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Research Article

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.

Key words: biological invasion, vector-based analysis, vessel screening, risk assessment

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
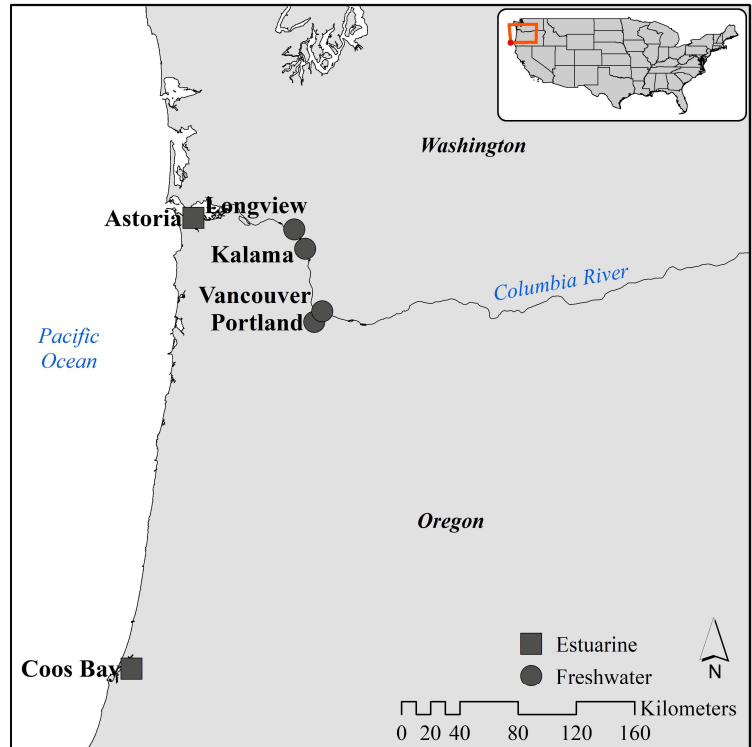
Figure 1. Primary estuarine and freshwater ports of the Columbia River and coastal Oregon (USA) that receive ballast water from commercial vessels.

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 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.

Table 1. 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*

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 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. 2014; 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 ($\geq 2,000$–$4,600$ m^3), medium ($> 4,600$–$9,900$ m^3), high ($> 9,900$–$17,200$ m^3), or very high ($> 17,200$ m^3) (Table 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 ($\geq 3,300$–$10,600$ m^3), medium ($> 10,600$–$22,400$ m^3), high ($> 22,400$–$67,700$ m^3), or very high ($> 67,700$ m^3) (Table 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 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 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
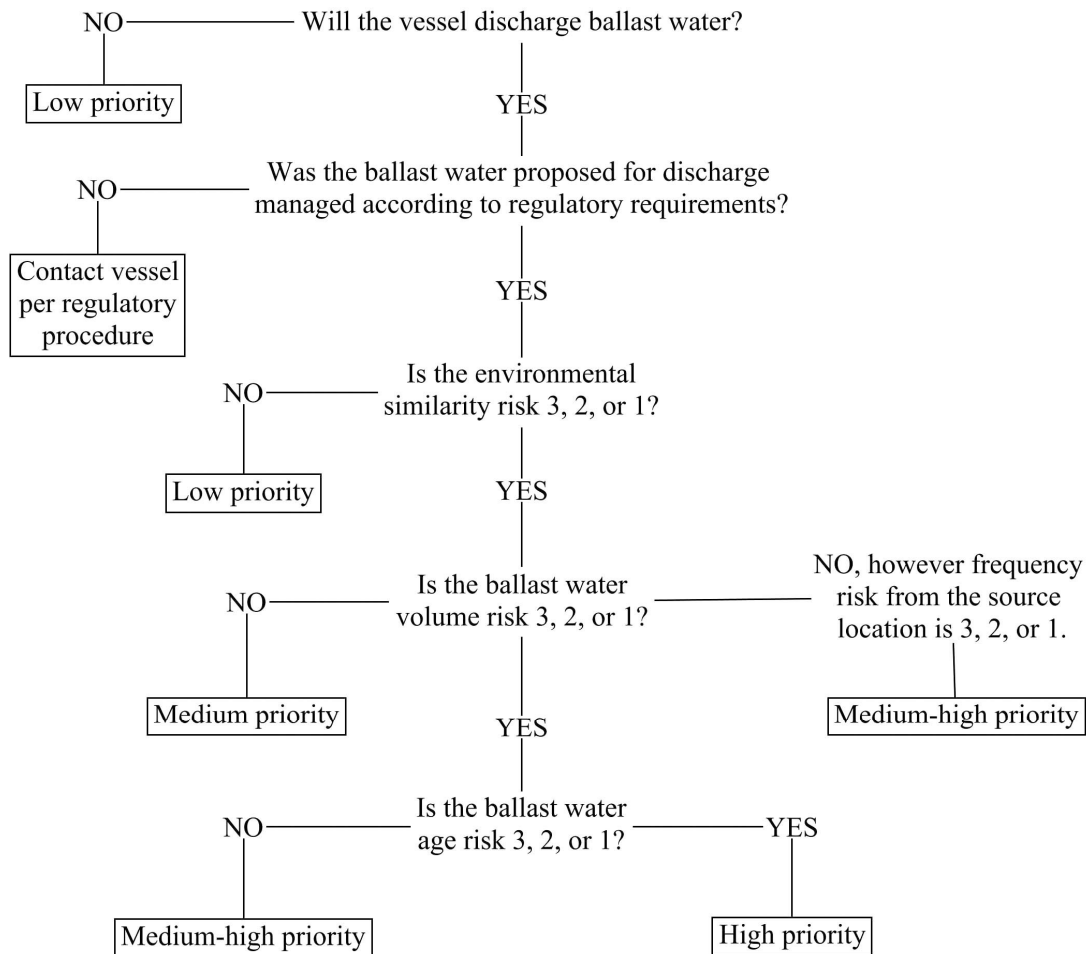
Figure 2. A decision tree to prioritize vessel arrivals as low, medium, medium-high, or high priority for further attention from regulatory personnel based on the characteristics of ballast water discharge.

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 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).

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 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 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 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 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
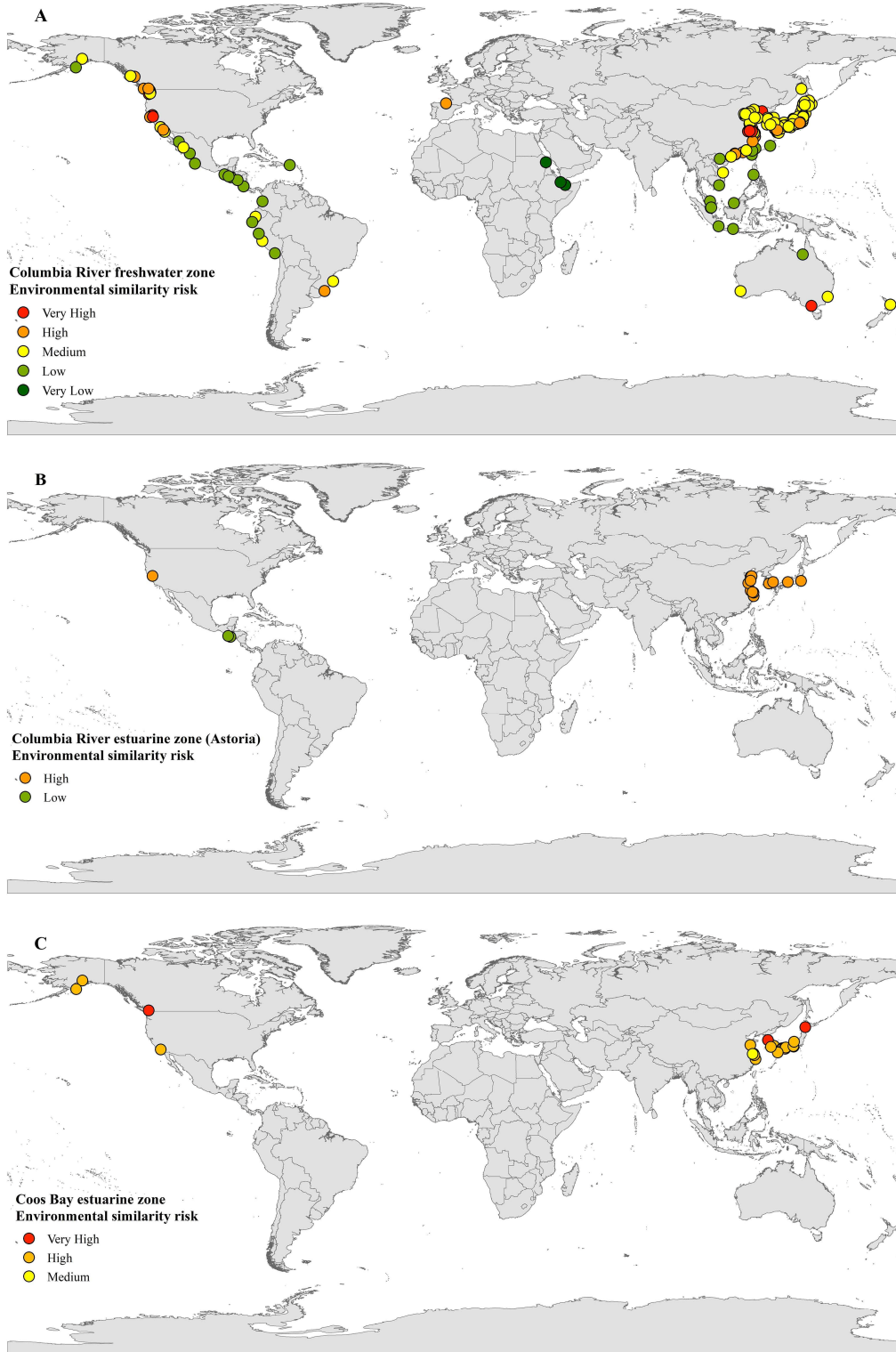
Figure 3. The environmental similarity risk and source locations of ballast water that was discharged to (A) the freshwater zone of the Columbia River (including the ports of Portland, OR, Kalama, WA, Longview, WA, Vancouver, WA), (B) the estuarine zone of the lower Columbia River (including the port of Astoria), and (C) an estuarine zone on the southern Oregon coast (Coos Bay), January–December 2016.
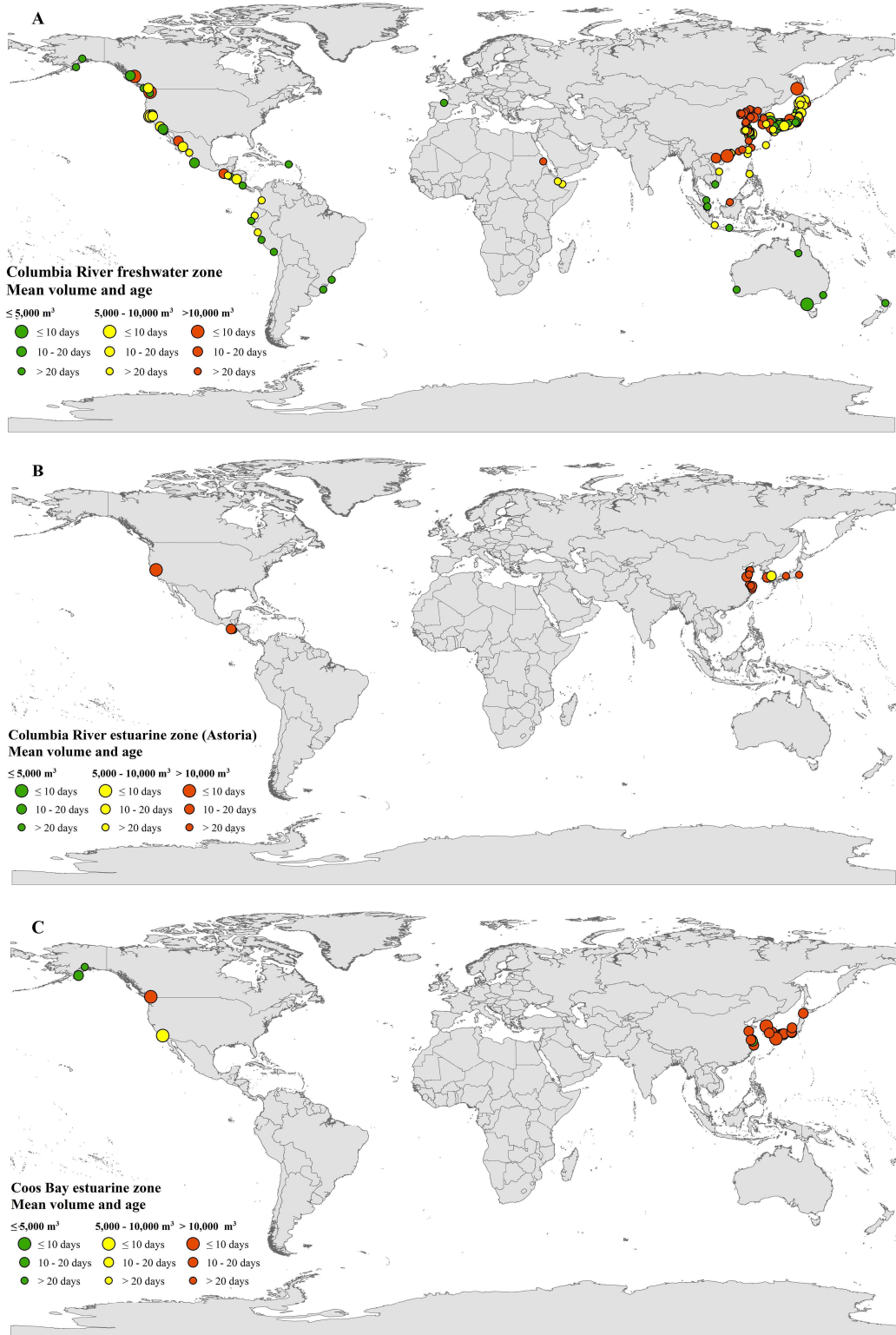
Figure 4. The mean volume and age of ballast water from each source location that was discharged to (A) the freshwater zone of the Columbia River (including the ports of Portland, OR, Kalama, WA, Longview, WA, Vancouver, WA), (B) the estuarine zone of the lower Columbia River (including the port of Astoria), and (C) an estuarine zone on the southern Oregon coast (Coos Bay), January–December 2016.

Table 2. 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%)**

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). 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.

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