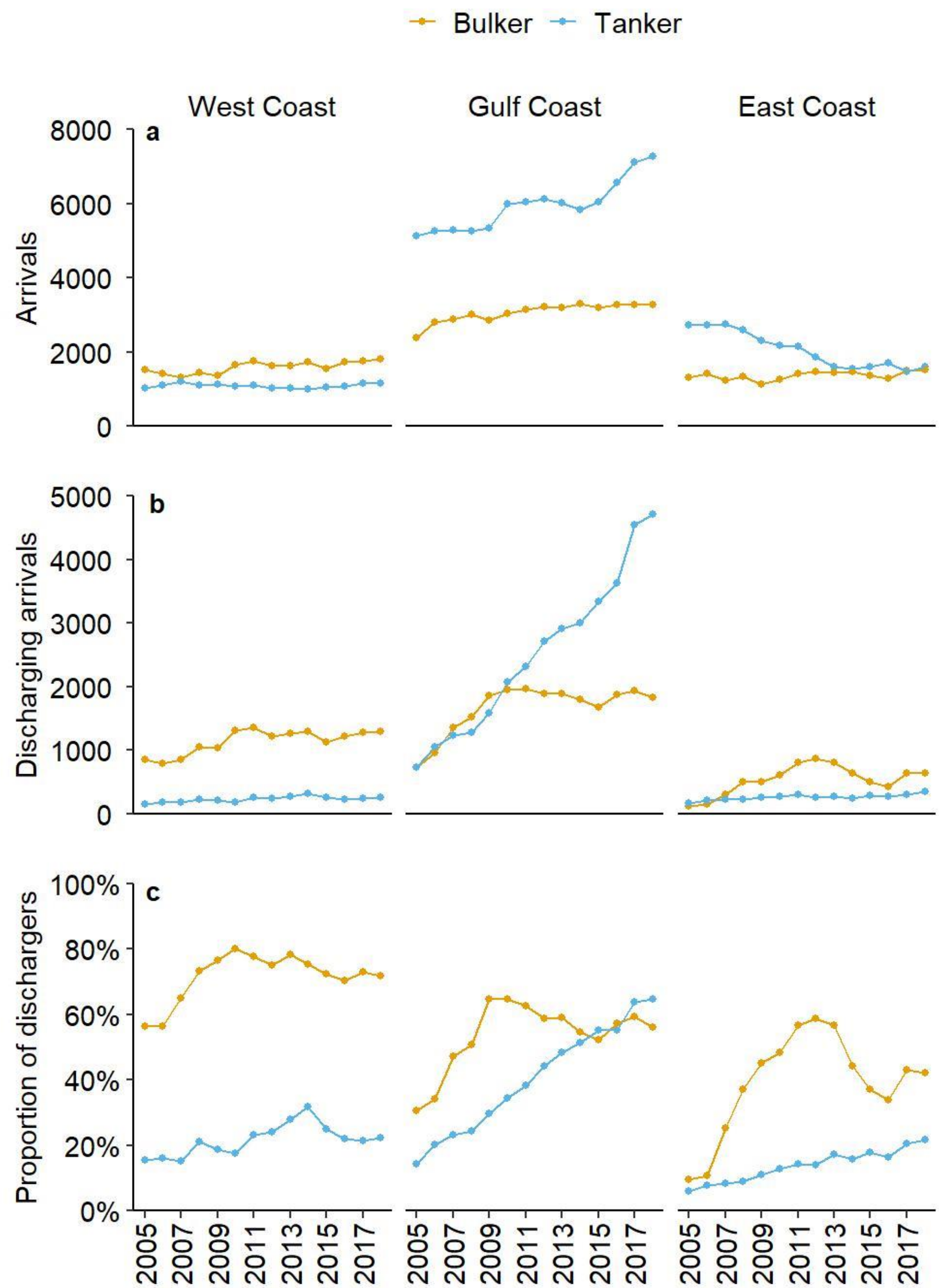


**Figure 2.3. Vessel arrivals and proportion of dischargers**
Overseas bulk and tank vessels that arrived and delivered ballast water on each coast of the United States. The dominant vessel type to arrive on each coast varies and the proportion of arrivals that deliver ballast water is influenced by the tonnage and type of exports.

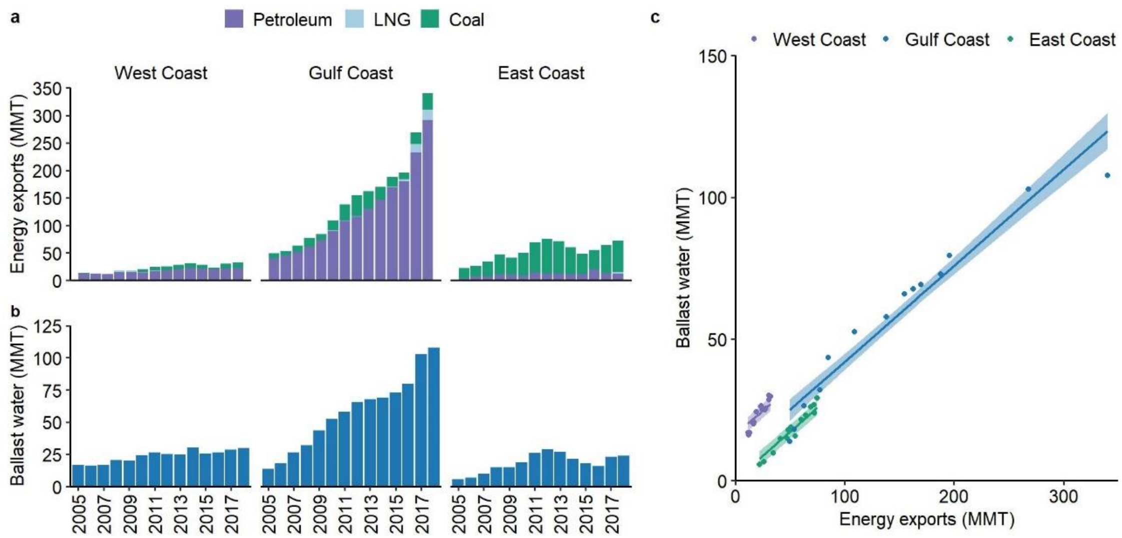


**Figure 2.4. Energy exports and ballast water imports**
The relationship between energy exports and ballast water imports on coasts of the United States. Values represent million metric tons. A linear regression model of the relationship can be described as: $y = 1.62 \times 10^{7} - 8.01 \times 10^{6}{}_{G} - 1.58 \times 10^{7}{}_{E} + 3.39 \times 10^{-1}x$ , where $G$ and $E$ represent dummy coded contrasts of the Gulf and East Coasts to the West Coast. Adjusted $R^2 = 0.97$. Shaded areas in panel c represent 95% confidence intervals.

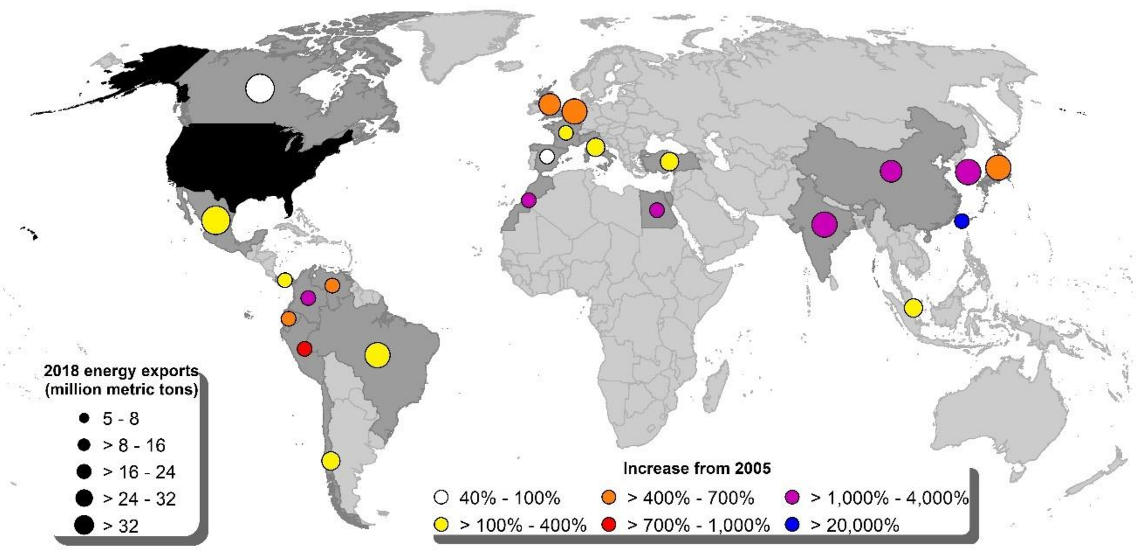


**Figure 2.5. Recent top destinations of energy exports from the United States**
The size of the circle indicates the magnitude of shipborne energy exports from the US to countries that received greater than five million metric tons in 2018. The color indicates the percentage increase in tonnage received between 2005 and 2018. See Appendix B Supplemental Figure 2 for the annual tonnages received in each country. Robinson projection.

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## Chapter 3
## Recent and projected ballast water dynamics from maritime shipping in Alaska

Abstract

Marine nonindigenous species (NIS) pose direct and indirect threats to coastal Alaska. Presently, Alaska's coastal ecosystems are relatively uninvaded with few substantial impacts to marine resources. To allocate detection efforts in a vast and changing coastline, it is useful to identify the possible effects of fluxes in dominant NIS vectors. The ballast water of ships is a leading vector of NIS to the marine environment, and the largest per capita ballast water volumes are discharged by ships that export bulk goods (e.g., coal, oil, timber). Here, I first examined spatial and temporal patterns of commercial vessel arrivals and ballast water discharge to Alaska from 2009-2018. Second, I identified trade and economic activities that drove shipping behavior in dominant ports. Third, I modeled the relationship between annual ballast water discharge volume and the number of discharging vessels. Lastly, I estimated annual ballast water discharge volume with a sensitivity analysis of tanker and bulker arrivals. I found that 90% of vessels arrived in 15 ports, and arrivals grew 38% across the ten-year period. Most arrivals were passenger ships engaged in tourism in southeast. Container and reefer vessels transporting seafood often arrived in Dutch Harbor and Kodiak. Mean (±SD) annual statewide ballast water volume was 12.99 (±0.44) million metric tons (MMT). Five ports received 96% of ballast water, driven by oil tankers in Prince William Sound and bulk carriers that exported mining ore from Red Dog and coal from Seward. The number of tankers that discharged ballast water annually explained 70% of the variation

in annual tanker discharge volume; the number of discharging bulkers explained 94% of bulker discharge volume. A sensitivity analysis, ranging from a 20% decrease to a 20% increase in the number of discharging tankers and bulkers found potential median annual discharge volumes of 11.3-14.9 MMT. New exports of liquefied natural gas from Nikiski could double the number of tankers arriving in Alaska annually, resulting in a median annual volume of 17.5 MMT. My results highlight the influence of natural resource extraction on shipping behavior and opportunity for ballast-borne NIS in coastal Alaska.

## Introduction

Maritime shipping introduces nonindigenous species (NIS) across geographic barriers and at speeds that would be impossible through natural dispersal, consequently leading to biological invasions globally (Mooney and Cleland 2001; Hulme 2009). Global trade networks are shown to be predictors of anthropogenic movement of NIS (Westphal et al. 2008; Chapman et al. 2017), and the scale and directionality of maritime shipping, driven by trade dynamics, can influence NIS delivery across time and space (Ruiz et al. 1997). As trade patterns change and new infrastructure is developed, scenario building of shipping patterns has indicated spatial shifts in exposure to NIS vectors including ballast water and biofouling (Muirhead et al. 2015).

Ships' ballast water is responsible for transporting NIS to novel locations on global and regional scales (Bailey 2015). A vessel takes on seawater as ballast to provide stability as it transits between locations without cargo. When the vessel loads cargo it discharges ballast water, inadvertently introducing entrained organisms to a different port or place. Vessels designed to transport bulk liquid and dry goods in large cargo holds (i.e., tankers and bulk carriers) typically carry goods in one direction and return laden with ballast water. Due to this unique ship behavior, tankers and bulk carriers discharge more ballast water than other vessel types (e.g., container, passenger, ro-ro ships), which tend to carry goods on every voyage (Davidson et al. 2018). While a region may receive a variety of vessel arrivals, ports that export bulk commodities often receive relatively high volumes of ballast water that put them at greater risk of NIS introductions. This behavior of tank and bulk vessels is evident across a range of ports and bulk commodities and can be used to predict potential changes in ballast water volume and NIS introduction opportunity over time (Verna et al., Chapter 1).

Transport and introduction are the first hurdles to a successful biological invasion, prior to a species' establishment and spread (Blackburn et al. 2011). Though the uncertainties associated with each step of the invasion process are substantial, prevention and early detection are considered most effective and least costly management options that lead to invasion failure (Epanchin-Niell 2017). An assessment of current and projected drivers of NIS introductions from maritime shipping is particularly informative for coastal areas with few invasions where management priorities emphasize prevention and early detection. Additionally, reviewing the prevalence of preventative management practices can highlight room for improvement or variation in risk. To reduce the concentration and abundance of coastal organisms in ballast water, two management approaches are typically used: mid-ocean exchange or onboard treatment systems (Casas-Monroy et al. 2015). While both management methods are effective at reducing likelihood of NIS introductions, treatment systems establish a numeric threshold for organism concentrations based on size class that is lower than what is typically achieved with ballast water exchange (Minton et al. 2005).

High latitude marine ecosystems, including those of Alaska, are relatively uninvaded, likely as a combined result of low anthropogenic disturbance (intact habitat) and climate (Mahanes and Sorte 2019). However, high latitude shipping is an emerging pathway of NIS given the increase in trans-Arctic and within-Arctic maritime trade facilitated by climate change (Miller and Ruiz 2014; Lassuy and Lewis 2013). Greater anthropogenic activity in the Arctic region will likely result in heightened invasion risk as a result of increasingly suitable climatic conditions and more NIS introductions (Chan et al. 2019). Potential hotspots of biological invasions from ballast water have been identified in several Alaskan ports, driven by exports of commodities derived from natural resource extraction including oil, coal, mining ore, and timber (McGee et al. 2006; D. Verna et al. 2016). Anticipated new port development and fluctuations in natural resource extraction will undoubtedly have an effect on vessel traffic and ballast water delivery throughout the state (Huntington et al. 2015; Holzer et al. 2017).

Given that NIS pose a significant threat to the health and integrity of marine ecosystems, modeling shipborne introduction opportunities with regards to commercial trade activity can inform management and encourage localized surveys (Seebens et al. 2013). Here I used a comprehensive dataset on vessel arrivals and ballast water discharge to examine commercial shipping dynamics in Alaska during a recent ten-year period and identified port activities that drove vessel behavior. Next, I considered arrival and ballast water discharge activity of unique vessel types to model annual ballast water volume across the state. Lastly, I explored how fluxes in bulk commodities trade from existing and proposed ports would influence ballast water discharge. This analysis provides insight into NIS introduction opportunity to Alaska and identifies data gaps that would improve future estimations. My approach to modeling and projecting ballast water discharge is transferable to other locations or time periods to inform invasion potential under anticipated changes in trade or vessel traffic.

## Methods

### *Study area*

This analysis focused on coastal marine ports and places within the state of Alaska. Alaska's coastline ranges from the temperate North Pacific Ocean to Arctic waters and contains six marine ecoregions including the North American Pacific Fjordland, Gulf of Alaska, Aleutian Islands, Eastern Bering Sea, Chukchi Sea, and Beaufort Sea (Spalding et al. 2007). These ecoregions consist of diverse habitat, high productivity, and abundant biota that support a variety of subsistence, sport, and commercial harvests integral to the way of life and economy of the region. There are commercial shipping ports in each ecoregion except for the Beaufort Sea, though most ports are located along the southern coast of the state.

### *Data sources and cleaning*

I obtained data on vessel arrivals and ballast water discharge to all ports and places in Alaska between 2009 and 2018 from the National Ballast Information

Clearinghouse (National Ballast Information Clearinghouse 2019). The NBIC collects data from commercial vessels that arrive in the United States on standardized forms that capture vessel behavior and ballast water history. Data include vessel descriptors (type, gross tonnage, name, IMO number, ballast water capacity); ports of call (arrival port, last port, next port); the location, volume, and date of ballast water source, management, and discharge; and management method.

Vessel reporting to the NBIC became mandatory for nearly all commercial vessels arriving to ports in the United States in late 2004. However, an exemption from recordkeeping and reporting was in effect for crude oil tankers engaged in coastwise trade until late 2008 when new regulations went into effect from the United States Environmental Protection Agency (Verna and Harris 2016). Since crude oil tankers are the leading source of ballast water to Alaska, this analysis began in 2009.

I made the following adjustments to the original dataset. First, arrival data from ferries engaged on the Alaska Marine Highway System were removed. These vessels reported arrivals in 2017 and 2018 only, inflating the number of ro-ro vessel arrivals compared to other years. Furthermore, these vessels did not report ballast water discharge on any arrival. Second, one arrival report and two ballast water discharge reports located at inland coordinates were removed for accuracy. Third, ballast water discharge locations reported at coordinates within 0.5 nautical miles from a port were spatially joined to that port. This step ensured that the total ballast water discharge volume received in a given port was accurately reflected, and was applied to 2 discharge points at Red Dog, 137 points at Whittier, and one point at Skagway. Lastly, a similar approach was used for discharge locations within bays including two points in Togiak Bay, one point in Bristol Bay, and ten points in Captains Bay. The vessel type "tankers" includes crude oil tankers and other tankers.

I reviewed material on planned or projected changes in vessel traffic, infrastructure, and natural resource development in Alaska. Some data sources covered statewide or regional growth, including a report on projections of vessel traffic in the Arctic from 2020 to 2030 (Harrison 2019), an online database inventory of current and proposed Arctic infrastructure (Durkee et al. 2021), and a planning document for Alaska's ports and harbors (Northern Economics, Inc. 2011). Other resources explicitly addressed fluctuations in currently active industries in Alaska such as petroleum, natural gas, timber, and mining (Holzer et al. 2017; Daniels et al. 2016; Federal Energy Regulatory Commission 2020; 85 Fed. Reg. 197 2020; US Energy Information Administration 2020). Using these materials, I identified projects that could potentially influence bulk trade in existing or new ports.

*Analyses*

I assessed commercial vessel arrivals to Alaska from 2009-2018 by type, arrival location, and whether arrivals discharged ballast water. I examined fluxes in the volume of ballast water received and number and type of vessels that discharged. I also examined ballast water source, management rates, and management methods across time. In addition, I identified the dominant trade commodities or economic activities in each port that influenced vessel behavior for all arrivals and the subset of vessels that discharged ballast water.

I developed linear models that estimated relationships between the annual number of discharging vessels and the annual volume of ballast water discharged for both tankers and bulkers. Using these models, I conducted a sensitivity analysis to assess how changes in the number of discharging vessels influenced ballast water discharge volume. To represent a decrease in the number of vessels, I assessed 10%, 20%, 30%, 40%, and 50% of the lowest annual number of discharging tankers and bulkers. To represent an increase in vessels, I assessed 10% - 50% of the highest annual number of both vessel types (Table 3.1).

I used the results of the sensitivity analysis to estimate the annual ballast water volume that would be received in Alaska under eight hypothetical changes in the number of discharging vessels (Table 3.2). Since different trade activities drive tanker and bulker arrivals, these scenarios allow for independent fluctuations in each vessel type. The first seven scenarios account for potential changes in the number of vessel arrivals at current ports in Alaska. The first scenario represents a 20% decrease in both tankers and bulkers. The second scenario represents a 20% decrease in tankers and the mean number of bulkers from 2009-2018. The third scenario represents a 20% decrease in bulkers and the mean number of tankers from 2009-2018. The fourth scenario represents business as usual, where the annual number of tankers and bulkers remains the same as the mean over the recent ten-year period. The fifth scenario represents a 20% increase in bulkers and the mean number of tankers. The sixth scenario represents a 20% increase in tankers and the mean number of bulkers. The seventh scenario represents a 20% increase in both tankers and bulkers. The eighth scenario accounts for proposed port development and exports of liquefied natural gas (LNG), where the mean number of tankers doubles and the mean number of bulkers remains the same.

## Results

### *Arrivals and ballast water discharge*

From 2009-2018, 27,116 arrivals to Alaska were reported to the NBIC. Most vessel arrivals were foreign-flagged passenger vessels (48%), followed by domestic tankers (16%), other vessels (14%), and containerships (10%), and to a lesser degree reefer, ro-ro, bulk, and general cargo ships (Figure 3.1). Total vessel arrivals grew 38% from 2009-2018, driven by an increase in passenger vessels. Most vessel arrivals (79%) did not discharge ballast water, though this varied by vessel type (Figure 3.2). Over the ten-year period, 131.7 million metric tons (MMT) of ballast water was discharged to Alaska, primarily by tankers and bulkers (91% and 8%, respectively). The annual volume of ballast water discharged statewide grew slightly through 2011 but decreased 4% overall (Figure 3.3). Both tanker and bulker ballast water discharge reached a maximum in 2011, followed by decline through 2015 for tankers and 2017 for bulkers.

Passenger vessels arrived primarily in the southeast Alaska communities of Juneau, Ketchikan, and Skagway, where cruise ship tourism is common. Most tankers (62%) arrived in Port Valdez at the terminus of the trans-Alaska pipeline to export crude oil. Container, reefer, and other vessels arrived primarily in Dutch Harbor where they transported seafood products. Bulkers arrived at Red Dog and Hawk Inlet for mining exports and at Afognak for timber exports (Figure 3.4a).

The location of tanker and bulker ballast water discharge varied by vessel type and bulk exports (trade) at the port, and most ballast water was received at only a few ports (Figure 3.4b). Port Valdez received 114 MMT of ballast water, accounting for 87% of total ballast water discharge and 96% of tanker discharge. Red Dog received 4.8 MMT of ballast water, the second largest volume at a single port, and 45% of bulker discharge. Seward received 2.2 MMT (21% of bulker discharge), but the volume of ballast water received annually declined from a peak of 0.5 MMT in 2011 to less than 0.01 MMT in 2017 and 2018 as exports of coal from the port ceased. Afognak received 0.88 MMT of ballast water and 8% of bulker discharge.

The source locations of tanker and bulker ballast water differed considerably. Most ballast water from tankers was sourced along the west coast of North America (97%), as tankers often transported oil from Port Valdez to terminals and refineries in Washington (Anacortes, Bellingham) and California (Long Beach, Benicia, Richmond). Conversely, bulkers predominantly sourced ballast water from overseas ports in China, Japan, Korea, and midocean locations during the voyage to Alaska (97%).

*Ballast water management*

Ballast water management was performed on 61.9 MMT (47%) of the total volume discharged to Alaska from 2009-2018. Annual management rates increased over the ten-year period. In 2015, management was reported on greater than 50% of annual ballast water discharge for the first time, increasing to 70% by 2018 (Figure 3.5). Of the ballast water that was reported managed, ballast water exchange was the most common method, totaling 57.5 MMT of discharge across the ten years. Use of onboard treatment systems for management was first reported in 2015 and increased annually through 2018, totaling 4.8 MMT in 4 years. When ballast water was not managed prior to discharge, vessels reported various reasons; most commonly safety of the vessel due to weather, ballast water was taken onboard from a mid-ocean source, and the vessel's route was exempt from management.

*Modeling annual ballast water volume*

The annual volume of ballast water received from tankers and bulkers was explained independently by the annual number of vessels of each type that discharged ballast water. The annual number of discharging tankers ranged from a low of 260 in 2014 to a high of 319 in 2011 (288 ± 5.5, mean ± standard error). The annual number of discharging bulkers ranged from a low of 51 in 2017 to a high of 88 in both 2010 and 2011 (71 ± 4.4, mean ± standard error). Given the range between the number of discharging tankers and bulkers and corresponding discharge volumes, we developed separate models for each vessel type.

The relationship between the annual number of dischargers and annual ballast water volume (MMT) for tankers can be described as: $y = 7.4 + 0.01562x$, $R^2 = 0.70$.

The relationship between the annual number of dischargers and annual ballast water volume (MMT) for bulkers can be described as: $y = 0.10039 + 0.01392x$, $R^2 = 0.94$.

*Sensitivity analysis and scenarios of ballast water discharge*

The review of bulk commodities forecasts, such as oil, timber, and minerals, seldom included projections of the number of vessels necessary for export. I identified one proposed project where additional natural resource extraction would lead to increased bulk exports. Specifically, proposed LNG exports from the port of Nikiski is anticipated to bring 204-360 (median 288) additional tankers to Alaska annually (Federal Energy Regulatory Commission 2020).

Hypothetically adjusting the number of tankers and bulkers that discharge ballast water annually, using the models described above, indicated a broad potential range of discharge volumes within and across vessel types (Table 3.1). Scenarios that involved changes in the number of tankers had a far greater impact on potential volume, as reflected in scenarios 3 and 5 where the number of tankers remained stable (Figure 3.6). In scenario 1, the number of both tankers and bulkers decreased by 20%; total annual median ballast water discharge volume was 11.32 (10.43, 12.21, 95% prediction interval) MMT. In scenario 2, tankers decreased by 20% and bulkers remained stable; annual discharge volume was 11.74 (10.87, 12.60) MMT. In scenario 3, bulkers decreased by 20% and tankers remained stable; annual discharge volume was 12.57 (12.01, 12.14) MMT. In scenario 4, business as usual, annual discharge volume was 12.99 (12.45, 13.53) MMT. In scenario 5, bulkers increased by 20% and tankers remained stable; annual discharge volume was 13.48 (12.90, 14.05) MMT. In scenario 6, tankers increased by 20% and bulkers remained stable; annual discharge volume was 14.47 (13.51, 15.43) MMT. In scenario 7, both tankers and bulkers increased by 20%; annual discharge volume was 14.96 (13.96, 15.95). Finally, in scenario 8, the mean number of tankers and bulkers from existing ports remained stable and an additional 288 tankers were added, doubling the number of discharging tankers; annual discharge volume was 17.49 (15.11, 19.86) MMT. The span of potential discharge volume between scenarios 1 and 8 was 6.2 MMT (55% difference).

## Discussion

### *Maritime shipping patterns*

This analysis reveals recent patterns of arrivals and ballast water discharge from commercial vessels in Alaska and describes potential fluxes in ballast water volume with eight scenarios. I show that commercial vessel arrivals in many ports of Alaska are often a single vessel type and/or driven by a specific industry, e.g., tourism, petroleum, mining, seafood, or forestry. Since vessel types behave differently with regards to ballast water delivery (Davidson et al. 2018), here the economic driver of a port can serve as an indication of NIS introduction opportunity from ballast water. Moreover, arrivals alone are not a suitable replacement for data on ballast water delivery since most arrivals did not discharge (Minton et al. 2015; Verling et al. 2005). During the study period, the number of arrivals grew (driven by tourism and passenger vessels) while ballast water discharge declined slightly, often at different ports.

Considering the behavior of unique vessel types, the models developed here indicated that annual number of discharging tankers and bulkers can robustly predict the volume of ballast water received statewide. This is in contrast to other studies (e.g., Chapter 1) where number of vessels, even bulk vessels, is not a good proxy for ballast water volume, since ports both import and export bulk goods, resulting in differing ballasting behavior among arrivals. In Alaska, ports that received bulk vessels were exporting but not importing goods, thus most arrivals discharged ballast water.

The growth in management rates during this study period reflects implementation of new regulations and a marginal transition from ballast water exchange to onboard treatment systems. This is noteworthy since the number and density of organisms in ballast water discharge depends on management. Ballast water exchange has been shown to have an efficacy rate of 90%, reducing mean zooplankton concentrations from $10^4$ to $10^3$ organisms per cubic meter (Minton et al. 2005). Ballast water treatment systems must meet a numeric discharge limit of 10 organisms per cubic meter ≥ 50 μm (typical zooplankton size class) (Verna and Harris 2016). While the exact relationship between NIS introductions and successful establishment is unknown, in general greater numbers and densities of organisms and increased frequency of delivery (propagule pressure) are expected to result in greater likelihood of invasion (National Research Council 2011). Orders of magnitude reduction in organism concentrations between unmanaged, exchanged, and treated ballast water will have a large impact on NIS introductions across the range of scenarios and ballast water discharge volumes explored here.

The variation in source region between tankers and bulkers is striking in its potential to effect NIS introductions and survival, as well as surveillance siting and design. The type and abundance of organisms in ballast water uptake is influenced by location and seasonality, while survival in recipient ports is dependent on environmental match between locations (Casas-Monroy et al. 2015; Seebens et al. 2016). Tankers primarily sourced ballast water from invaded west coast port systems containing species shown to survive in Alaskan waters, including Port Valdez (Ruiz et al. 2011; Hines and Ruiz 2000). Bulker ballast water from Asian countries is likely to have less similarity to high latitude ports such as Red Dog, though further study is needed to assess the species source pool and risk from these vessels to lower latitude ports. Moreover, bulkers that originated in overseas ports tended to have higher rates of management than coastal tankers, further reducing likelihood of NIS introduction.

Commercial vessel arrivals and ballast water discharge were often concentrated in a few regions and ports within the state (Figure 3.4). These patterns of arrivals and ballast water effectively concentrated the likelihood of primary NIS introductions from ballast water to key locations driven by key industries. Prince William Sound, located in the southcentral region of the state, clearly received the largest volume of ballast water due to oil exports form Port Valdez. Thus, oil and gas is by far the leading industry to drive ballast water delivery in Alaska. New LNG exports would increase the influence of that industry, although at a new location in Cook Inlet.

*Drivers of ballast water discharge and sources of uncertainty*

Alaska's economy is driven largely by the extraction or use of natural resources involving seafood, mining, petroleum, timber, and tourism (Goldsmith 2010). Due to the geographic isolation of Alaska and the destinations of predominant bulk exports, maritime shipping is an important component of these economic drivers. Fluxes in ballast water delivery have been associated with, and predicted by, exports of bulk commodities derived from natural resource extraction (Cope et al. 2015; Carney et al. 2017; Holzer et al. 2017, Chapter 2). As production and export of bulk commodities from Alaska changes through time, vessel behavior and ballast water discharge may also change.

Variability in bulker vessel traffic was evident in current ports. When the Usibelli Coal Mine discontinued exports from the Seward Coal Terminal in 2016, bulker arrivals and ballast water discharge likewise ended, dramatically changing the potential NIS propagule pressure to the southcentral port of Seward. In contrast, a possible expansion of the Red Dog Mine in northwest Alaska could bring an additional 6 bulkers per year to its port for exports of zinc and other metals (Harrison 2019), well within the range of scenarios explored here. Without this expansion, bulker arrivals to the Red Dog port are expected to remain stable. The Greens Creek Mine brings bulkers to southeast Alaska for exports of silver, gold, zinc, and lead. A recent proposal to expand tailing facilities would extend the life of the mine (85 Fed. Reg. 197 2020), likely resulting in additional bulker arrivals and ballast water discharge through time, though whether the annual number or source of arrivals would differ from recent years is unclear.

Infrastructure developments and new natural resource extraction projects will affect maritime shipping, but not necessarily ballast water discharge, depending on the commodity and vessel type used for exports. Proposed mining of graphite from Graphite Creek on the Seward Peninsula in northwest Alaska would result in 60,000 metric tons of concentrate per year loaded in containers and placed on barges for transport (Harrison 2019; Durkee et al. 2021). While this project has the potential to double the number of large barges in the port of Nome (Harrison 2019), barges discharge minimal ballast water. Likewise, the proposed Donlin Gold Mine in southwest Alaska would rely on barge traffic on the Kuskokwim River (Donlin Gold 2021). The concentrate from copper mining proposed in the Ambler district would be filled into shipping containers and sent by rail to the Port of Alaska in Anchorage for loading onto ships, likely not resulting in substantial ballast water discharge from container vessels (Staples et al. 2018). A recently authorized deep-water port in Nome would allow for nearshore large commercial vessel moorings and cargo imports to the region, rather than exports. In contrast, the proposed LNG pipeline from the North Slope of Alaska to the port of Nikiski would double the number of discharging tankers statewide and conservatively increase tanker ballast water discharge by 38%, as described in scenario 8. Prospective natural resource extraction projects will be affected by market, price, permits, technological developments, and other barriers (Northern Economics, Inc. 2011).

This approach to scenario development provides snapshots of hypothetical changes to the number of discharging tankers and bulkers. While these scenarios are grounded in potential changes from some ports (described above), they would be improved by additional data. Tonnage of bulk exports is a reliable predictor of ballast water delivery, but in absence of those data for bulk trade from Alaska, I used information collected in the NBIC to test a variety of vessel and voyage characteristics as predictors of ballast water discharge volume. The link between fluctuations in commodity production and vessel arrivals was often not considered in current industry projections or available from current export activity. For instance, the volume of crude oil throughput in the trans-Alaska pipeline declined during the study period (Alyeska Pipeline Service Company 2019), but the number of discharging tankers fluctuated through time and was not significantly correlated, indicating that other factors such as oil price, terminal storage, or vessel size affect exports. Crude oil production on Alaska's North Slope is projected to rise through 2040 and will depend on discoveries and production in current oil fields of the National Petroleum Reserve – Alaska and possible drilling in the Alaska's Arctic National Wildlife Refuge (US Energy Information Administration 2020). It is unclear how production will influence pipeline throughput or tanker traffic. Similar uncertainties exist for the timber industry, where projections of increasing timber harvest may translate into changes in bulker traffic in southeast or Afognak Island (Daniels et al. 2016).

I assumed the relationship between the number of discharging vessels and ballast water volume would remain the same through the range of scenarios developed. There was no evidence to suggest ports in Alaska received vessels at or near capacity during the study period, nevertheless I conservatively chose 20% fluctuations in vessel arrivals in scenarios 1 through 7. Scenario 8 includes a port facility with known capacity, and I conservatively chose the median value of expected arrivals. At some point of increased commodity production and export, the number of vessels that could call at a port and the volume of ballast water delivery would reach a maximum.

*Invasion opportunities*

Despite the known history of shipping as an NIS vector to coastal ports in Alaska (McGee et al. 2006; Verna et al. 2016; Scianni et al. 2017), these ecosystems are relatively uninvaded compared to lower latitudes. However, high latitude ecosystems are at increasing risk of NIS introductions and range expansions. Notable marine NIS present in Alaska include the colonial tunicates *Didemnum vexillum* (Cohen et al. 2011), *Botrylloides violaceus*, and *Botryllus schlosseri* in southeast; the clam *Mya arenaria* in southcentral (Powers et al. 2006), the amphipod *Caprella mutica* in southeast, southcentral, and the Aleutian Islands (Ashton et al. 2008), and the bryozoan *Schizoporella japonica* in southcentral (Fofonoff et al. 2021). Current habitat conditions in temperate waters ranging from southeast to the southern Bering Sea are considered suitable for other NIS to establish as well (de Rivera et al. 2011; Droghini et al. 2020). Particularly, European green crab (*Carcinus maenas*) are an encroaching threat to seagrass beds, juvenile fishes, and native crabs as their range expands northward along the Pacific coast (Grosholz et al. 2011), currently as far north as British Columbia.

Climate change may facilitate NIS introduction and establishment in Alaska and other high latitude coastal ecosystems (Cárdenas et al. 2020; Lassuy and Lewis 2013). Subarctic and arctic waters in the Bering and Chukchi Seas are experiencing dramatic change (Huntington et al. 2020), and temperature-salinity modeling indicates suitability for NIS in the Bering Sea region will move northward by mid-century (Droghini et al. 2020). An emergence of high latitude shipping is anticipated to shift current global vessel traffic patterns, bringing new NIS to the Arctic region (Miller and Ruiz 2014). The Arctic Invasive Alien Species Strategy and Action Plan developed by working groups of the Arctic Council acknowledged NIS introduction potential from shipping and ballast water in its goal to “undertake prevention and early detection/rapid response initiatives” (CAFF and PAME 2017). How exactly these changes will directly impact vessel traffic, port calls, or bulk exports in Alaska remains unknown, but increased human disturbance and

NIS vectors in the region are likely to positively influence opportunities for biological invasions. Studies such as the one described here can aid planning for new NIS monitoring locations and design.

Components of maritime shipping beyond ballast water are also important vectors of NIS. In particular, biofouling on vessel hulls and niche areas is a leading source of NIS introductions to aquatic ecosystems (Williams et al. 2013). The likelihood of introductions from biofouling depends on factors such as when and how frequently the underwater surface of the vessel is cleaned and vessel residence times in source and recipient ports (Davidson et al. 2016). Given the increase in commercial vessel arrivals to Alaska from 2009-2018, and anticipated additional growth described above, a biosecurity assessment of these vessels would reveal potential risks or hotspots for managers. Moreover, segments of maritime traffic not captured by the NBIC, notably fishing vessels and transient recreational vessels, may also introduce NIS (Ashton et al. 2014; Droghini et al. 2020). Many fishing vessels, barges, and docks travel or are transported solely between ports or places within Alaska, increasing the possibility of secondary invasions (Vander Zanden and Olden 2008), though more work is needed to assess the risk of intra-state vessel traffic.

*Conclusions*

Global maritime trade is well known to influence ballast water transfer and invasion dynamics, shaped by the unique behavior of vessel types and exports of bulk commodities (Hulme 2009; Ruiz et al. 1997; Sardain et al. 2019). Here I quantified potential fluxes in ballast water discharge volume under scenarios of tanker and bulker traffic in Alaska and qualitatively describe how fluxes in natural resource extraction and exports may impact vessel traffic. Faced with uncertainty about future trade dynamics, scenario development represents possible and feasible outcomes that can inform research and management. For example, the source location and management rates of ballast water is an indication of NIS type and abundance. Those factors can be used to target species for monitoring in ports that export bulk goods. Future studies can assess the likelihood of NIS survival between source and recipient ports under current and changing abiotic conditions.

Modeling existing and future NIS introduction dynamics with respect to trade is foundational to biosecurity, prevention, and early detection planning. Climate change has the potential to affect natural resources, infrastructure development, and maritime shipping in Alaska (Berman & Schmidt 2019), influencing likelihood of NIS establishment. I recommend continued evaluation of NIS vectors and their economic drivers in high latitude systems. Furthermore, implementation and oversight of preventative management practices, particularly among vessels sourcing ballast water in high risk locations, is critical to reducing NIS introductions to Alaska and other places.

Tables

**Table 3.1. Modeled ballast water discharge volume**
Projected median volumes and 95% prediction intervals (MMT) of ballast water from tankers and bulkers as the number of discharging vessel arrivals decreases or increases from 10%-50% of the lowest or highest number of arrivals from 2009-2018. The number of discharging vessels when percent change is zero indicates the mean number of vessels from 2009-2018.

| | Tanker | | | | Bulker | | | |
|---|---|---|---|---|---|---|---|---|
| Percent change | Number of vessels | Ballast water volume | Lower limit | Upper limit | Number of vessels | Ballast water volume | Lower limit | Upper limit |
| -50% | 130 | 9.43 | 8.14 | 10.72 | 26 | 0.46 | 0.29 | 0.64 |
| -40% | 156 | 9.84 | 8.74 | 10.94 | 31 | 0.53 | 0.37 | 0.70 |
| -30% | 182 | 10.24 | 9.32 | 11.16 | 36 | 0.60 | 0.45 | 0.76 |
| -20% | 208 | 10.65 | 9.90 | 11.40 | 41 | 0.67 | 0.53 | 0.82 |
| -10% | 234 | 11.06 | 10.46 | 11.65 | 46 | 0.74 | 0.60 | 0.88 |
| 0 | 288 | 11.90 | 11.48 | 12.32 | 71 | 1.09 | 0.97 | 1.21 |
| +10% | 351 | 12.88 | 12.24 | 13.52 | 97 | 1.45 | 1.31 | 1.59 |
| +20% | 383 | 13.38 | 12.54 | 14.23 | 106 | 1.58 | 1.42 | 1.73 |
| +30% | 415 | 13.88 | 12.82 | 14.95 | 114 | 1.69 | 1.52 | 1.86 |
| +40% | 447 | 14.38 | 13.09 | 15.68 | 123 | 1.81 | 1.63 | 2.00 |
| +50% | 479 | 14.88 | 13.35 | 16.41 | 132 | 1.94 | 1.73 | 2.14 |

**Table 3.2. Scenarios**
Eight hypothetical fluctuations in the number of tanker and bulker arrivals that discharge ballast water in Alaska. ‘Stable’ refers to the mean number of discharging vessels from 2009-2018.

| Scenario | Tanker | Bulker |
|---|---|---|
| 1 | -20% | -20% |
| 2 | -20% | Stable |
| 3 | Stable | -20% |
| 4 | Stable | Stable |
| 5 | Stable | +20% |
| 6 | +20% | Stable |
| 7 | +20% | +20% |
| 8 | Stable + new exports | Stable |

Figures

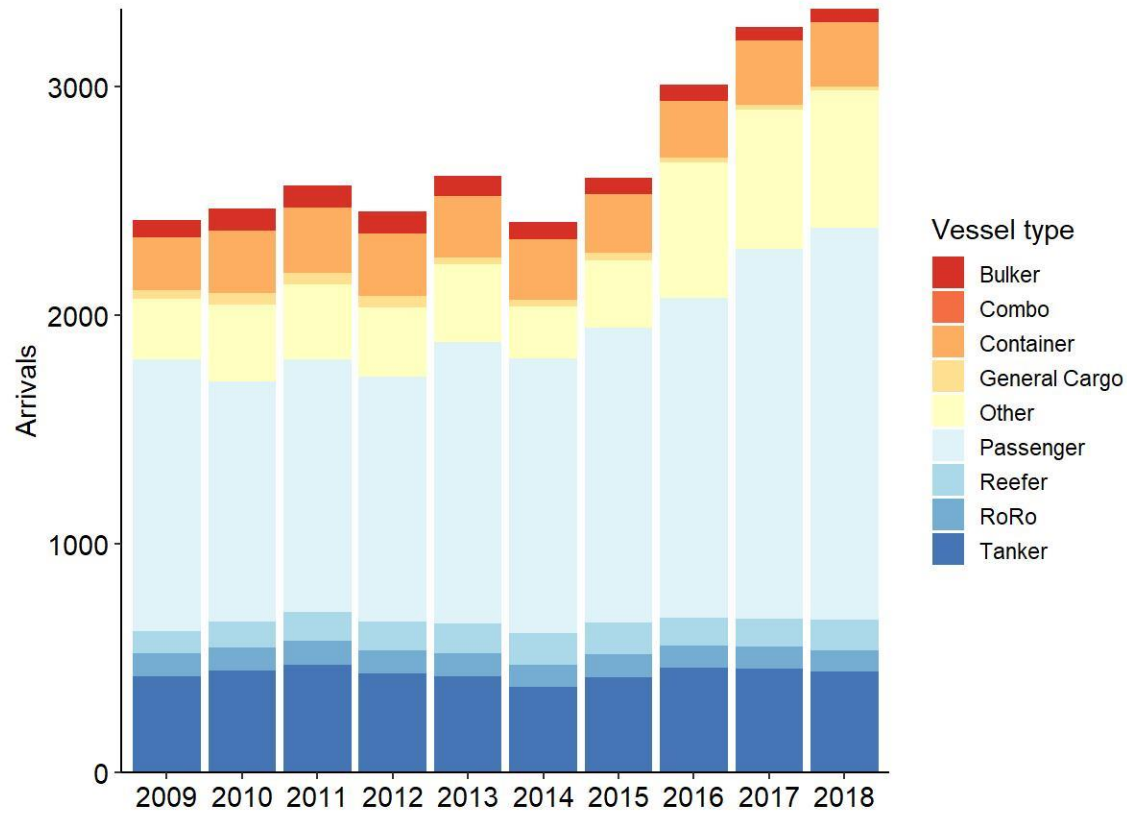


**Figure 3.1. Annual arrivals by vessel type**
Annual arrivals by vessel type to Alaska, 2009-2018

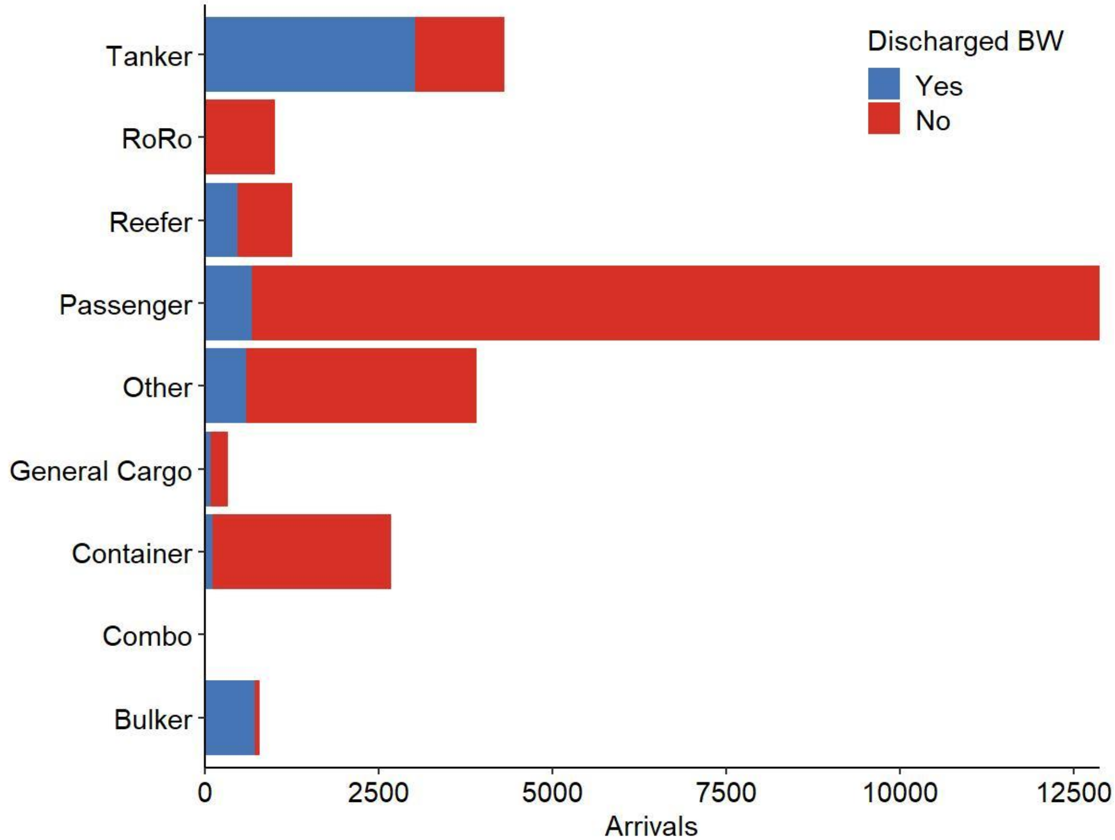


**Figure 3.2. Arrivals that discharged ballast water**
The number of arrivals of each vessel type that discharged ballast water (BW) in Alaska, 2009-2018.

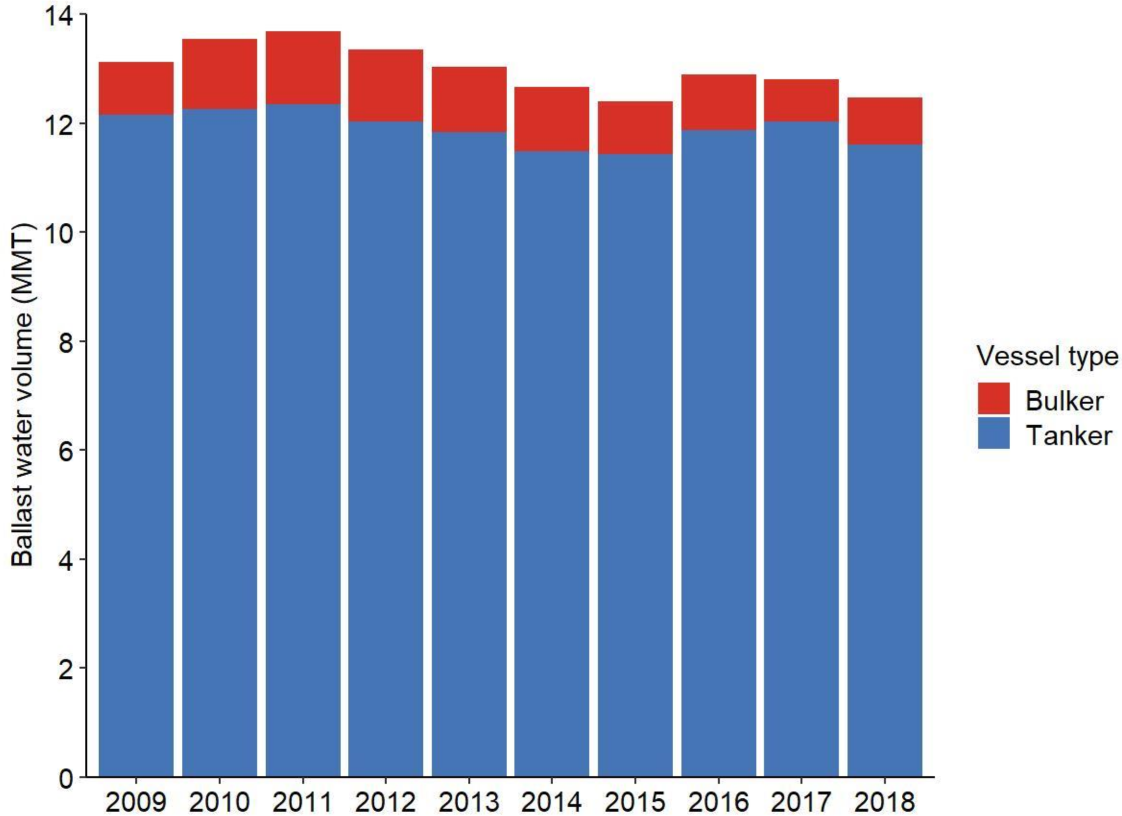


**Figure 3.3. Annual ballast water discharge by vessel type**
Annual ballast water discharge from tankers and bulkers in Alaska, 2009-2018. Tankers and bulkers discharged 99% of the volume of ballast water received statewide (tankers – 91%, bulkers – 8%).

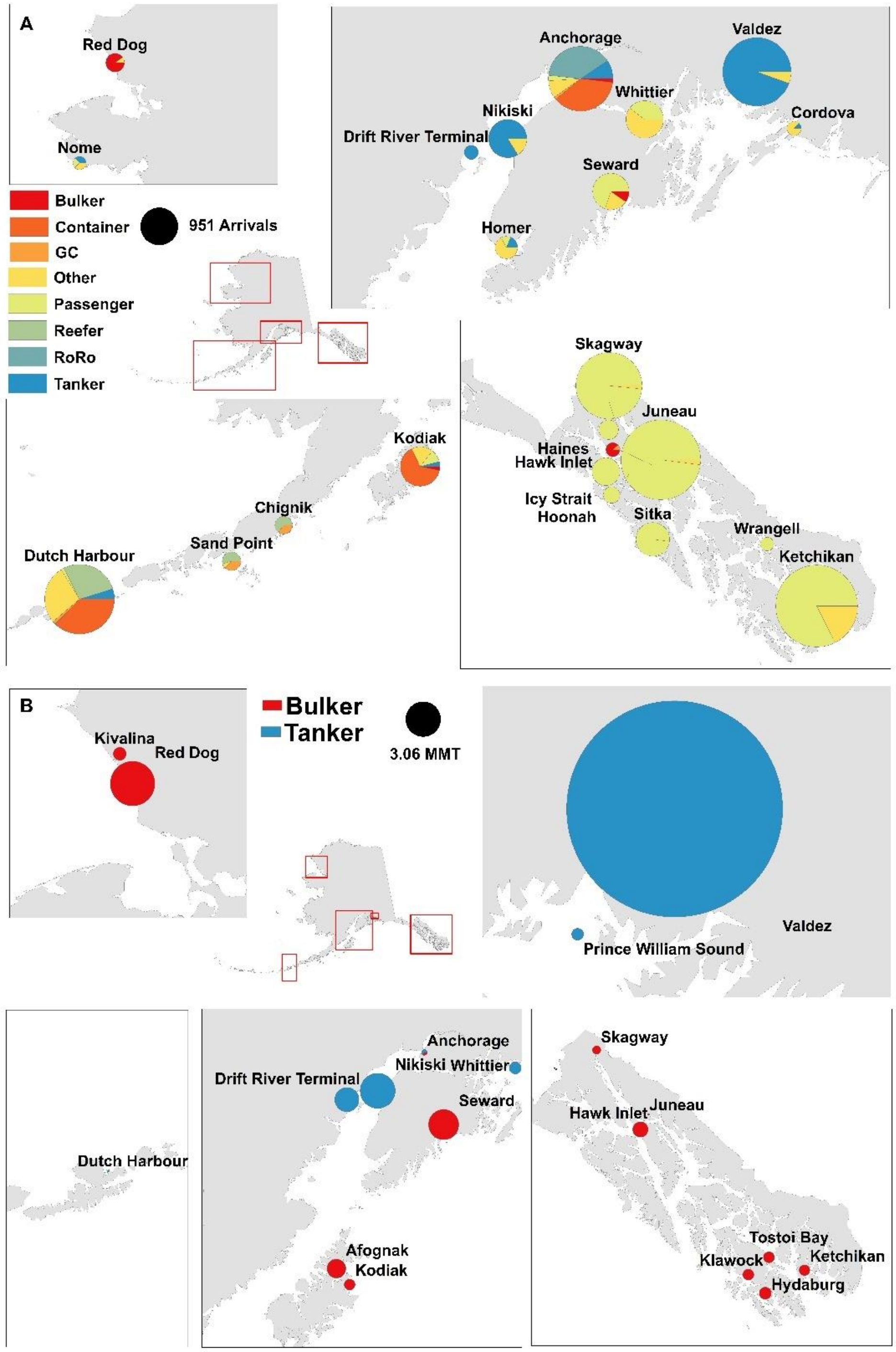


**Figure 3.4. Spatial arrivals and ballast water discharge**
Relative (A) arrivals and (B) ballast water discharge by vessel type to ports and places in Alaska from 2009-2018. Arrivals are shown for only locations that received at least 10 cumulative vessels. Ballast water is shown for only locations that received at least 100,000 metric tons. Ballast water discharge is shown from tankers and bulkers only (99% of total volume). GC = general cargo; MMT = million metric tons.

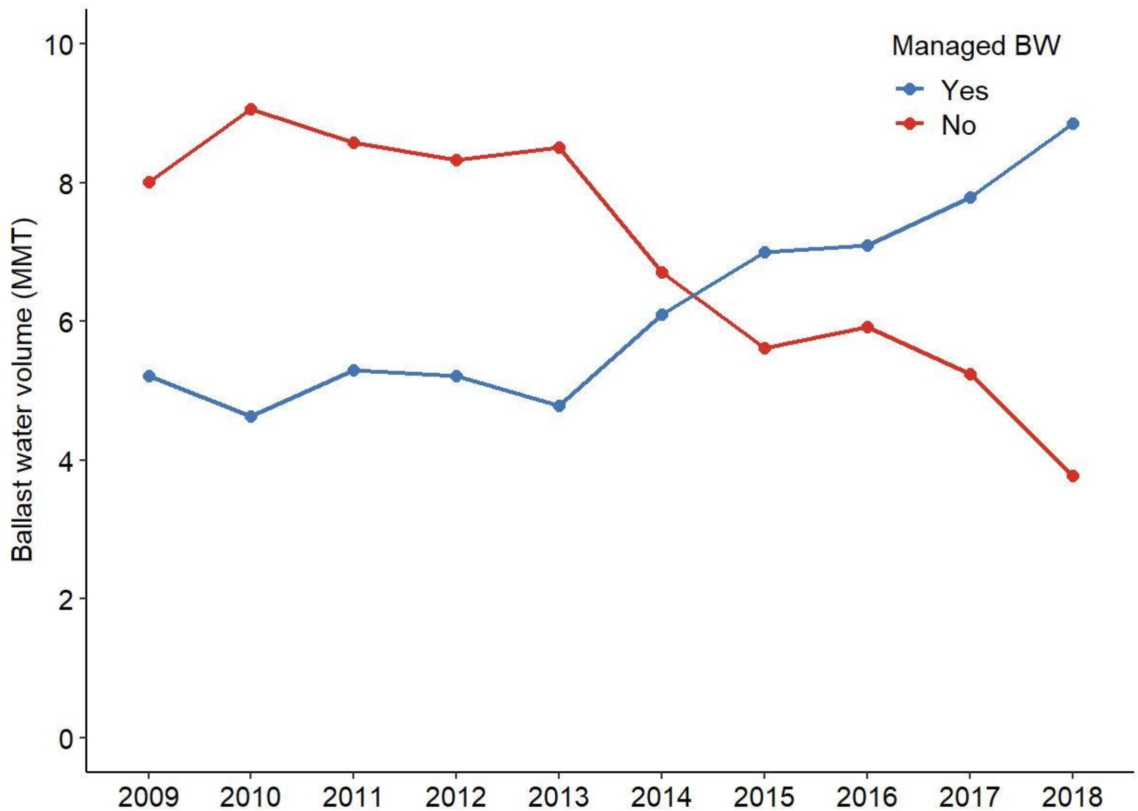


**Figure 3.5. Annual management of ballast water discharge**
Annual volume of ballast water (BW) discharge to Alaska that was reported managed and unmanaged, 2009-2018. More than half of annual discharge was reported managed for the first time in 2015, improving to 70% by 2018.

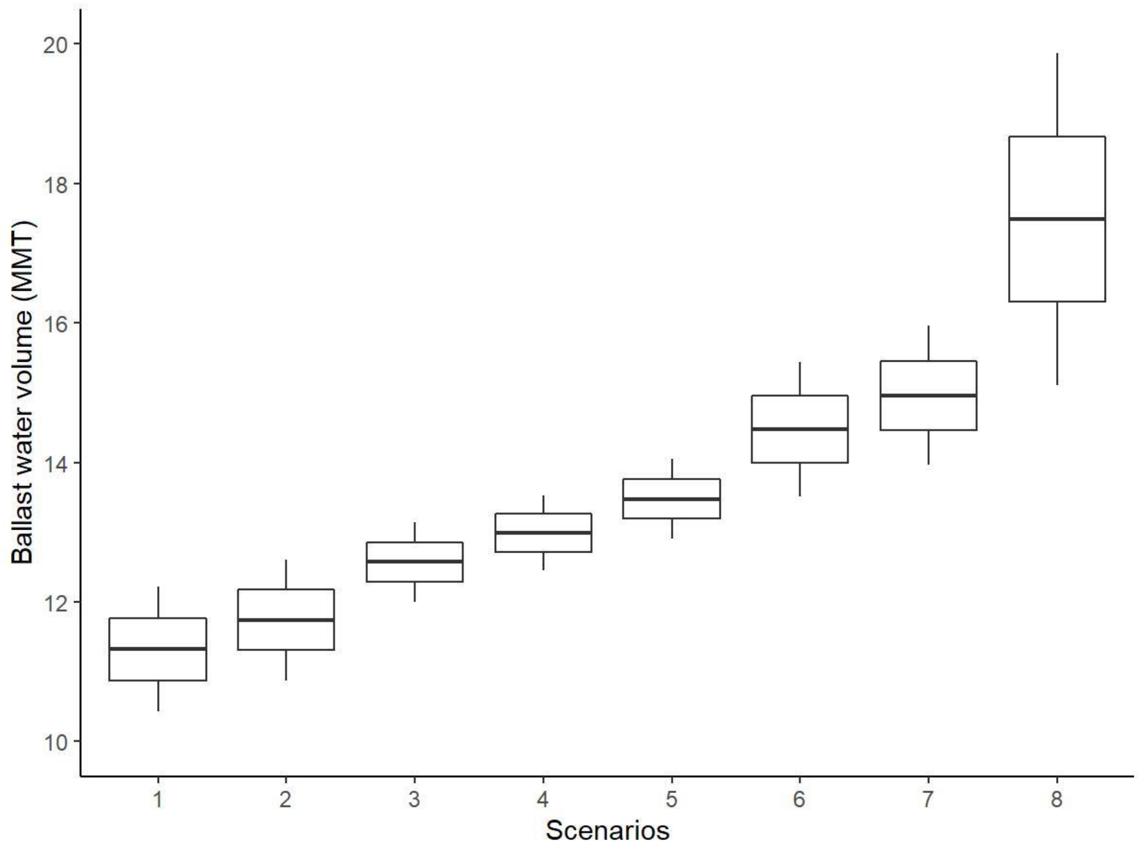


**Figure 3.6. Projected ballast water discharge volumes**
Projected ballast water discharge volume with 95% prediction intervals in eight scenarios of decreasing and increasing numbers of discharging tankers and bulkers in Alaska.

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Chapter 4

A decision tree analysis of nonindigenous species risk from ballast water to the lower Columbia River and Oregon coast, USA

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Abstract

Hazard characterization and risk assessment are commonly used to prioritize vectors of nonindigenous species (NIS) for inspection or other prevention opportunities. Commercial shipping vessels are a target of such vector-based management since ballast water has been known to transport NIS between aquatic ecosystems globally. Here we used a risk-based screening protocol to prioritize vessels discharging ballast water to the lower Columbia River and Oregon coast. We began by adapting established methods of assessing risk factors that influence the initial stages of the invasion process (arrival and survival). We created relative risk scales for each factor using data collected from vessels that discharged ballast water in three unique zones within our study area. We then organized a decision tree based on the confidence level of the proxies used for each risk factor to create a tool that prioritizes vessels with high risk ballast water for attention from regulatory personnel. In order of consideration, decision tree factors included: intent to discharge ballast water, reported adherence to required management practices, environmental distance between source and discharge locations (habitat suitability), ballast water discharge volume (propagule pressure number and frequency), and ballast water age (organism viability). As a result, vessels were prioritized on a scale of low,

medium, medium-high, or high. We applied the decision tree to a 2016 dataset of vessel arrivals and found that 173 of 1,592 arrivals were deemed high priority, with most occurring at ports in the freshwater zone of the Columbia River (158), followed by fewer in the estuarine zone of the Columbia River (4) and in Coos Bay (11). The decision tree is transferable to NIS prevention and regulatory efforts in other port systems. The vessel prioritizations are adaptable for managers using risk assessment strategies to allocate limited regulatory program resources for vector screening.

## Introduction

Globalization contributes to the intentional and unintentional transport of nonindigenous species (NIS). Consequently, biological invasions occur as NIS establish and spread into novel environments (Hulme 2009). Vectors such as commercial shipping, recreational boating, and aquaculture have emerged as leading contributors over time (Carlton and Geller 1993; Murray et al. 2014; Williams et al. 2015). Strategies for managing these and other vectors with an aim to limit NIS introductions have become common and progressively more rigorous (Ojaveer et al. 2014; Lodge et al. 2016). However, unintentional introductions from persistent vectors continue to pose a management challenge given the scope of global trade, limited resources allocated to prevention and early detection/rapid response measures, and the variety of probable NIS connected through a web of primary and secondary pathways (Simberloff et al. 2013).

Complete restriction of unintentional NIS transfer is neither practical nor cost effective (Costello and McAusland 2003), and therefore management depends upon voluntary or regulatory measures that reduce risk of uptake, transport, introduction, and/or establishment. A common approach to characterizing NIS risk is the absolute or relative measurement of threats posed by each vector (Mandrak and Cudmore 2015). The factors that influence risk are identified from a foundation of ecological theory and defined by the traits of the vector itself. Many threat assessments of unintentional introductions are designed with consideration that the initial stages of the invasion process, arrival and survival, are prerequisite to the subsequent stages of establishment and spread (Herborg et al. 2007; Casas-Monroy et al. 2015). It follows that an analysis of risk factors at these initial stages provides a reasonable starting point for identifying high risk vectors and selecting mitigation techniques (Heger and Trepl 2003; Lodge et al. 2016).

Critical factors for evaluating species arrival and survival in a new environment are habitat suitability and propagule pressure (Hayes 1998; Kolar and Lodge 2001). Habitat suitability is commonly quantified as environmental similarity, whereby abiotic parameters are measured in the source and recipient ranges to determine likelihood of survival following release to the receiving environment (Keller et al. 2011; Seebens et al. 2016). Environmental similarity is also the most effective way to determine whether large numbers of species will survive in a novel environment, as single species ecological modeling requires extensive resources and a priori assumptions of which species pose high risk (Barry et al. 2008). Propagule pressure consists of the number or density of individuals, the frequency of releases, and the viability of organisms (Simberloff 2009). As the number of individuals or the number of release events increases, propagule pressure and the likelihood of invasion also increases (Lockwood et al. 2005). The importance of considering propagule pressure in invasion success is well supported (Verling et al. 2005; Colautti et al. 2006; NRC 2011; Britton and Gozlan 2013), even though there is uncertainty associated with the shape of the dose-response relationship for NIS (Ruiz and Carlton 2003; David et al. 2015). Viability strongly affects likelihood of invasion success, which cannot occur unless organisms survive the voyage between source and release locations (Carlton 1996). Organisms that are viable upon release may establish self-sustaining populations that subsequently spread (Gollasch et al. 2000a). Thus, NIS viability is also an important risk factor to consider when assessing potential threat of invasion (Kang et al. 2010).

The management of ballast water from commercial shipping vessels stands out as an example of effective application of risk reduction measures. Ballast water routinely transports organisms between novel locations and the factors that influence NIS introduction likelihood in coastal waters are common across vessels and ports (Seebens et al. 2013). Efforts to manage the ballast water vector have focused on reducing the number and viability of organisms entrained in ballast water tanks and conveyed between port systems. The predominant management strategy has relied upon ballast water exchange, wherein ballast water sourced from nearshore is replaced with open ocean water. This practice decreases coastal organism density and alters the ambient salinity inside the tank to reduce likelihood of survival (Molina and Drake 2016). Recent regulatory developments aim to achieve far greater reductions in organisms discharged per unit volume by employing ballast water management systems based on chemical, ultraviolet, filtration, or other treatment methods (Tsolaki and Diamadopoulos 2009).

In the United States, commercial vessels are subject to federal ballast water management regulations (i.e., United States Coast Guard and Environmental Protection Agency) as well as management requirements specific to some states (Albert et al. 2013). State ballast water programs operate with the goal of protecting against NIS while considering the specific ballast water management options, traffic patterns, and environmental conditions within their jurisdictions. For example, in the state of Oregon, the Department of Environmental Quality (DEQ) conducts pre-arrival screening of commercial shipping as well as vessel inspections and enforcement (Oregon DEQ 2016). Both federal and state agencies typically require vessels to maintain a ballast water management plan and record book. Ballast water activities are reported on standardized forms that contain the locations, volumes, and dates of ballast water source, management, and discharge (NBIC 2017). Data from these reports may be used to analyze long-term trends and to identify voyage-specific factors that contribute to NIS introduction risk; they may also be used for compliance verification screening.

Reporting and inspections are tools often employed by regulatory agencies to ensure compliance with regulations and to track program efficacy. Ballast water inspections by federal and/or local authorities may be routine or prompted by concerns raised from ballast water reports, such as missing or incomplete data or elevated risk factors discussed in detail here. Due to limited resources, most regulatory jurisdictions are unable to inspect and conduct compliance verification sampling on all vessel arrivals.

Therefore, it is important to target limited inspection resources on vessel arrivals that pose greater threat of introducing NIS.

Here we applied established methods of assessing risk factors to the development of a tool that meets the needs of resource-limited prevention programs engaged in vector screening. Previous vector-based studies on the risk of NIS from ballast water have identified or used similar proxies for risk factors associated with species arrival and survival (e.g., Keller et al. 2011; Chan et al. 2013; Seebens et al. 2013; Ware et al. 2015; Verna et al. 2016). We relied on Keller et al.'s (2011) approach to approximating environmental similarity with a global dataset of parameters and adapted Verna et al.'s (2016) approach to approximating propagule pressure number and viability. We arranged the risk factors into a decision tree designed to identify high risk ballast water and prioritize boarding and inspection effort for commercial vessels based on relative NIS threat. Our study area on the lower Columbia River and Oregon coast serves as a case study of applying these methods by creating unique relative risk scales with data collected from local commercial vessel traffic. The application of these methods is adaptable to NIS prevention in other ports and can be beneficial to programs lacking formalized risk assessment frameworks.

## Methods

### *Data and study area*

Ballast water data were provided by the Oregon DEQ for the period January–December 2016. Oregon DEQ regulates ballast water discharge and collects data from commercial vessels greater than 300 gross tons that are equipped with ballast water tanks (foreign and domestic). Vessel operators reported to Oregon DEQ 24 hours prior to arrival in state waters using the federal ballast water reporting form (OMB 1625-0069). Data were manually entered from this form into a DEQ Microsoft Access database and standardized for consistency of port names (vessels may report e.g., for Portland, Oregon: Portland, OR; PORTLAND OR; Portland O.R.) and conversion to metric units. When multiple tanks on a vessel contained similarly sourced, managed, and discharged ballast water, those data were entered as one record with a combined ballast water volume. When ballast water characteristics differed across a vessel's tanks, those data were entered separately. Each vessel was assigned a unique arrival identification number.

The primary ports in Oregon for arriving commercial vessels are within freshwater zones of the lower Willamette and Columbia Rivers near Portland, as well as estuarine zones of the lower Columbia River at Astoria and on the southern Oregon coast at Coos Bay (Figure 4.1). All vessels destined for Columbia River ports in Washington transit through Oregon waters and are therefore regulated under Oregon DEQ reporting requirements and are included here.

*Risk factors*

We used established risk factors that influence the initial stages of the invasion process (arrival and survival): environmental similarity between source and discharge port and propagule pressure (number, frequency, and organism viability) (Hayes and Hewitt 2000). Using the Oregon DEQ dataset, we assessed these factors individually and in order of the associated confidence levels of their proxies before applying them to a decision tree.

Although a variety of bioregional factors can influence invasion potential, only temperature and salinity measurements were included in our analysis of environmental similarity as these are generally predictive of species' ability to survive and are broadly available at a global scale (Barry et al. 2008). Environmental parameters including mean temperature of the warmest month, mean temperature of the coldest month, mean annual temperature, and a single salinity value were obtained from Keller et al. (2011) for 6,651 ports globally. Keller et al. (2011) obtained surface water temperature and salinity values through direct measurement, the World Ocean Atlas, or by utilizing a generalized additive regression model to interpolate missing values from measured data for freshwater and estuarine locations. We supplemented the global dataset with observed temperature and salinity data for the Columbia River freshwater and estuarine zones (Center for Coastal Margin Observation and Prediction 2017) and the Coos Bay estuarine zone (South Slough National Estuarine Research Reserve 2017). The four environmental parameters in each zone were standardized with a Z-transformation. Due to the differences in salinity between freshwater and estuarine zones, we created a Euclidian distance model for three distinct regions (focus ports):

(1) The distance between ports in a freshwater zone of the Columbia River (i.e. Portland, Clatskanie, Kalama, Longview, Rainier, St. Helens, Vancouver) and the remaining 6,644 global ports;

(2) The distance between the estuarine port zone of the Columbia River (i.e. Astoria and surrounding waters) and the remaining global ports;

(3) The distance between the estuarine zone at Coos Bay and the remaining global ports.

Ballast water reported as sourced and discharged between our focus ports was rare (0.4% of the total volume) and was considered low risk. Ballast water sourced from an oceanic location (i.e. an open ocean location greater than 200 nautical miles from shore) was also considered low risk. Non-specific coastal source locations (e.g., “coastal Japan”) and unreported locations were considered high risk. The resulting environmental distance scores (range 0.6–4.1 for relevant source ports where lower numbers indicate increased similarity) were used to create a five-category risk scale of very low (> 4), low (> 3–4), medium (> 2–3), high (> 1–2), or very high (≤ 1) (Keller et al. 2011) (Table 4.1). We assumed a high level of confidence in the use of temperature and salinity as a proxy for habitat suitability due to widespread use in similar assessments (Chan et al. 2013; Ware et al. 2013; Casas-Monroy et al. 2015).

Given the importance of propagule pressure to invasion success but due to the lack of assessment on the relationship between propagule number and frequency we addressed these components independently. Ballast water discharge volume was used as a proxy for propagule number given the high degree of variability in density of organisms or species richness in ballast water tanks (Chan et al. 2013). Although it is not a direct measure (Drake et al. 2015), ballast water volume data are readily available and provide a better estimate of propagule pressure than number of vessel arrivals (Miller et al. 2011).

A five-category relative risk scale for propagule number was created based on the 20th, 40th, 60th, and 80th percentiles of ballast water discharge volume, rounded to the nearest hundred cubic meters for ease of analysis. Relative risk from ballast water volume was categorized as very low (< 2,000 $m^3$), low (≥ 2,000–4,600 $m^3$), medium (> 4,600–9,900 $m^3$), high (> 9,900–17,200 $m^3$), or very high (> 17,200 $m^3$) (Table 4.1). Frequency is defined by NRC (2011) as the "rate of propagule delivery per a given cohort of vessels over a given time period." We used an indirect approach to create a relative risk scale for propagule frequency based on the 20th, 40th, 60th, and 80th percentiles of the volume of ballast water discharged per month per source country or U.S. state. Relative risk from propagule frequency per source location was categorized as very low (< 3,300 $m^3$), low (≥ 3,300–10,600 $m^3$), medium (> 10,600–22,400 $m^3$), high (> 22,400–67,700 $m^3$), or very high (> 67,700 $m^3$) (Table 4.1). We assumed a medium level of confidence in the use of ballast water volume as a proxy for propagule pressure number and frequency due to its lack of specificity in estimating organism composition and abundance with an understanding that robust biological data are often not readily available to resource managers.

Propagule pressure is also influenced by the viability of organisms upon release. Within ballast water tanks, organisms may be affected over time by physical, chemical, and biological conditions. Most studies have demonstrated a decrease in diversity and abundance of organisms with increased holding time (Cordell et al. 2009; Gollasch et al. 2000a; Klein et al. 2010), though occasionally reduced competition and predation or increased food resources can cause some taxa to flourish (Gollasch et al. 2000b) and organisms have been known to survive for multiple weeks or even months (Gollasch et al. 2000a; Klein et al. 2010). Given the generally inverse relationship between organism survival and time in ballast water tanks, ballast water age was used as a proxy for viability (Verna et al. 2016). The age of ballast water was determined as the difference between source and discharge dates. Undetermined ages were considered high risk. Five-day age bins (sensu Cordell et al. 2009) were used to create a five-category risk scale of very low (> 20 days), low (> 15–20 days), medium (> 10–15 days), high (> 5–10 days), or very high (1–5 days) (Table 4.1). We assumed a low level of confidence in ballast water age as a proxy for species viability given the potential for variability in species composition and fitness across and within vessels and voyages.

*Decision tree*

Screening-level risk assessments often use decision trees to characterize the relative threat of a species or vector (Mandrak and Cudmore 2015). Decision trees are composed of a series of questions that are typically dichotomous, where the end nodes of the tree prioritize risk level (e.g., low/medium/high; invasive/not invasive; pass/fail; further study warranted) (Kolar and Lodge 2002; Daehler et al. 2004). After the initial identification and characterization of risk factors, decision trees provide a transparent and efficient method of focusing prevention or compliance verification efforts on sources that represent the greatest threat.

The first question in the decision tree presented here (Figure 4.2) screened vessels by whether they intended to discharge ballast water, where vessels with no intent to discharge were considered low priority. The second question asked whether ballast water proposed for discharge was managed in accordance with regulatory requirements. If the vessel has not conducted required management in real time, identifying the threat during screening presents an opportunity to ensure that management takes place before noncompliant discharge occurs. Next, all vessels, regardless of ballast water management regulatory requirements, were screened through the remainder of the decision tree using data collected on ballast water characteristics. We refer to ballast water from a vessel with similar characteristics as a "parcel". Some vessels discharged ballast water with multiple parcels, (i.e., varying characteristics such as source location or discharge date). When a vessel discharged multiple parcels of ballast water, we ran multiple decision tree analyses. Vessel priority was assigned based on the highest risk parcel.

The remainder of the decision tree was hierarchically arranged according to the confidence level of the proxies used for the risk factors. The third question screened ballast water by environmental similarity (high confidence), where a risk score of 4 or 5 (low, very low) was deemed low priority and scores of 3, 2, or 1 (medium, high, or very high) called for further screening. The fourth question screened ballast water by discharge volume (medium confidence), where a risk score of 4 or 5 (low, very low) was deemed medium priority to account for the risk posed by medium–very high environmental similarity. Scores of 3, 2, or 1 (medium, high, or very high) called for screening at the final question in the decision tree, which screened ballast water by age (low confidence). A risk score of 4 or 5 (low, very low) was deemed medium-high priority to account for the medium–very high risk posed by both environmental similarity and propagule number. If the risk score was 3, 2, or 1 (medium, high, or very high), the ballast water was considered high priority for further attention from regulatory personnel. If the ballast water discharge volume risk score was 4 or 5 but the risk score from propagule frequency (ballast water source location) was 3, 2, or 1, the ballast water was considered medium-high priority to account for the medium–very high risk posed by environmental similarity and the potential cumulative risk of several small discharges from a similar location over time.

## Results

In 2016, 953 of 1,592 commercial vessel arrivals reported discharging approximately 14 million $m^3$ of ballast water to ports within our study area of the Columbia River, lower Willamette River, and Coos Bay. Among the three zones, 173 vessel arrivals (11%) and approximately 2.4 million $m^3$ (17%) of ballast water were identified from the decision tree process as high priority for inspection and compliance verification. The number of vessels that were prioritized for inspection was roughly distributed across months, ranging from a minimum of 10 in April to a maximum of 19 in November (mean 14 ± SD 3).

Vessels discharged ballast water in the freshwater zone of the Columbia River that was sourced from 259 locations. The environmental similarity risk was high or very high for 85 of these source locations, medium for 130 locations, and low or very low for 44 locations. In the estuarine zone of the Columbia River, vessels discharged ballast water that was sourced from 20 locations. Environmental similarity risk was high for most locations (17) while the remainder (3) were low. In Coos Bay, vessels discharged ballast water that was sourced from 28 locations. Environmental similarity risk was high or very high for 24 locations, medium for two locations, and low for two locations. Many of the medium, high, and very high risk source locations (ports) for each environmental distance model were found in countries of eastern Asia (e.g., China, Japan, South Korea, Philippines), though some locations were identified in western North America (e.g., Canada, California, Washington) (Figure 4.3).

The mean volume per parcel of ballast water discharged to the freshwater zone of the Columbia River was 8,739 (SD ± 7,511) $m^3$. Ballast water age per parcel ranged from zero to 442 days, though the mean age was 26 days and most was less than 30 days old. The mean volume per parcel of ballast water discharged to the estuarine zone of the Columbia River was 12,684 (SD ± 6,448) $m^3$ and the mean age was 22 (SD ± 14) days. In Coos Bay, the mean volume per parcel of ballast water was 17,760 (SD ± 6,401) $m^3$ and the mean age was 20 (SD ± 11) days. Ballast water that was high risk from discharge volume tended to be sourced in locations that were also high risk from environmental similarity, though the age was often low risk (Figure 4.4).

Of 1,213 vessel arrivals to the Columbia River freshwater zone, 888 discharged ballast water; the remaining 325 non-dischargers were deemed low priority. Environmental similarity risk was medium to very high for 832 of the 888 dischargers, thus an additional 56 vessels were low priority and did not proceed through the remainder of the decision tree. Risk from ballast water volume was medium to very high for 699 of the 832 vessels. Of the 133 vessels that did not proceed to the final question on ballast water age, 110 had medium to very high risk from ballast water source location (propagule frequency) and were thus medium-high priority; the remaining 23 vessels were medium priority. Ballast water age risk was low or very low for 541 of the 699 vessels and these were additionally medium-high priority. The remaining 158 vessels had medium to very high risk ballast water age and were therefore high priority (Table 4.2). High priority vessels predominantly called on four ports in the Columbia River freshwater zone: Portland (62), Longview (41), Kalama (28), and Vancouver (24). An average of 13 (SD ± 3.0) high priority vessels per month were identified through the decision tree for targeted inspection.

Of 328 vessel arrivals to the Columbia River estuarine zone, 22 discharged ballast water; 326 non-dischargers were low priority. Environmental similarity risk was high for most (20) discharging vessels, thus only two vessels were additionally deemed low priority. Risk from ballast water volume was medium to very high for 19 of the 20 vessels. The remaining vessel had very high risk from ballast water source location and was thus medium-high priority. Ballast water age risk was very low or low for 15 of the 19 vessels and these were also considered medium-high priority. The remaining four vessels had medium or high ballast water age risk and were high priority for inspection (Table 4.2). Astoria received high priority vessels for inspection in March, August, and November.

Of 51 vessel arrivals to Coos Bay, 47 discharged ballast water; four vessels did not discharge and were low priority. Environmental similarity risk was medium to very high for 45 of the 47 vessels, thus only two vessels were additionally deemed low priority. Risk from ballast water volume was medium to very high for 42 of the 45 vessels. The remaining three vessels had very high risk from ballast water source location and were thus medium-high priority. Ballast water age risk was very low or low for 31 of the 42 vessels and these were additionally medium-high priority. The remaining 11 vessels had medium to very high risk ballast water age and were high priority (Table 4.2). Coos Bay received vessel arrivals deemed high priority for inspection in February, March, April, August, September, and December.

## Discussion

Vector management to reduce the risk of NIS introduction is a widely employed practice that can be made more robust with a standardized approach (Williams et al. 2013). Here, relative priority of vessels is determined through a decision tree that provides a basis for next-step risk management action and appropriate allocation of resources for a prevention-based regulatory program in Oregon. The screening protocol is designed to identify high risk ballast water from ships, a well-documented vector responsible for the introduction of NIS to freshwater and marine ecosystems globally. Prioritization is especially important when management agencies have limited financial resources and personnel to screen all incoming vessels.

An advantage of the decision tree is its adaptability to local agency goals and resources. Choices on how to implement the decision tree may depend on management priorities and local or regional ballast water discharge characteristics. For example, the Oregon DEQ aims to inspect 12% of vessel arrivals; the decision tree used here identified high priority vessels within the realm of available resources (Table 4.2). Individual jurisdictions may choose to prioritize vessels as resources allow or as risk factors are deemed important. Each factor is beneficial in refining the number of prioritized vessels and the risk they pose, but defining relative risk among vessels is not necessarily dependent on answering all questions, i.e. managers may choose to only screen by environmental similarity and volume if resources are available to inspect all medium-high priority vessels. Lastly, prior inspection and compliance history have been used by management agencies to influence inspection priority. For example, vessels arriving to the states of Oregon or California are more likely to be boarded on first arrival, if they have had a prior violation, or if they have not been boarded recently (CSLC 2013).

The decision tree can also be adapted for risk analysis based on data availability. In our analysis, accuracy and format of vessel data presented a challenge to answering the questions in the decision tree. Managing agencies may choose to allocate personnel to manually standardize data across vessel reports or commit resources upfront for automation and maintenance. A further challenge was missing or incomplete data. Managers may attempt to solve this problem by contacting the vessel prior to arrival, but some data discrepancies are unavoidable. In this case, we suggest that ballast water is at least screened by environmental similarity. If these data are not available, the vessel should be considered high priority. When implementing the decision tree in real time, we suggest a monthly rolling assessment of the previous 12 months of data for the propagule pressure number and frequency risk factors to routinely account for changes in vessel patterns. Agencies could shorten or lengthen this time frame depending on the quantity and quality of data available.

Computational ability may likewise be an agency limitation. If processed manually when individual vessels may discharge both high and low risk ballast water, the decision tree need only be applied until high risk ballast water is identified. If processed in an automated environment, we suggest the decision tree be applied to the entire vessel for a comprehensive assessment of risk, though a vessel with at least one high risk tank or parcel of ballast water should be considered for compliance verification or inspection. The number of high risk tanks/parcels per vessel may be further used to prioritize if necessary.

An example of method adaptability may be found at the Oregon DEQ. As of March 1, 2017, vessels that are operating an approved ballast water treatment system and source ballast water with a salinity of less than or equal to 18 parts per thousand must additionally perform ballast water exchange (Oregon DEQ 2017). The combination of ballast water exchange and treatment is expected to reduce the risk of NIS introductions to freshwater environments (Briski et al. 2015). In this scenario, the decision tree question on ballast water management would be expanded to address whether or not the vessels completed the appropriate type of management depending on source location. Vessels that source ballast water in low salinity ports may immediately become high priority based on their expected environmental similarity to Columbia River ports and their heightened requirement for management. This risk management approach is valuable for the state of Oregon’s freshwater and estuarine resources given that NIS delivery from both trans-Pacific and intra-coastal ballast water has been documented in nearby Puget Sound, Washington (Lawrence and Cordell 2010), and several species of

Asian copepods have already been introduced to the Columbia River from vessels originating in California (Cordell et al. 2008; Bollens et al. 2012; Dexter et al. 2015).

In applying the decision tree to Oregon data from 2016, many vessels discharged ballast water that was deemed medium to very high risk from environmental similarity and propagule number. Considering ballast water age, therefore, was key to reducing the number of vessels prioritized for inspection to a manageable amount. However, the ballast water age proxy is associated with low confidence. Oregon DEQ may choose to restrict the number of prioritized vessels earlier in the decision tree using factors with higher confidence by only considering vessels with high or very high environmental similarity and propagule number risk (i.e. vessels deemed medium risk would not advance through the decision tree).

Agencies that are implementing prevention-based vessel inspection programs can use the results of the decision tree to inform long-term management strategies for their jurisdictions. A record of high and low risk ballast water per location may reveal patterns within each factor, e.g., ports in the Columbia River often receive environmentally similar ballast water from San Francisco Bay and southeast Asia, though of varying ages (Figure 4.4). Establishing a baseline allows managers to document spatial and temporal shifts and set acceptable levels of risk. Furthermore, documentation of relative risk among ports can aid decision making on whether and where to implement early detection/rapid response measures. For example, is a survey of the receiving waters warranted? How frequently should surveys be conducted? What NIS are likely to have been transported from ballast water source regions? Should species-specific risk assessments be conducted? For a more robust management approach, particularly when data are lacking, expert opinion and stakeholder involvement should be solicited (Maguire 2004). Experts may provide insight into species-specific risk(s) associated with each factor. Stakeholders may provide opinions or values that would otherwise not be recognized.

A vector screening protocol such as the decision tree presented here can be standardized across port systems to encourage consistent management strategies. Standardization and collaboration may be particularly valuable amongst agencies that collect similar data such as U.S. west coast states. The data collected from pre-arrival reporting forms facilitate screening for regulatory compliance as well as identification of higher risk ballast water that may be targeted for inspection. Ballast water vessel inspection efforts have a goal of ensuring that management requirements have been adequately performed; compliance verification may include checking vessel logs, management plans, crew knowledge, or the salinity of water in a tank. Inspections are also a time to share outreach about NIS and communicate with captains and crews on prevention objectives and best management practices. Consistency of message and management tools reduces confusion and encourages transparency between regulators and industry.

Our model relies heavily on proxies to determine environmental similarity and components of propagule pressure. A more accurate measurement of environmental parameters, though perhaps difficult to obtain on a global scale, would provide a more robust assessment of environmental similarity risk. Furthermore, environmental similarity does not account for the ability of NIS to adapt to conditions outside of those encountered in their native habitat. We note, however, that we do not use species-specific tolerance levels for temperature and salinity as this is a vector-based assessment where many species have the potential to be introduced. Likewise, our approach to propagule pressure frequency assumes species assemblages throughout a country or state present uniform risk and that risk is cumulative over a given time frame (e.g., one month). When available, an ecoregion or port-specific list of known NIS may increase the resolution of risk from particular species (Molnar et al. 2008; Verna et al. 2016). However, here we collectively allow for both native species and NIS to be considered possible invaders sourced throughout a broad spatial range. The frequency measurement is not intended to identify high risk species but rather to proxy a component of propagule pressure, and can be spatially and temporally adjusted as data allow. Lastly, the risk categories assume a linear increase in risk. Less arbitrary category divisions based on empirical data are needed and would substantially strengthen the assessment of risk from environmental similarity and propagule pressure.

Risk assessment provides an opportunity to intersect science and real time management. First, risk is broken into components to encourage practical measurements, calculations, and data collection, ideally reducing uncertainty (Hayes 1998). Second, the risk components are incorporated into a screening protocol such as a decision tree. Third, agency personnel use the decision tree as a tool to streamline decision making for risk management. Regular acknowledgement of uncertainties and adaptability will result in continuous program development and improved efficiency of resource allocation. As NIS continue to pose a threat to terrestrial and aquatic ecosystems, management tools such as the decision tree presented here can help reduce vector-based risk of introductions.

Tables

**Table 4.1. Risk factors and scales**
Risk factors and five-category risk scales for ballast water discharged to ports of the Columbia River and coastal Oregon (USA), January–December 2016. See Methods for a description of relative risk scales. The final column represents the confidence level of the proxy used for each risk factor.

| | Very Low (5) | Low (4) | Medium (3) | High (2) | Very High (1) | *Confidence Level* |
|---|---|---|---|---|---|---|
| Habitat suitability: Environmental distance | > 4 | > 3–4 | > 2–3 | > 1–2 | ≤ 1 | *High* |
| Propagule number: Volume ($m^3$) | < 2,000 | ≥ 2,000–4,600 | > 4,600–9,900 | > 9,900–17,200 | > 17,200 | *Medium* |
| Propagule frequency: ($m^3$/month/source location) | < 3,300 | ≥ 3,300–10,600 | > 10,600–22,400 | > 22,400–67,700 | > 67,700 | *Medium* |
| Organism viability: Age (days) | > 20 | > 15–20 | > 10–15 | > 5–10 | 1–5 | *Low* |

**Table 4.2. Vessel prioritization**
Vessel prioritizations based on a decision tree analysis of ballast water risk factors for introducing NIS to ports of the Columbia River and coastal Oregon (USA), January–December 2016. Percentages represent proportion of arrivals in each zone.

| | Columbia River freshwater zone | Columbia River estuarine zone | Coos Bay estuarine zone | All zones |
|---|---|---|---|---|
| **Arrivals** | **1213** | **328** | **51** | **1592** |
| **Low priority** | **381 (31.4%)** | **308 (93.9%)** | **6 (11.7%)** | **695 (43.7%)** |
| *Low priority (not discharging)* | *325* | *306* | *4* | *635* |
| *Low priority (environmental similarity risk)* | *56* | *2* | *2* | *60* |
| **Medium priority** | **23 (1.9%)** | **0 (0%)** | **0 (0%)** | **23 (1.4%)** |
| **Medium-high priority** | **651 (53.7%)** | **16 (4.9%)** | **34 (66.7%)** | **701 (44.0%)** |
| *Medium-high priority (environmental similarity and volume risk)* | *541* | *15* | *31* | *587* |
| *Medium-high priority (environmental similarity and frequency risk)* | *110* | *1* | *3* | *114* |
| **High priority** | **158 (13.0%)** | **4 (1.2%)** | **11 (21.6%)** | **173 (10.9%)** |

Figures


**Figure 4.1. Ports that received ballast water**
Primary estuarine and freshwater ports of the Columbia River and coastal Oregon (USA) that receive ballast water from commercial vessels.

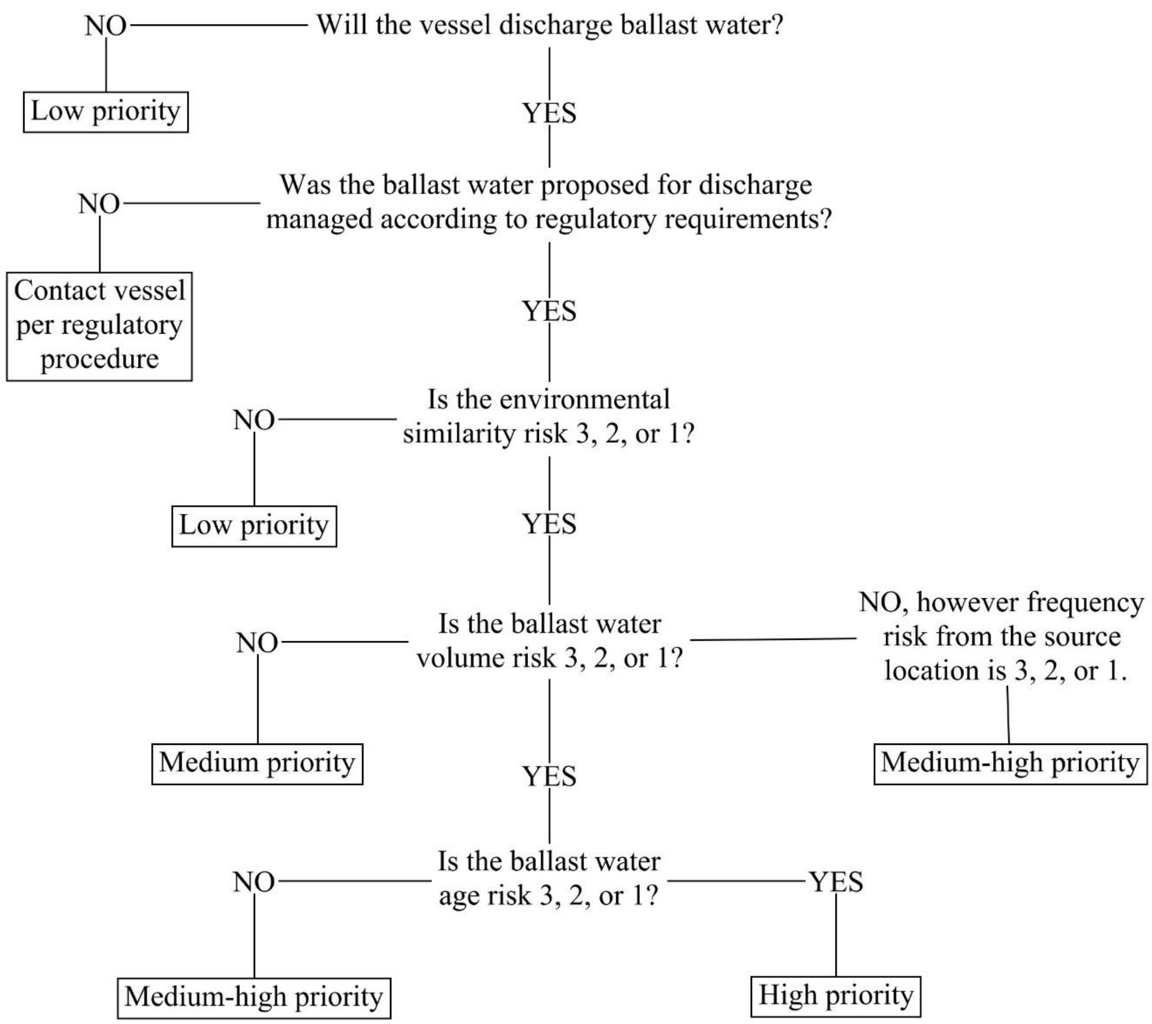


**Figure 4.2. Decision tree**
A decision tree to prioritize vessel arrivals as low, medium, medium-high, or high priority for further attention from regulatory personnel based on the characteristics of ballast water discharge.

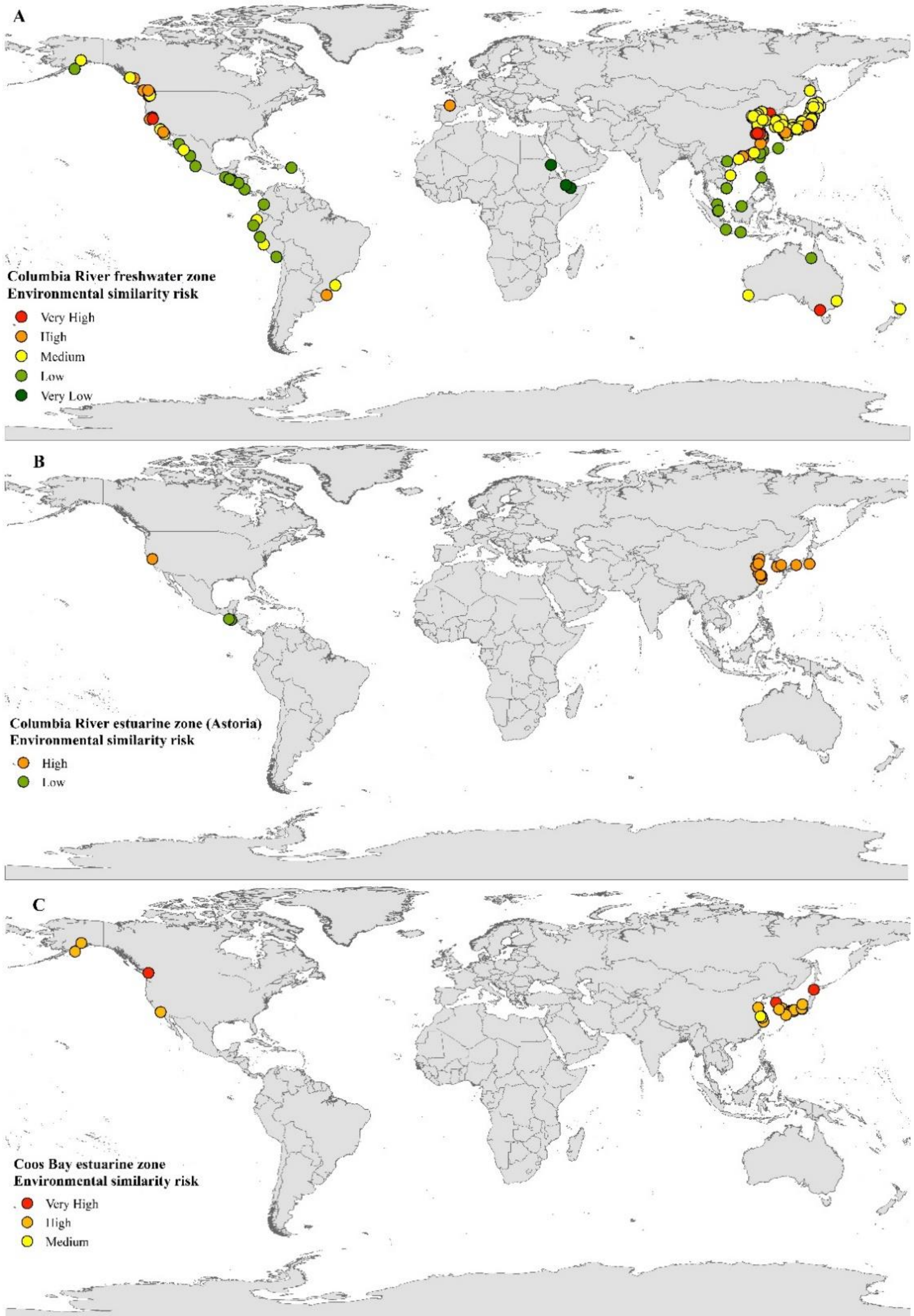


**Figure 4.3. Environmental similarity risk of ballast water**
The environmental similarity risk and source locations of ballast water that was discharged to (A) the freshwater zone of the Columbia River (including the ports of Portland, OR, Kalama, WA, Longview, WA, Vancouver, WA), (B) the estuarine zone of the lower Columbia River (including the port of Astoria), and (C) an estuarine zone on the southern Oregon coast (Coos Bay), January – December 2016.

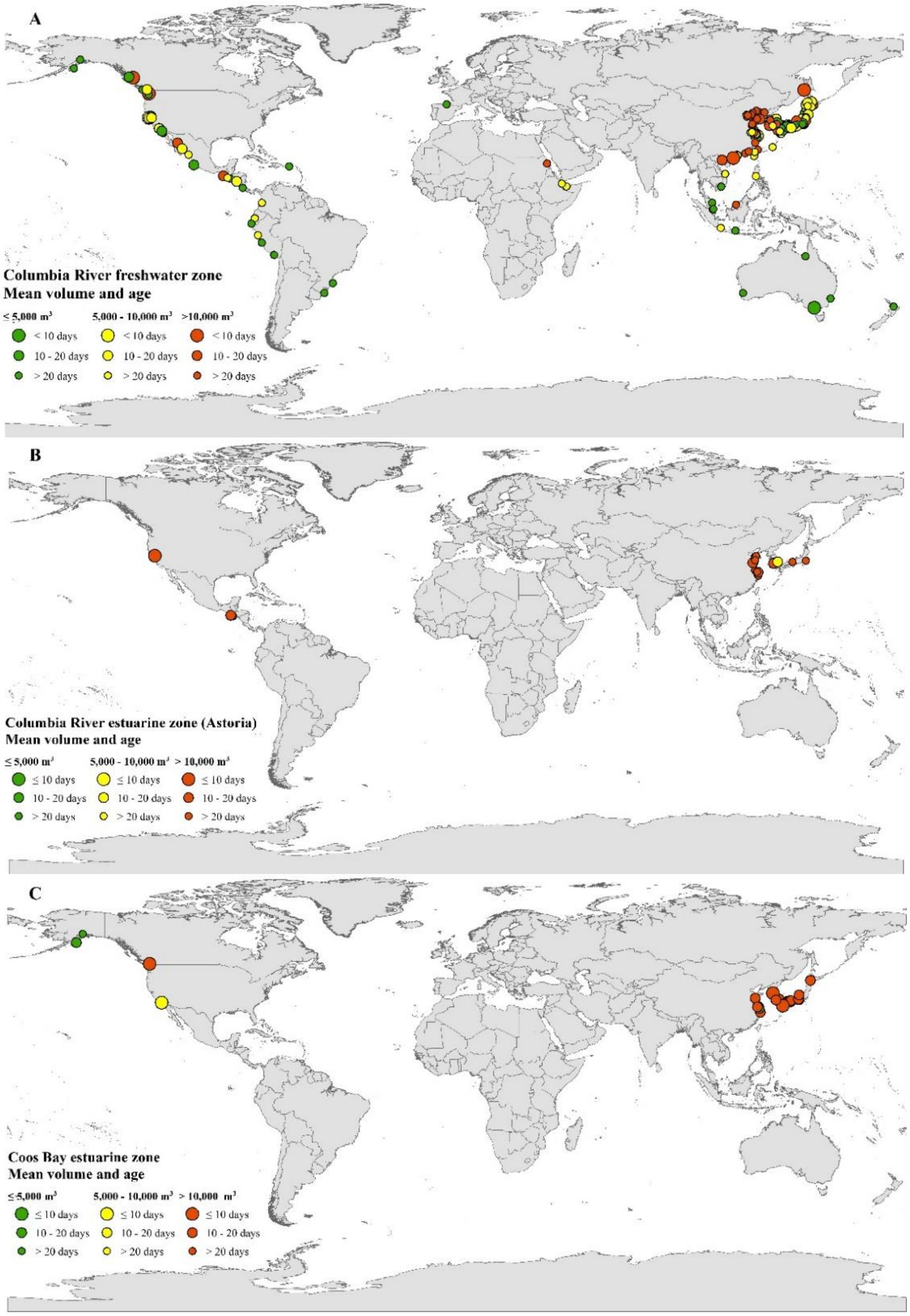


**Figure 4.4. Volume and age of ballast water**

The mean volume and age of ballast water from each source location that was discharged to (A) the freshwater zone of the Columbia River (including the ports of Portland, OR, Kalama, WA, Longview, WA, Vancouver, WA), (B) the estuarine zone of the lower Columbia River (including the port of Astoria), and (C) an estuarine zone on the southern Oregon coast (Coos Bay), January – December 2016.

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# Conclusion

The chapters presented in this dissertation examine aspects of globalization, trade, maritime shipping, and biological invasions. The methods and results described here fill existing research gaps by examining unique behaviors of vessel types, defining relationships between trade and ballast water dynamics, and identifying key drivers of vessel arrivals and ballast water delivery across national, regional, and local scales and varying degrees of invasion. The findings are useful for advancing invasion ecology and management in the dynamic and global network of maritime trade.

Trade is recognized as a driver of biological invasions in coastal ecosystems as ships transport most goods and commodities between countries. However, the exact relationships between trade and key vectors of nonindigenous species (NIS) have been difficult to quantify. Ballast water is a leading vector of NIS, but most ship arrivals do not discharge, and the volume and frequency of ballast water delivery is variable across ship types. Here, I examined the unique trade and ballasting behaviors of various ship types to identify a novel proxy of ballast water delivery. Specifically, I found that exports of bulk commodities drive the ballast water discharge behavior of bulk and tank ships, and that tonnage of bulk exports reliably predicts ballast water volume.

I found this relationship held across spatial scales, time periods, and trade commodities, further demonstrating its robustness and usefulness for improving our understanding of invasion dynamics. In San Francisco Bay, California, where nearly 20 different ports traded thousands of goods transported by a variety of ship types, the tonnage of only a few bulk exports explained bay-wide ballast water delivery. On all coasts of the United States, growth of bulk energy exports explained annual variation in national ballast water volume, with implications for forecasting the effects of policy and trade shifts on vessel behavior and invasions.

Furthermore, I demonstrated that trade partner and export commodity can elucidate ballast water and invasion dynamics. Trade partners have shifted through time in response to changing markets, production, and demand, in turn influencing patterns of maritime shipping. The models developed here can estimate ballast water delivery across longer time periods when ballast water data are unavailable, but trade data are available. Using historical trade data, hindcasted estimates of ballast water delivery would identify events that led to fluctuations in volume, shifts in trade partners, and changes in exports of dominant bulk commodities. These data would support the development of a timeline to reveal patterns of known invasions and their drivers. Since mandatory ballast water management went into effect around the same time as mandatory reporting, estimates of ballast water delivery prior to management could reveal the effects of past and current management strategies (i.e., ballast water exchange), and establish a baseline for detecting the effects of up-and-coming management (i.e., onboard treatment systems).

The models developed here are also useful for forecasting ballast water delivery. In Chapter 2, demand for fossil fuel energy combined with availability of resources and technological advances (e.g., hydraulic fracturing) in the United States led to a recent dramatic spike in ballast water. While that demand is not likely to drop precipitously soon, as the world moves toward ‘cleaner’ energy resources I anticipate a shift away from coal (dry bulk) toward liquefied natural gas (liquid bulk), in addition to renewables. Since the United States has abundant natural resources, it may continue to export large tonnages of energy commodities but receive more tank than bulk vessels. This flux in vessel type would influence the volume and location of ballast water delivery (and degree of propagule pressure) since tank ships discharge less per capita than bulk ships and commodity-specific export terminals vary spatially across coasts.

Future fluctuations in trade of other bulk goods will likewise influence ballast water and invasions. As seen in Alaska, mining and timber production (in addition to oil and coal) are leading drivers of bulk exports and ballast water delivery. Additional bulk carriers will be needed to export ore as existing mines expand or new mines are developed to meet demand for metals, minerals, and rare earth elements. These mined materials are used in the production of electronics, generators, and batteries that are necessary for electric vehicles and wind turbines, among other things. As such, demand may continue to grow with the global shift toward renewable energy sources, spurring mining exploration and production. Waste products, recycling, and agricultural goods from the West Coast, including San Francisco Bay, are also leading bulk exports that may vary depending on handling locations and demand.

The locations of refineries and smelters are important to shipping dynamics since raw materials are often transported to separate facilities before further dissemination as a refined or finished product. For example, crude oil exports from Alaska are delivered to the US West Coast and mineral ore is delivered primarily to China. On the US Gulf Coast, where refineries recently adjusted their practices to process domestic oil, there was in increase in export tonnage across an assortment of refined fuel types. Policy and regulations that affect the production and refinement of raw materials, including the relatively stringent oversight in the United States, will influence the source and destination of energy commodities, and associated trade partners.

Identifying fluctuations in trade and markets can inform scenario development of potential changes in the abundance of vessel traffic and in-port activity. Since the source locations of ballast water and biota, and the magnitude of discharge, are a by-product of bulk exports, this approach can aid future predictions of NIS invasions. Expressly, trade partner is an indication of the species source pool and abiotic match to the recipient port, and tonnage of bulk exports is an indication of ballast water volume and propagule pressure. Incorporating these risk factors into management decisions can emphasize previously unappreciated consequences of resource development, infrastructure expansion, or changes to trade patterns.

Resource managers can apply the methods and models developed here to track bulk exports and related ballast water imports and predict new or changing bulk trade that may influence the likelihood of NIS introductions. As a result, managers can efficiently allocate resources for both vessel compliance verification and NIS surveillance, where vessel that import relatively large volumes of ballast water and ports that export bulk goods to trade partners with similar coastal habitat conditions are prioritized. A transparent screening tool, such as developed in Chapter 4, can aid the decision making process and standardize its application. This approach is useful across port systems, even in places that lack comprehensive ballast water data.

Variable trade patterns and partners can influence delivery of NIS, while changing climatic conditions can influence likelihood of survival and establishment in novel ecosystems. In high latitudes, climate change is anticipated to improve abiotic match to lower latitude conditions, allowing species to colonize new habitat or expand ranges in a poleward direction. Climate change is also leading to altered trade routes, resulting in new infrastructure development (e.g., ports). The combination of increased propagule pressure and anthropogenic disturbance to previously remote coastlines will likely affect biological invasions. Recognizing this threat, resource managers can proactively ensure that management actions are taken by ships prior to ballast water discharge and strategically deploy surveillance equipment for NIS early detection. It is also an opportunity to prioritize sites for protection, for instance within marine protected areas and other ecologically or culturally significant zones as recognized by local stakeholders.

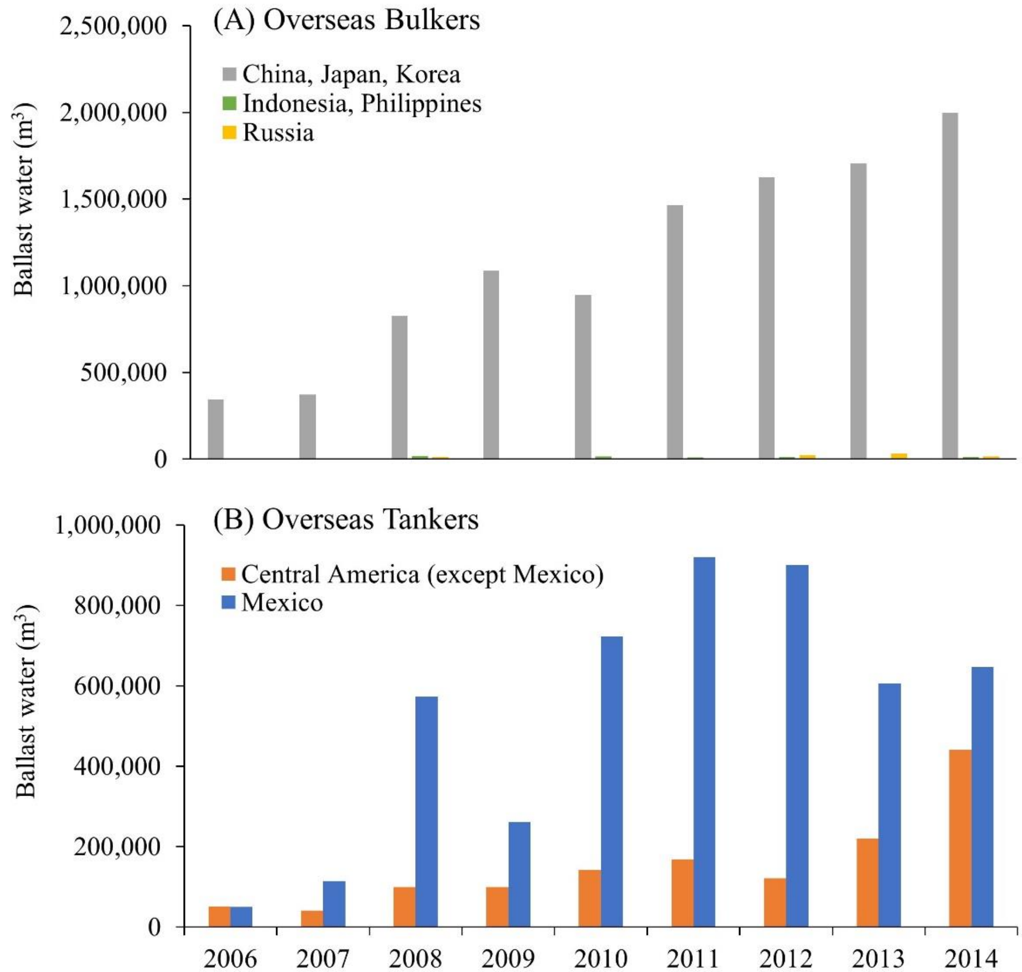
This dissertation improves understanding of the relationships between trade, ballast water, and biological invasions. Applying the concepts and results advanced here, scientists and managers can aim to proactively prevent invasions by (1) hindcasting ballast water delivery to identify temporal invasion patterns and effects of management, (2) identifying ports that currently export bulk goods and estimating ballast water volume, and (3) forecasting changes in trade and maritime shipping that will influence NIS introductions. Coupled with targeted NIS surveillance, this approach can advance synergistic management of biological invasions alongside other global challenges.

Appendix A: Supplemental Material to Chapter 1

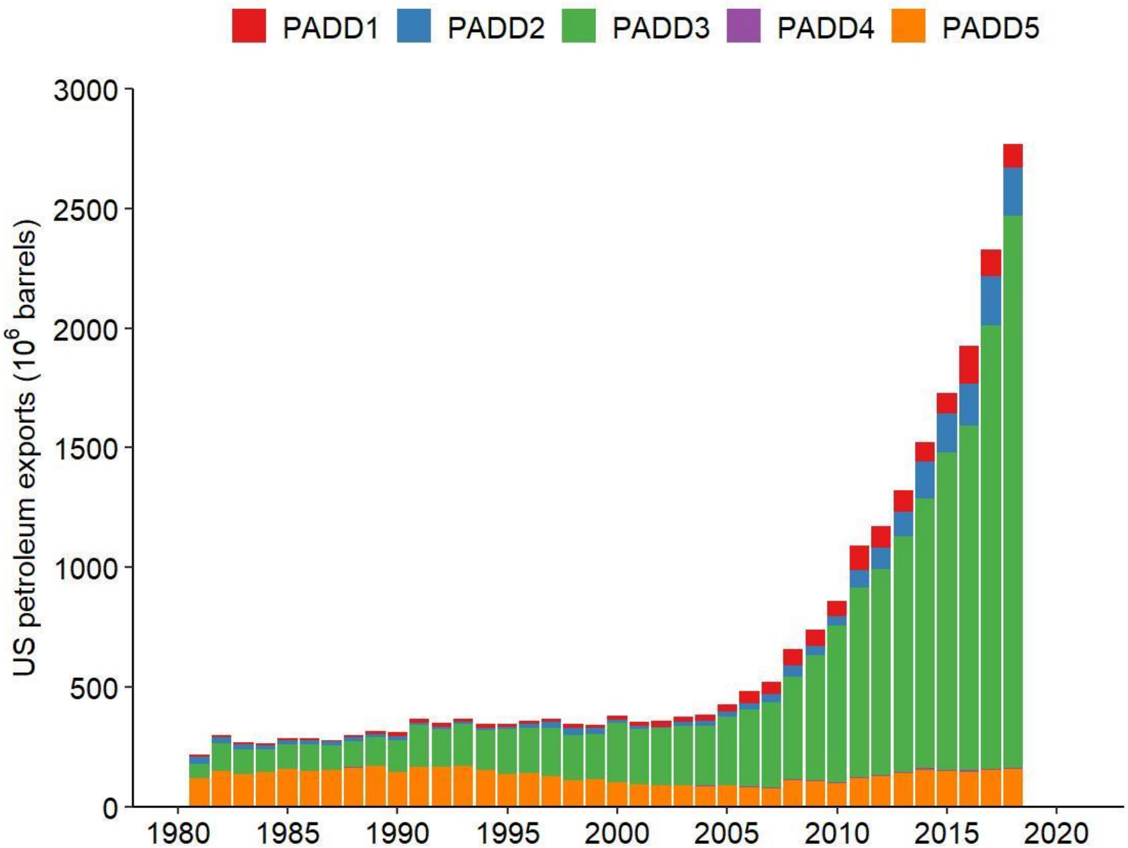
**Supplemental Table 1.** The proportion of vessel arrivals and ballast water discharge to San Francisco Bay from overseas tankers from Hawaii and remaining bioregions. Total number of vessels (n) shown for % discharging vessels.

| Overseas Tankers | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|---|---|
| Hawaii Source Region* % Discharging (n) | 44% (25) | 44% (25) | 72% (18) | 67% (12) | 45% (11) | 67% (9) | 45% (22) | 73% (22) | 71% (17) |
| Other Source Regions % Discharging (n) | 9% (218) | 11% (218) | 18% (265) | 18% (241) | 26% (213) | 30% (213) | 31% (245) | 40% (223) | 53% (228) |
| Contributions from Hawaii | | | | | | | | | |
| % Total arrivals | 10% | 10% | 6% | 5% | 5% | 4% | 8% | 9% | 7% |
| % Dischargers | 35% | 32% | 21% | 15% | 8% | 9% | 12% | 15% | 9% |

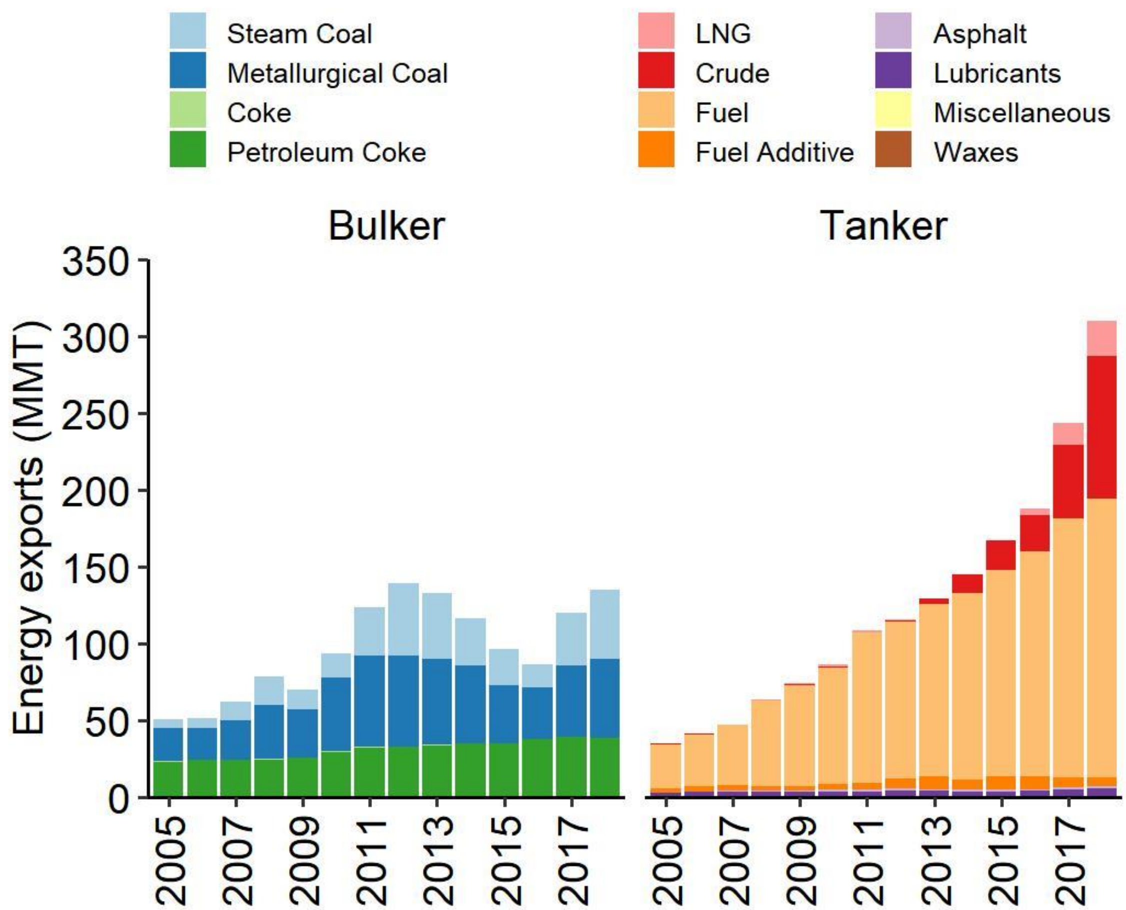
*Hawaii bioregion: SP-XXI



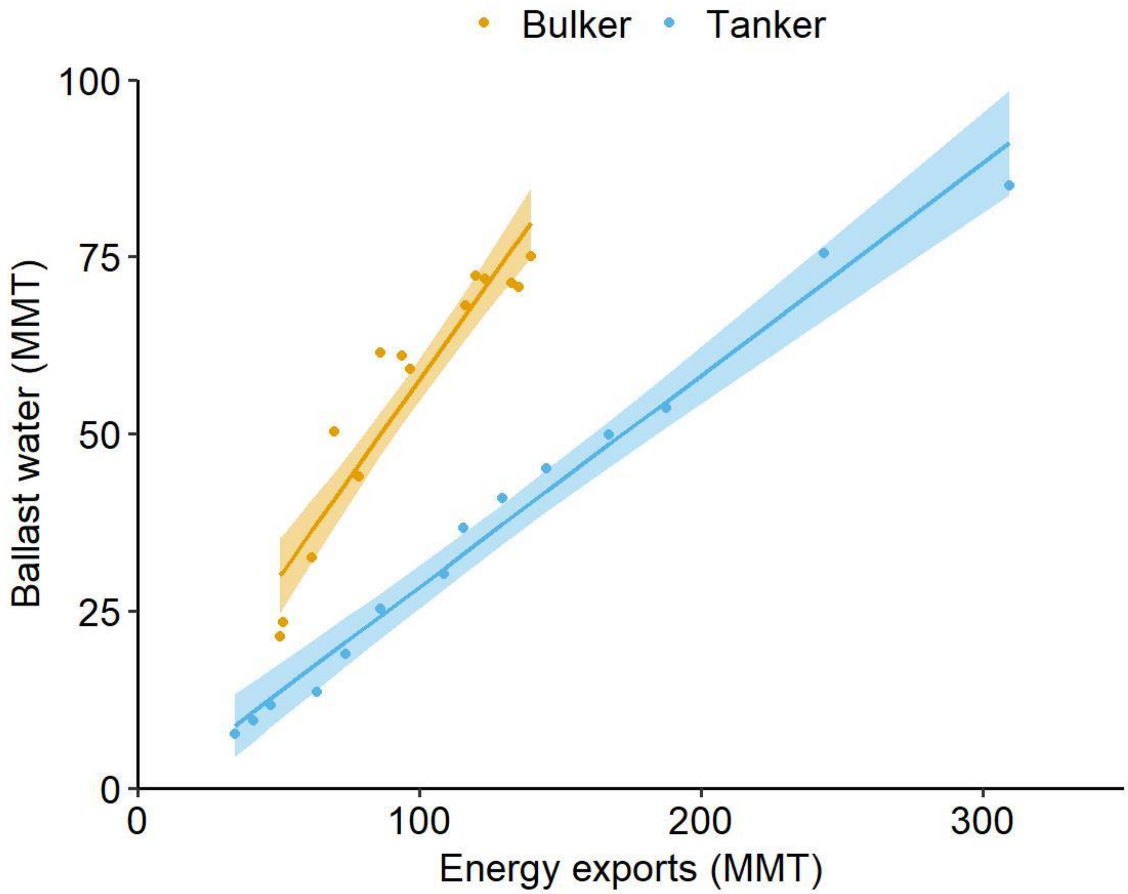

**Supplemental Figure 1.** The contribution of ballast water by (A) overseas bulk carriers originating from countries in the Asia source region and (B) overseas tankers originating from the Central America source region.



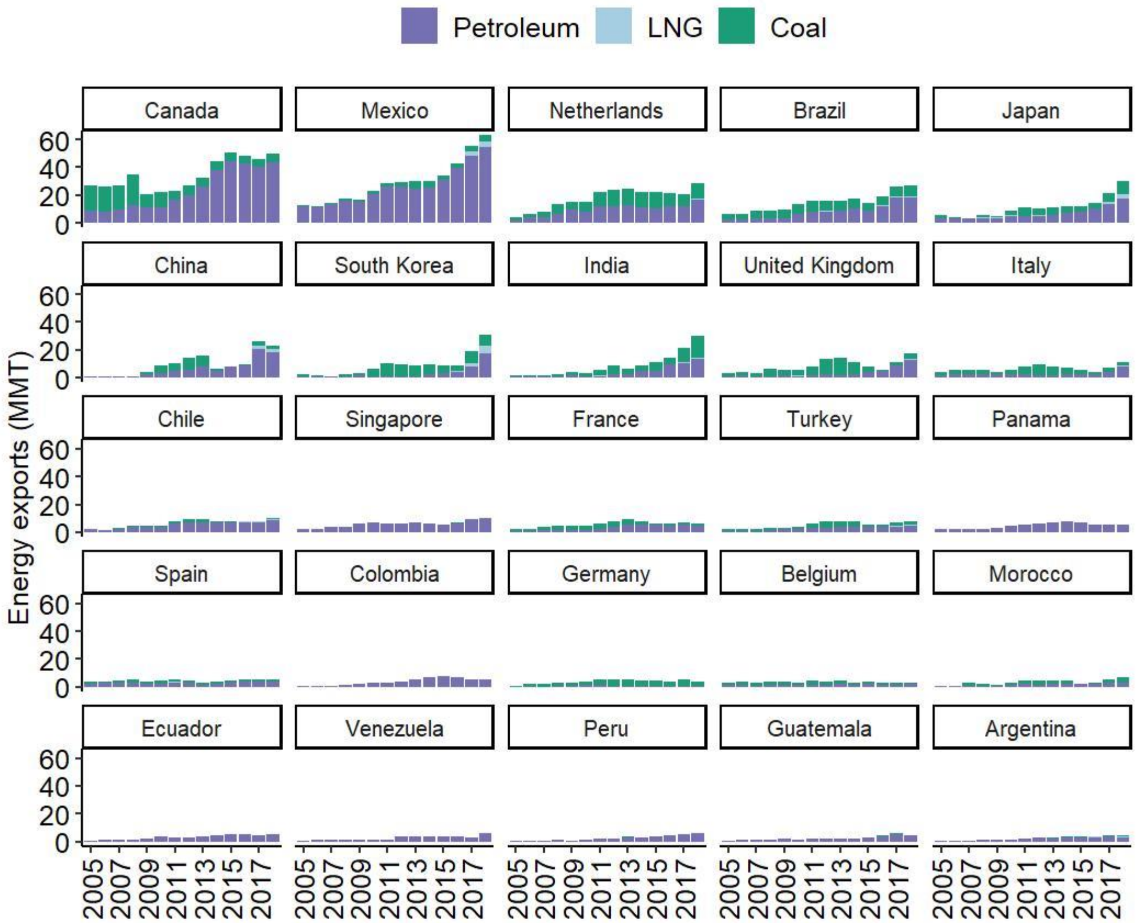

**Supplemental Figure 1.** Annual petroleum exports from the United States. Regions are denoted by Petroleum Administration for Defense Districts (PADDs 1 – 5), see Figure 2.2 for locations. This study captured the rise in US energy exports from 2005 through 2018.



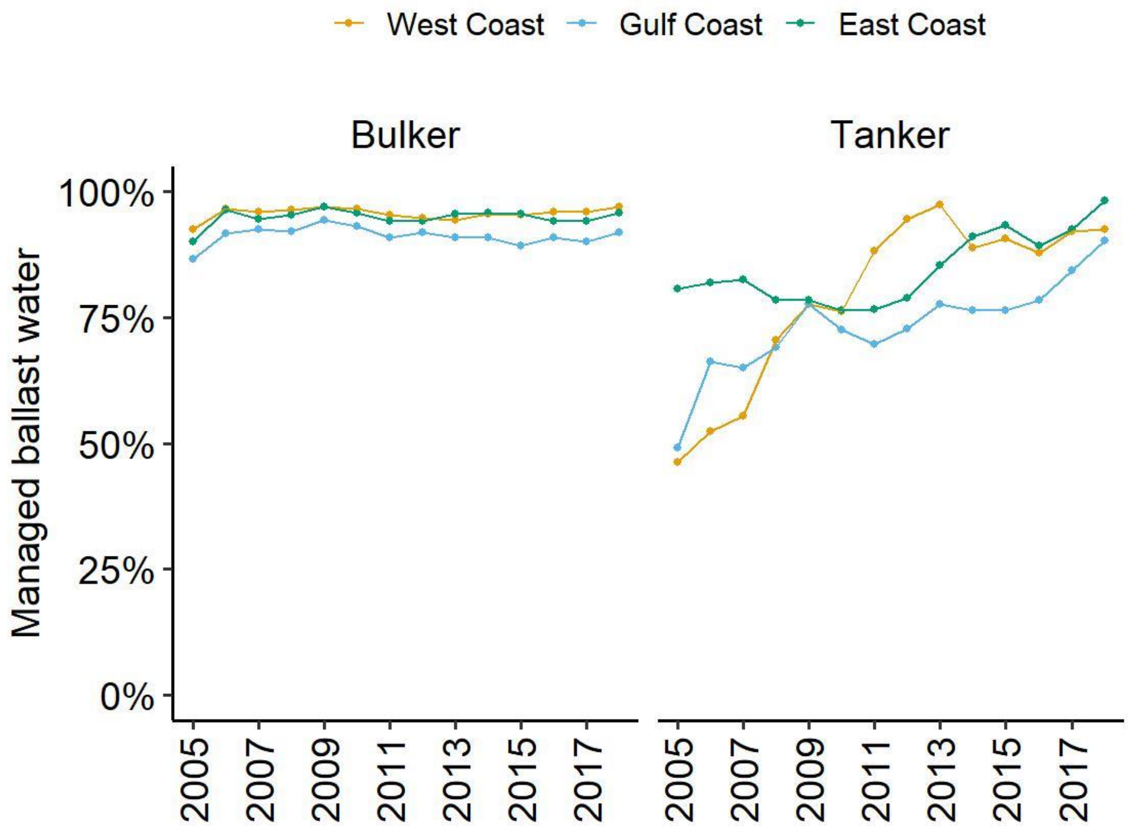

**Supplemental Figure 2.** Energy goods exported by bulk and tank vessels from the coastal United States. Values represent million metric tons.



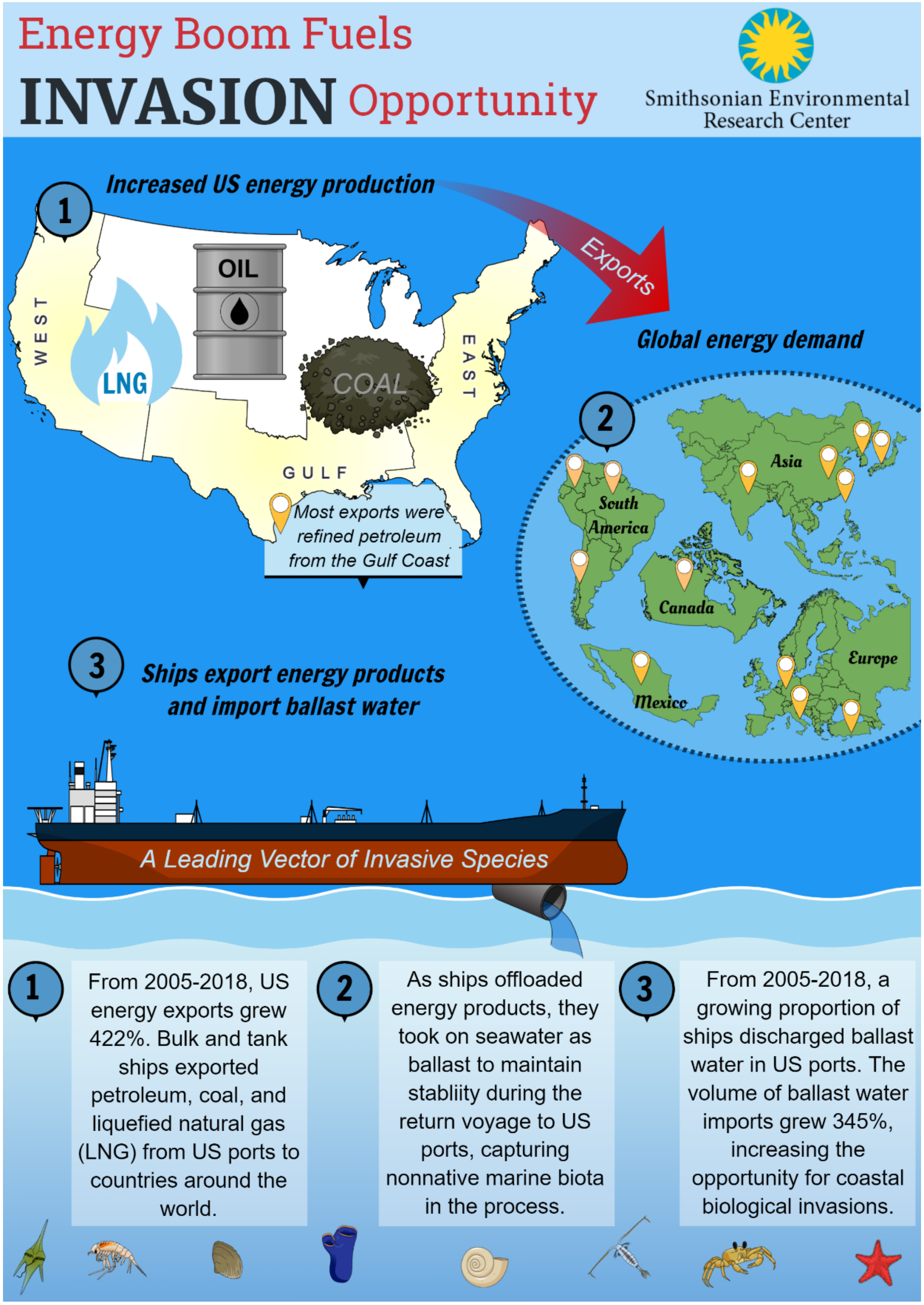

**Supplemental Figure 3.** The relationship between energy exports and ballast water imports by vessel type. Values represent million metric tons. A linear regression model of the relationship can be described as: $y = 1.69 \times 10^{6} - 3.19 \times 10^{6}{}_{T} + 5.60 \times 10^{-1}x - 2.61 \times 10^{-1}{}_{Tx}$, where $T$ is the dummy coded contrast between tankers and bulkers, and $Tx$ is the interaction between ship type and energy exports. Adjusted $R^2 = 0.95$. Shaded areas represent 95% confidence intervals.




**Supplemental Figure 4.** Top 25 destinations for shipborne energy exports from the United States.




**Supplemental Figure 5.** The percentage of ballast water imports that were reported managed by bulk and tank vessels on each coast of the United States.




**Public infographic for Chapter 2.**