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Research Article

Ballast-borne marine invasive species: exploring the risk to coastal Alaska, USA

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Abstract

The relatively uninvaded coastline of Alaska currently faces a heightened risk of novel biological introductions as a result of increasing regional vessel traffic, emerging Arctic trade routes, and proposed coastal and nearshore development. Alaska currently receives the majority of its ballast water discharge in the port of Valdez (86%), largely from crude oil tankers engaged in coastwise trade. These crude oil tankers were exempted from managing and reporting ballast water prior to the United States Environmental Protection Agency's 2008 Vessel General Permit (VGP). Here we present a comprehensive statewide risk assessment of ballast-borne marine invasive species throughout coastal Alaska, and the first study to characterize the risk from the ballast water vector following inclusion of ballast water reporting by the VGP. We examined ballast water discharge volume, environmental similarity between source and discharge regions, ballast water age, and marine invasive species richness in source regions annually from 2009 – 2012 for the top 15 ports/discharge locations in Alaska. The majority (80%) of the more than 54 million metric tons of reported ballast water discharged during this time period was sourced from the west coast of North America, including highly invaded port systems such as San Francisco Bay, California and Puget Sound, Washington. Overall about 38% of the ballast water discharged to our focus locations was managed using ballast water exchange. We conclude that the risk of invasion is highest for the ports of Valdez and Drift River Terminal and lowest for the ports of Klawock, Skagway, and Tolstoi Bay. This analysis and risk matrix can inform further fine-scale assessments of ballast water management activity and identify areas of Alaska most likely to benefit from focused management efforts.

Key words: ballast water, risk assessment, vector-based analysis, invasive species, Arctic

Introduction

Ballast water from ships is a well-known and significant transport vector of non-native and invasive aquatic species on regional and global scales (Carlton and Geller 1993; Ruiz et al. 2000; McGee et al. 2006; Keller et al. 2011). Globalization is implicated as a major contributor to the increasing rate of ship-borne species invasions (i.e., introductions via ballast water and biofouling) (Carlton and Geller 1993; Ruiz and Carlton 2003), and the number of introduced species attributed to ballast water has been on the rise since 1900, particularly during the 1980s and 1990s (Bax et al. 2001). Ships use ballast water on both trans-oceanic and coastwise voyages; however, coastwise voyages that transit relatively short distances typically present a heightened risk of successfully transporting invasive species due to environmental similarity between source and discharge ports and shorter voyage duration (David et al. 2013b). Additionally, coastwise voyages are responsible for the secondary spread of invasive species, as invaded ports become sources for the transfer of species to other ports in the region (Simkanin et al. 2009; Rup et al. 2010). Efforts to reduce the transfer of ballast-borne invasive species have been ongoing for decades in the form of international, national and state recognized ballast water management guidelines and regulations (Firestone and Corbett 2005; Cordell et al. 2009; Albert et al. 2013) and scientific studies on ballast water composition, treatment strategies, and risk assessment have also been prevalent (Bailey 2015). Nevertheless, the staggering volume of shipping traffic worldwide continues to pose a substantial threat (Drake and Lodge 2004; Seebens et al. 2013), as ships travelling between ports regularly disperse diverse mixtures of species by ballast water and biofouling. As new trade routes continue to emerge, previously unaffected areas are exposed to risk of invasion (Ruiz and Carlton 2003; Seebens et al. 2013).

Most recently, changing environmental conditions have led to increased opportunities for high-latitude shipping traffic. Reduced seasonal ice cover in the Arctic has made way for new viable vessel traffic routes such as the Northern Sea Route (NSR) and the Northwest Passage (NWP) (Stroeve et al. 2008; Somanathan et al. 2009; Khon et al. 2010). These emerging routes will shorten transit times compared to traditional routes through the Panama and Suez Canals, expand the opportunity for natural resource extraction in the Arctic, and create the opportunity for a new era in tourism (Miller and Ruiz 2014). In response, the United States National Oceanic and Atmospheric Administration is creating and updating nautical charts in the Bering, Beaufort, and Chukchi Seas and the United States Coast Guard (USCG) is heightening their regional presence in preparation for increased vessel traffic and development. As evidence of this anticipated change, the State of Alaska and the United States Army Corps of Engineers intend to develop a deep draft port along Alaska's northwestern coastline (State of Alaska 2013).

Miller and Ruiz (2014) predicted that additional Arctic shipping will result in novel biological invasions to the region. As the Atlantic and Pacific Oceans become increasingly connected via ice-free northern waters, the global shipping industry may shift preferred vessel routes toward the NSR and NWP, although the degree and timing of these changes remain unknown. Over time this could result in increased opportunities for introductions of species that previously did not have a pathway to invade Alaska's coastline. In addition, changes in ocean temperature and salinity and reduced ice cover alter pathways by adding or removing physical or ecological barriers, allowing for the natural extension of species' ranges into higher latitudes, and resulting in shifts in the intensity of their impacts (Elton 1958; Hellmann et al. 2008; Rahel and Olden 2008). Assessing risk of high-latitude invasions is therefore critical, particularly in areas that expect to experience increased rates of shipping (Miller and Ruiz 2014).

Risk assessments identify the source and degree of potential hazards and are a first step in successful risk management (Pysek and Richardson 2010). Invasive species risk assessments predict the likelihood of introduction and can be subsequently used to identify potential impacts (Andersen et al. 2004; IMO 2007), allowing managers to test plausible scenarios and develop proactive methods to mitigate risk. Although the risk associated with invasive species in ballast water discharge is a function of numerous factors, at the core are fundamental categories: environment, ballast journey (length of voyage and management practices), and species (number and variety of organisms) (Hayes 1998; Wonham et al. 2013). Successful vector-based risk assessments review these factors individually before assessing their impacts collectively to reveal unique risks per location (Keller et al. 2011; Chan et al. 2013; Ware et al. 2013) and aid development of subsequent management actions based upon the findings.

The aims of this analysis are to: (1) develop a risk assessment framework for ballast-borne marine invasive species in Alaska following other high-latitude risk assessments (e.g., Leppäkoski and Gollasch 2006; Chan et al. 2013; Ware et al. 2013) and (2) characterize risk throughout coastal Alaska by developing a relative risk matrix for the 15 ports/discharge locations with the highest ballast water discharge volume. McGee et al. (2006) conducted a preliminary risk analysis for Alaska by identifying dominant vessel types arriving in regions and ports from 2003 – 2004 and summarizing the volume and management of ballast water discharge from 1999 – 2003. The risk matrix presented here is based on the flux of ballast water to the 15 locations, environmental similarity between source and discharge locations, ballast water age, and invasive species richness present in source ecoregions. This study presents the first assessment of ballast water discharge and associated risk for coastal Alaska following mandated comprehensive vessel reporting in the United States.

Methods

Vessel behavior data

The National Ballast Information Clearinghouse (NBIC) was created in 1997 as mandated by the National Invasive Species Act of 1996 and is maintained by the Smithsonian Environmental Research Center in conjunction with the USCG. Nearly all vessels capable of carrying ballast water are required to submit a ballast water report to the NBIC at each arrival in a United States port (see Minton et al. 2014 for specifics).

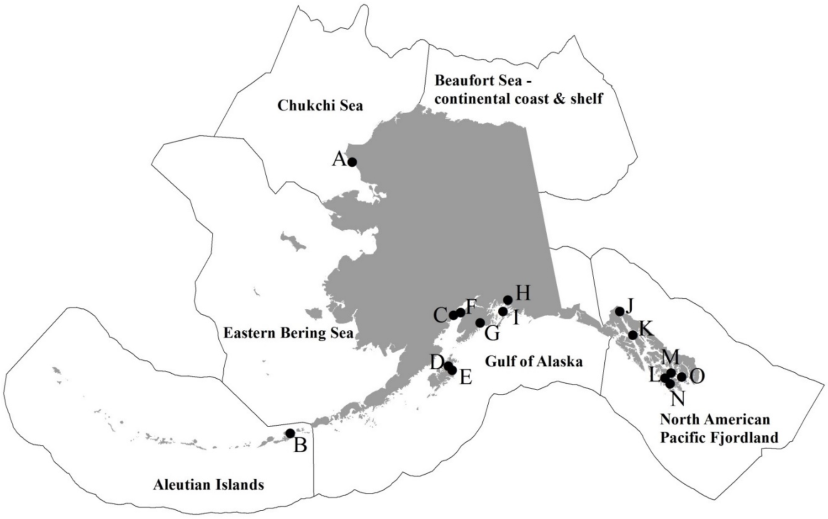

Figure 1. Ecoregions of Alaska, as described in the Marine Ecoregions of the World bioregionalization (Spalding et al. 2007), and the top 15 ballast water discharge ports/locations by volume. Locations are labeled: A = Red Dog; B = Dutch Harbor; C = Drift River Terminal; D = Afognak; E = Kodiak; F = Nikiski; G = Seward; H = Valdez; I = Prince William Sound; J = Skagway; K = Hawk Inlet; L = Klawock; M = Tolstoi Bay; N = Hydaburg; O = Ketchikan.

These ballast water reports include ballast source, discharge, and management activities (e.g., date, location, volume, and management method). Mandatory reporting by overseas vessels arriving to the United States began in 1999 and was expanded to include coastwise arrivals in 2004. Regulatory exemptions, however, allowed for crude oil tankers engaged in coastwise trade to forego submitting ballast water reports until required to by the United States Environmental Protection Agency's Vessel General Permit (VGP) in 2008 (EPA 2008). Since crude oil tankers involved in coastwise trade are the dominant source of ballast water discharge to Alaska, we chose to analyze risk using post-VGP data reported from 2009 – 2012. All ship transit and ballast water data were obtained from the NBIC (NBIC 2012). During the time period of interest, annual compliance with the USCG reporting requirements averaged 91.9% (SE: ± 3.2%) and 76.3% (SE: ± 1.8%) for Alaskan overseas and coastwise arrivals, respectively (Miller et al. 2012; Minton et al. 2012; Minton et al. 2014).

Focus locations

The focus locations for this risk assessment were identified as the 15 ports/locations in Alaska that received the greatest cumulative volume of ballast water from 2009 – 2012 as reported to the NBIC (NBIC 2012). These were: Red Dog (Chukchi Sea ecoregion), Dutch Harbor (Aleutian Island ecoregion), Afognak, Kodiak, Drift River Terminal, Nikiski, Seward, Prince William Sound, Valdez (Gulf of Alaska ecoregion), Skagway, Hawk Inlet, Tolstoi Bay, Klawock, Hydaburg, and Ketchikan (North American Pacific Fjordland ecoregion) (Figure 1).

Estimating propagule supply

The likelihood of ballast-borne introductions increases with the number and frequency of discharge events (Kolar and Lodge 2001; NRC 2011). Although ballast water volume and discharge frequency are not a direct measure of propagule pressure (David et al. 2013a; Ruiz et al. 2013), given the large variability in species composition and abundance in ballast water (Minton et al. 2005; Verling et al. 2005) it is a better proxy than ship arrivals alone (Miller et al. 2011; NRC 2011) and is a suitable alternative when vessel-specific biology data are lacking (Lo et al. 2012; Chan et al. 2013). Efforts to characterize the density and diversity of organisms arriving in ballast water to select Alaskan ports were conducted by the Smithsonian Environmental Research Center from 1997 – 1999 (Hines and Ruiz 2000) and 2012 – 2014 (unpublished data), but these data do not characterize all ports, or even regions, within the state. Alternatively, ballast water discharge volumes are readily available across time and have been used by others (McGee et al. 2006; Chan et al. 2013; Muirhead et al. 2015) as a proxy for determining risk associated with species abundance.

Relative risk associated with ballast water discharge volume was assessed annually for each port. First, similar to Chan et al. (2013), a correction

Table 1. Ranking system of parameters used to categorize relative risk of ballast-borne marine invasive species in coastal Alaska.

	Effective volume of ballast water discharge (log_{10}MT)	Environmental similarity	Ballast water age (days)	Species richness
(0) No risk	*No ballast water received*			
(1) Low risk	< 2.6	< 1	> 10	< 110
(2) Medium risk	2.6 – 5.1	1 – 2	6 – 10	110 – 219
(3) High risk	> 5.1	> 2	< 6	> 219

factor of 0.1 was applied at the tank level to managed ballast water (i.e., ballast water that underwent mid-ocean exchange) to represent a 90% efficacy rate for empty refill and flow through ballast water exchange across multiple vessel types (Ruiz and Reid 2007; Muirhead et al. 2015). Although efficacy of ballast water exchange depends upon vessel type and exchange method, this correction factor implies retention of 10% of the high-risk coastal organisms entrained from the source port. Second, effective discharge volumes (i.e., volumes corrected for management activity) were summed for each year. Lastly, total annual effective discharge volumes were log_{10} transformed and applied to the ranking system. The ranking system was based on the maximum total volume of ballast water discharged in a port from 2009 – 2012, (4.7 million metric tons (MT) to Valdez). This value was log_{10} transformed (7.7 log_{10}MT) and divided into three risk categories: low (<2.6), medium (2.6 – 5.1), and high (>5.1) (Table 1).

Estimating environmental similarity

Environmental similarity between source and discharge ports strongly influences a species' ability to survive once released from a ballast tank and is positively correlated with risk (Paavola et al. 2005; Herborg et al. 2007; Keller et al. 2011). In the Marine Ecoregions of the World bioregionalization developed by Spalding et al. (2007), 'ecoregions' are the smallest-scale delineation of marine biogeographic regions characterized by "relatively homogenous species composition determined by the predominance of a small number of ecosystems and/or a distinct suite of oceanographic or topographic features" (Figure 1). Given the spatial extent of this risk assessment and the vast length of Alaska's coastline (10,686 kilometers), ecoregion-based comparisons provide the most practical method for an initial statewide risk assessment of marine invasive species (Hunsaker et al. 1990; Wiegers et al. 1998, David et al. 2013a). Barry et al. (2008) warn of masking risk by including additional environmental variables that do not directly influence invasion potential and suggest only temperature and salinity be used as indices of environmental similarity. However, ecological niche models have successfully predicted suitability for species survival using a variety of environmental and climate variables in aquatic and terrestrial ecosystems (Peterson 2003; Thuiller et al. 2005; Herborg et al. 2007; Zanden and Olden 2008; de Rivera et al. 2011; Kulhanek et al. 2011), and the G7 Guidelines of the BWM Convention indicate that environmental matching for risk assessments should consider conditions within biogeographical regions (IMO 2007). In addition, the majority of ecoregions relevant to this study lie within the Temperate Northern Pacific realm (the largest spatial unit described by Spalding et al. 2007), suggesting basic similarity of higher taxonomic biota and environmental influences. Therefore 'environmental similarity' between ballast water discharge locations in Alaska and source ports throughout the Pacific was based upon the physical proximity of source and discharge ecoregions. Ballast water sourced and discharged within the same ecoregion was considered high risk (3), adjacent ecoregions were considered medium risk (2) and non-adjacent ecoregions were considered low risk (1) (Table 1). We then annually calculated a weighted average of the assigned risk score (1, 2, or 3) based on the effective discharge volume from each source ecoregion. The highest weighted average (2.9) was divided into three equal categories: low (<1), medium (1 – 2), and high (>2). Ballast water with an unknown source was considered low risk, and ballast water that was discharged to unspecified regions of Alaska was not considered.

Calculating ballast water age

Ballast water age, the time elapsed (days) between ballast water uptake and subsequent discharge, is negatively correlated with the survival of ballast-borne organisms. Lavoie et al. (1999) found high abundances of organisms survived short voyages (1 – 2 days) and consequently determined that coastwise voyages have the potential to be vectors for the transport of non-native species. The length of time that organisms can survive in ballast tanks varies, but the largest decrease in abundance typically occurs within the first five days of transit (Gollash et al. 2000a; Gollasch et al. 2000b; Olenin et al. 2000; Cordell et al. 2009) and density (organisms m^{-3}) generally decreases with time (Verling et al. 2005). For example, ships arriving to the Canadian Arctic and Great Lakes showed a decrease in zooplankton abundance and species richness with an increase in ballast water age (Chan et al. 2014). In some cases, Gollasch et al. (2000b), Cordell et al. (2009) and Klein et al. (2010) found organisms alive after long voyages (20 – 30 days), but densities were significantly lower than at the start of the voyage. During the two voyages sampled by Gollasch et al. (2000b) with durations greater than ten days, the number of zooplankton taxa found present in ballast tanks generally decreased between six and ten days. In addition, Cordell et al. (2009) found a decreasing trend in mean zooplankton density in ballast water aged 1 – 5 days, 6 – 10 days, 11 – 15 days, etc. We therefore considered ballast water age less than six days as high risk (3), age from 6 to 10 days as medium risk (2), and age greater than 10 days as low risk (1) (Table 1). Risk from ballast water age was determined from the average age of ballast water discharged to each port annually.

Estimating species richness

The ranking system for the relative risk from species richness was based on the maximum total number of established species known or likely to be introduced by ballast water to source ecoregions of any port from 2009 – 2012 (329 records from source ecoregions of Dutch Harbor) divided into three equal categories: low (<110), medium (110 – 219), and high (>219) (Table 1). The annual relative risk to receiving ports based on species richness was calculated as the total species richness in all source ecoregions in a given year (Figure 3). Species counts were taken from The Nature Conservancy's Database of Global Marine Invasive Species Threats (Molnar et al. 2008), the most recent comprehensive list of global marine invasive species available (Ware et al. 2013), and include all species associated with only the "ballast water and sediments" pathway of introduction to each source ecoregion. The implicit assumption is that a greater number of non-native species in the donor port/region will result in a greater risk of invasion in the recipient region (sensu Chan et al. 2013).

Results

Patterns

From 2009 – 2012 a total of 54,018,612 MT of ballast water was reported discharged to Alaska's top 15 ports/discharge locations by 1,877 arrivals with an average ballast water age of 10 days (SE: ±0.1 days). Corrected for management activity (i.e., ballast water exchange), the effective volume of reported ballast water discharge was reduced by 34% to 35,551,259 MT (Figure 2). Bulk carriers (bulkers) were the dominant vessel type that discharged ballast water in most (10) locations, followed by tankers (4 locations). In contrast, only one port (Dutch Harbor) received mostly container and reefer vessels. With the exception of the Red Dog port facility, all ports are located along the southern coast of Alaska or the Aleutian Island chain and are accessible to vessel traffic year-round. Red Dog is located along the Chukchi Sea and received ballast water discharge only between June and October due to sea ice.

Ballast water discharge characteristics of volume, age, source, and species richness varied among ports. Valdez received by far the most ballast water discharge, cumulatively receiving 96% more ballast water than the next highest port (Red Dog) and 86% of total discharge. Correcting for management activity (i.e., scaling ballast water discharge by 0.1 for tanks that underwent ballast water exchange) did not change the top ranking; however, Nikiski surpassed Red Dog in effective discharge, due to the relatively higher rate of ballast water management by vessels discharging at Red Dog (82%). Drift River Terminal received ballast water discharge with the youngest average age of 6 days and only two other ports received ballast water with an average age of <10 days (Prince William Sound and Valdez), both approximately 7 days. The oldest ballast water was discharged in Dutch Harbor, with an average age of 36 days. Average age at all other ports ranged from 11 – 24 days (Figure 2). Source ecoregions of ballast water discharged in Dutch Harbor had the greatest recorded species richness of ballast-borne marine invasive species (cumulative 329 records from 31 ecoregions), followed by Valdez (cumulative 197 records from 17 ecoregions).

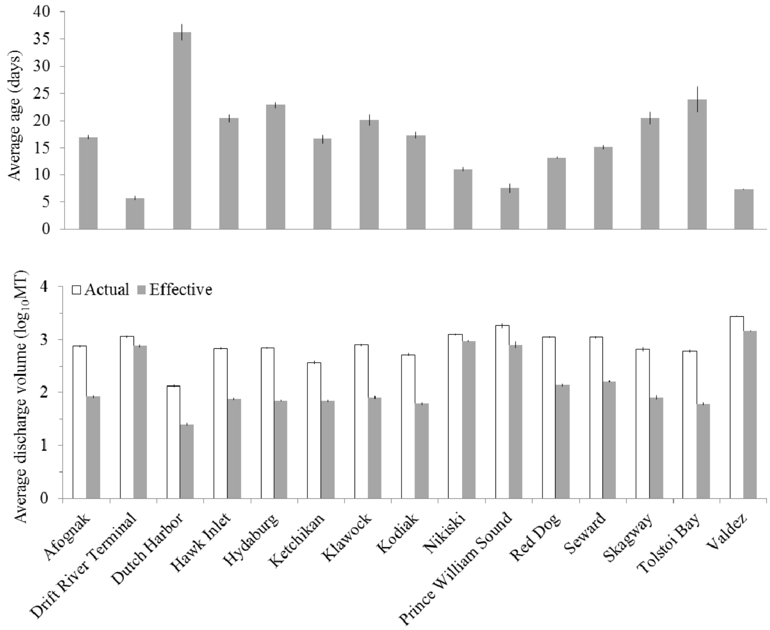

Figure 2. The average age and average actual and effective volumes of ballast water discharge in the top 15 Alaskan ports, 2009 – 2012; error bars depict standard error. Effective volumes account for a 90% efficacy rate of ballast water exchange in managed ballast tanks.

Ballast water source ecoregions for Klawock and Tolstoi Bay had the smallest pool of potential invasive arrivals, at 29 records each, from six and eight ecoregions, respectively.

Relative risk

Risk of ballast-borne species invasion varied by parameter and across ports, but was highest for Valdez and Drift River Terminal, which consistently received medium to high-risk ballast water across all years. Risk was low for the ports of Klawock, Skagway and Tolstoi Bay (Figure 4). Medium or high risk from propagule pressure (i.e., effective ballast water discharge volume) was evident across all years for 10 of the 15 ports. Notably, Valdez was the only port to maintain high risk across all years for this parameter. The ports of Klawock, Kodiak, Prince William Sound, Skagway, and Tolstoi Bay received no ballast water discharge or low risk volumes during at least one of the four years. Risk associated with environmental similarity was highest for Drift River Terminal, medium for Ketchikan, Nikiski, Red Dog, Kodiak, Seward, and Valdez, low to medium for Afognak, Hawk Inlet, Hydaburg, Prince William Sound, and Skagway, and low for Klawock and Tolstoi Bay. The majority of ports received relatively low risk ballast water greater than 10 days old on average. Only Valdez and Drift River Terminal received ballast water of medium or high risk age across all years. Ballast water discharged to Prince William Sound ranged from 6 – 10 days old (medium risk) from 2009 – 2011, but no ballast water was received during 2012. Risk associated with invasive species richness in ballast water source ecoregions was medium to high across all years in only Dutch Harbor and Valdez. Drift River Terminal, Hawk Inlet, Nikiski and Prince William Sound had midlevel overall risk from this parameter that varied on an annual basis in each location. The majority of ports had low risk from species richness. However, 43 of the 49 unique source ecoregions contained at least one known ballast-borne marine invasive species and dominant source ecoregions tended to have the highest counts (Figure 3).

Temporal variations of risk were most evident in Prince William Sound, Tolstoi Bay, Drift River Terminal, Red Dog, Nikiski, and Kodiak. Prince William Sound saw a 76% reduction in effective discharge volume between 2009 and 2010, and a 44% reduction between 2010 and 2011. Environmental similarity risk increased to medium in 2010 but returned to low in 2011. Risk from ballast water age and species richness remained constant before all parameters were reduced to zero in 2012. Conversely, Tolstoi Bay did not receive ballast water discharge during 2009 or 2010 but saw a 44% increase in effective volume between

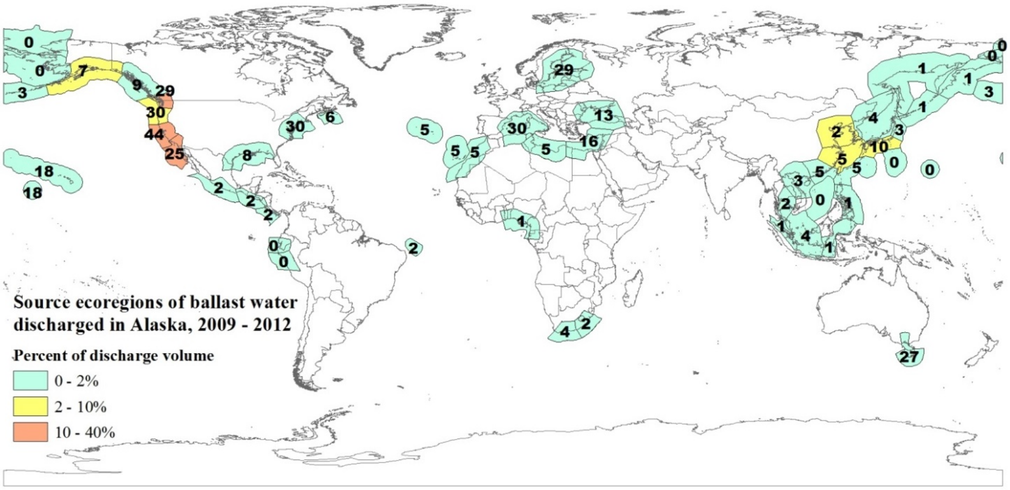

Figure 3. The number of ballast-borne marine invasive species known to occur in each source ecoregion of ballast water discharged in Alaska, 2009 – 2012. Species data were obtained from Molnar et al. (2008).

2011 and 2012. Risk from all other parameters was low during those two years. Drift River Terminal received increasing volumes of ballast water discharge each year from 2009 – 2012, increasing its risk from medium to high in 2011. Average ballast water age decreased annually, increasing risk from medium to high between 2011 and 2012. Risk from source ecoregion species richness increased to medium during 2010 – 2012. Red Dog received an 84% increase in effective volume between 2010 and 2011, increasing risk from medium to high. Conversely, Nikiski received a decrease of 86% ballast water discharge volume between 2011 and 2012, reducing its relative risk from high to medium. Ballast water age risk in Nikiski increased to medium during 2010 and 2011 before returning to low in 2012. Kodiak received an extremely low volume of ballast water from within the same ecoregion in 2009, resulting in an increase in effective discharge volume of 1720% and increasing risk to medium during 2010 – 2012. Risk from environmental similarity decreased, however, to medium in 2010 and low in 2012.

Discussion

Our four-year composite risk assessment provides insight into the relative risk of ballast water mediated introductions at 15 target locations in Alaska while detailing the annual variability of risk from four influential risk factors (Figure 4). We infer risk to ports of Alaska based upon proxies of propagule pressure (effective discharge volume), habitat suitability (environmental similarity), species viability (ballast water age), and species richness in source ecoregions. Each of the four risk parameters were assessed independently, as risk ultimately depends on port and species-specific details and we do not assume an equal influence of each parameter across all risk scenarios. However in general, ports at greatest risk were characterized as those that received a high volume of relatively young and unmanaged ballast water from source ports with similar environmental conditions known to host invasive species. Comparable to studies from other high-latitude ports in Canada and Europe (Leppäkoski and Gollasch 2006; Chan et al. 2013; Ware et al. 2013), we find coastal Alaskan waters are at risk from ballast-borne marine invasive species. Specifically, our multifactor vector based risk matrix revealed that Valdez and Drift River Terminal are at highest risk, while Nikiski, Prince William Sound, and Dutch Harbor are also hotspots for potential invasion (i.e., medium to high risk within and across most years) whereas Klawock and Tolstoi Bay had relatively low risk (Figure 4).

Exports of natural resources (e.g., fossil fuels, fish, minerals, timber, and coal) drive the majority of commercial vessel traffic in Alaska responsible for discharging ballast water to coastal areas. Availability and demand of these resources strongly influences the risk of invasion to a particular port; this is most notable in Valdez where regular crude oil exports made by tankers engaged in

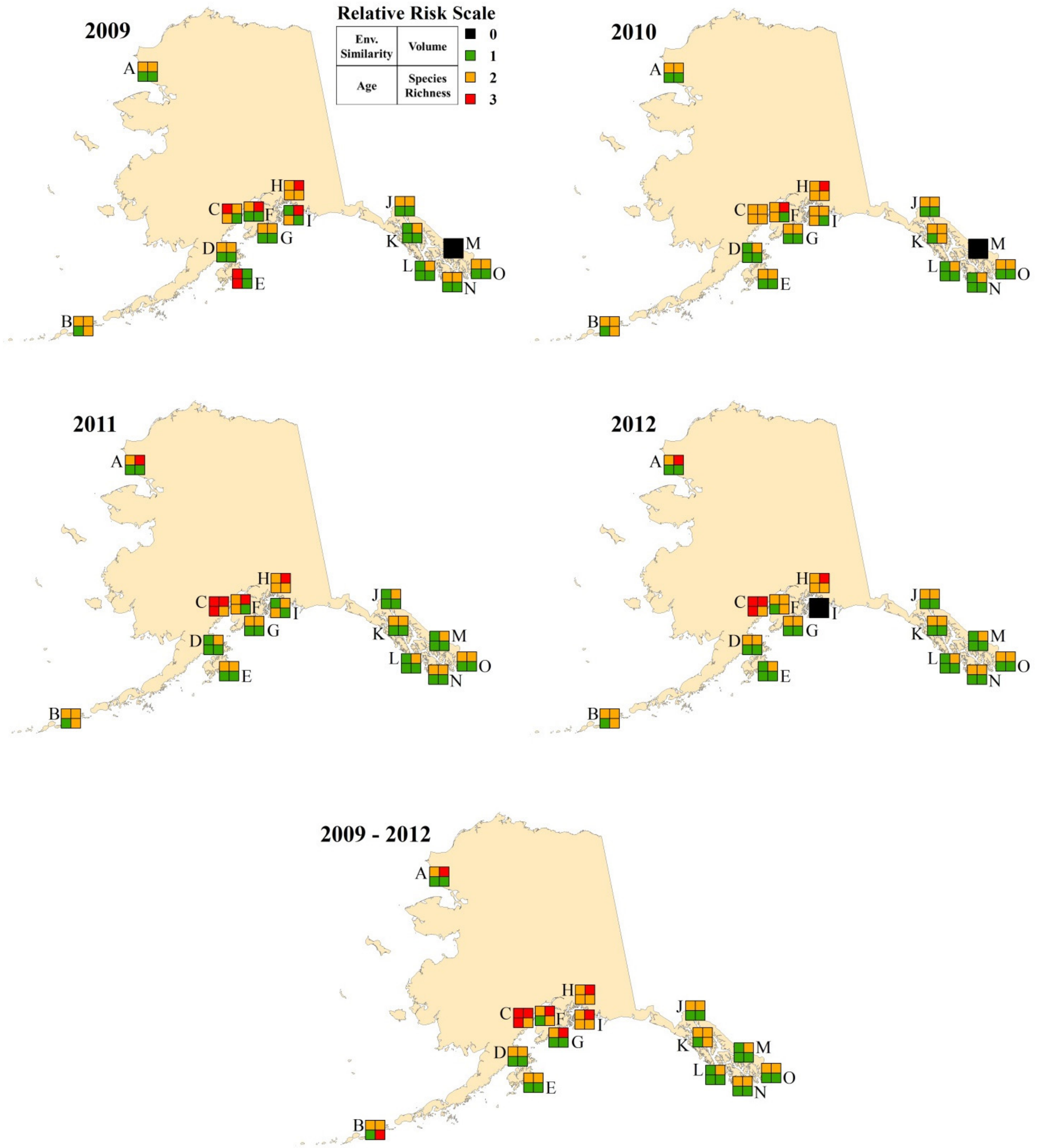

Figure 4. Relative risk of ballast-borne species invasions in 15 ports of Alaska, 2009 – 2012, represented by a 4-tier scale where 3 (red) indicates the highest risk and 0 (black) indicates no risk (i.e., no ballast water received). Ballast water discharge locations are labeled as follows: A = Red Dog; B = Dutch Harbor; C = Drift River Terminal; D = Afognak; E = Kodiak; F = Nikiski; G = Seward; H = Valdez; I = Prince William Sound; J = Skagway; K = Hawk Inlet; L = Klawock; M = Tolstoi Bay; N = Hydaburg; O = Ketchikan.

coastwise trade resulted in relatively high annual invasion risk, and in Tolstoi Bay where the start of timber sales introduced invasion risk from ballast water discharge in 2011. With consideration for these trends in risk and also regional expectations of changes to vessel traffic or development, the risk assessment developed here (Table 1) can be applied to future focused management and policy and can also serve as a baseline to evaluate changes. Nevertheless, decreases in risk to Nikiski coupled with increases to Drift River Terminal, both ports located in close proximity to one another, could be a result of a number of economic factors but do not necessarily equate to an overall change in risk to the Cook Inlet region. In addition, the 2015 affirmation of oil and gas lease sales in the Chukchi Sea (DOI 2015) and the resulting expected increase in vessel traffic through the Arctic and Bering Strait may influence management activity in ports such as Dutch Harbor, which already receives ballast water from a variety of sources and has the greatest overall risk from species richness.

However, some uncertainty should be accounted for within vessel practices and reporting accuracy. For instance, in some cases vessels may not discharge all ballast tanks at berth, but instead may begin to discharge ballast water while still approaching a port or at anchorage, particularly if inside protected waters. This practice may reduce time in port by allowing a vessel to load cargo immediately upon arrival without needing to wait while de-ballasting, thus reducing costs and delivering product more efficiently. However, reporting the location of ballast water discharge is often at the discretion of the vessel. The decreasing trend in ballast water discharge to Prince William Sound suggests that either vessels no longer discharged ballast water at large throughout the Sound or instead attributed all ballast water discharge to the arrival port (i.e., Valdez). This represents a level of uncertainty that may have implications for where risk of invasion is likely to occur. The cumulative assessment of multiple risk parameters may aid in determining where to focus management or survey efforts.

When considering possible management strategies, our findings may be applied to the decision-making process in a variety of ways. Ports may be targeted (or prioritized) for management (e.g., land-based treatment for clean ballast) due to one or several of the four invasion risk parameters. A large volume of ballast water discharge or the threat posed by a high number of invasive species in dominant source locations may be enough to prioritize a port for focused risk management strategies, depending upon other risk factors such as environmental similarity. Increased survey efforts both in arriving ballast tanks and the surrounding receiving waters may be warranted in a port that receives high volumes of ballast water from closely matched source ports, despite the age of ballast water discharge above the associated threshold for high risk. These management decisions may depend upon the assets valuable to that region.

As this is a preliminary statewide risk assessment of ballast-borne marine invasive species to marine ecosystems of Alaska, outstanding questions warrant further fine-scale analysis. Our model provides a broad overview of regional (e.g., ecoregion scale) environmental characteristics rather than port-specific variability or seasonality; however, it is unclear how a finer temporal or spatial scale may affect the relative risk by providing refuge or additional barriers. For example, a relative risk assessment of a variety of ecological stressors (not including invasive species) in the Port Valdez area alone focused on eleven subareas representing eight habitat types (Wiegers et al. 1998). Spring snow and glacial run-off in coastal ports of Alaska can add a substantial freshwater lens to marine environments (Neal et al. 2010) that may influence species' seasonal establishment potential. In addition, the wide range in volume of ballast water discharge among the top 15 ports resulted in skewed discharge volumes controlled by log transformation to create a linear relative risk scale. Although Valdez was at greatest risk by volume across all years, our scale does not portray that port as an outlier, as other ports (Drift River Terminal and Nikiski) also had overall high risk from volume, but received substantially lower volumes of ballast water discharge. It is worth noting, however, that although we assume an increase in propagule pressure is positively correlated with an increase in invasion risk (Simberloff 2009), the exact relationship between propagule pressure, colonization pressure, and proxies used for vector-scale introductions is currently unknown (NRC 2011; Briski et al. 2012; Wonham et al. 2013). Consequently, the implication for such highly skewed discharges is unclear.

Incorporating frequency as a second component of propagule pressure may also strengthen future analyses. Minton et al. (2005) suggested that propagule pressure is an additive parameter of volume and frequency, rather than solely a function of ballast water discharge volume. Depending upon the frequency considered (e.g., monthly, seasonally, or annually) the risk in each port may be different than currently recognized. For example, arrivals to the Red Dog port facility may be consistent within a season, while arrivals to Valdez are fairly consistent year-round. Although several studies indicate the importance of the number of introduction attempts to invasion success (reviewed by Simberloff 2009), success as a result of frequent introductions may also be species-dependent (Wonham et al. 2013). For instance Wonham et al. (2000) showed that behavioral traits common to specific fish families (Gobiidae and Blenniidae) may increase their invasion success by positively influencing rates of both introduction and establishment. Similar studies on other taxonomic groups could provide better resolution on this relationship for a wider range of marine organisms.

Species-specific assessments would also be of value to further understanding risk posed to coastal Alaska from invasive species. A similar framework to ours could be used to analyze the risk posed by specific high impact species known to be located in source ecoregions, as an established invader or in its native range. This approach may be valuable when implementing targeted monitoring and control efforts at corresponding receiving ports, perhaps with the engagement of citizen science programs. These species-based risk assessments have the management appeal of using early detection/rapid response techniques to mitigate known harmful impacts. For example, European green crabs (*Carcinus maenas* Linnaeus, 1758) have the potential to impact shellfish and habitat in southeast Alaska and can be transported in the ballast water of ships as juveniles or adults (de Rivera et al. 2011). Analysis of additional vectors and species' life-history traits could also be incorporated into the risk assessment (sensu Bradie and Leung 2015).

It is also important to consider latitude-based environmental similarity indices. We assume that the proximity of ecoregions is positively correlated with risk, and although Leppakoski and Gollasch (2006) use a similar approach with global temperature bands in their risk assessment of the Baltic Sea (i.e., a relatively small region), this method lacks the necessary specificity for global scale comparisons. For example, ballast water sourced in the southern hemisphere and discharged at an equivalent latitude in the northern hemisphere would be considered low risk on our scale, despite the potential for similar environmental conditions. Although this scenario is unlikely for ballast water discharged in Alaska, as most ballast water (80%) is sourced from ecoregions on the west coast of North America which include all major port systems in California, Oregon, and Washington (Puget Trough/Georgia Basin, Oregon, Washington, Vancouver Coast and Shelf, Northern California, and Southern California Bight; Spalding et al. 2007), a more refined environmental similarity index would alleviate this uncertainty. Likewise, the anticipated increase in Arctic vessel traffic will likely deliver ballast water from other non-adjacent ecoregions with similar biotic and abiotic influences.

The Arctic, including much of Alaska, is currently undergoing substantial and rapid regional environmental changes that may increase the potential for marine invasive species establishment as well as vessel traffic, the primary vector for delivering those species (Miller and Ruiz 2014). The current method of managing risk of ballast-borne introductions, ballast water exchange, reduces propagule pressure one order of magnitude on average, but there remains a risk of introduction (Minton et al. 2005; Bailey et al. 2015) and the biological significance of this reduction may depend on the magnitude of discharge (Figure 2). As the global vessel fleet shifts towards the mandatory use of onboard ballast water management systems to achieve a pre-determined discharge standard of species' density (Albert et al. 2013), the risk of introduction may be reduced, but not eliminated (Gollasch et al. 2007, Mamlook et al. 2007). In addition, ballast water exchange will continue to be the primary management strategy as these systems are gradually phased in over time (IMO 2004, USCG 2012, EPA 2013). Our risk assessment identifies those areas in Alaska that are currently at risk of invasion based on recent history of vessel behavior, but future policy should also consider anticipated shifts towards a more developed and traveled region.

The efficacy of future policies may depend on reducing the number of vessel exemptions and implementing regulations or guidelines that account for regional ecological attributes and species-specific concerns. For example, vessels operating or taking on and discharging ballast water exclusively within one USCG Captain of the Port (COTP) Zone are currently exempted from ballast water management requirements (USCG 2012; EPA 2013). Despite its large coastline, the State of Alaska contains only three COTP Zones that span six ecoregions (North American Pacific Fjordland, Gulf of Alaska, Aleutian Island, Eastern Bering Sea, Chukchi Sea, and Bering Sea – continental coast and shelf) and a wide range of habitats. The western COTP Zone encompasses a significant portion of the state, stretching across multiple degrees of latitude and longitude including all or part of four ecoregions, and seven of the ports included in our risk assessment. Although this area currently receives a lower volume of traffic than the Prince William Sound or Southeast Zones, expected increases in vessel traffic throughout the Arctic may soon result in port development and increases in seasonal arrivals as a result of regional development and subsequent need for import and export of resources. For vessels that operate solely within a single COTP Zone, the noted value of ballast water management (exchange or treatment) and reporting may be worth consideration in large or ecologically diverse Zones and between high-risk ports located in the same Zone, aimed at reducing the likelihood of secondary spread.

Whether vector-based or species-based, risk assessment for invasive species is a valuable tool to inform policy decisions and management efforts, particularly with the incorporation of standardized components (sensu the G7 Guidelines (IMO 2007)). Global-scale vectors such as shipping incorporate a variety of biotic and abiotic influences on invasion potential and are particularly well suited for risk assessment analyses. Our study summarizes the risk of ballast-borne marine invasive species to coastal Alaska, an area that is currently relatively uninvaded but increasingly susceptible to invasion as changes to trade routes and the potential for future natural resource exports result in previously unseen exposure to vessel traffic and coastal development (e.g., a deepwater port in western Alaska, a liquefied natural gas terminal in southcentral Alaska, increased timber sales in southeast Alaska). Alaska also remains susceptible to secondary spread of invasive species as it currently receives the majority of its ballast water from highly invaded port systems along the west coast of North America. Compounded by gaps in policy that are uniquely critical to Alaska's expansive coastline, we conclude that proactive survey and management effort is crucial to reducing statewide risk from marine invasive species introductions via ballast water or biofouling. We suggest that the risk matrix developed here be used to identify areas for fine-scale risk analysis, review of vessel traffic patterns and ballast water management activity, and serve as a baseline in a rapidly changing environment with increasing development intensity.

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