Abstract

1. Despite the availability of research which has direct applications to environmental management, there is often a disconnect between scientific research and applied management that presents challenges for using academic knowledge in day-to-day operations by non-scientists.

2. A science-based decision support tool was developed in partnership with Canada's marine authority, Transport Canada, for use by ballast water inspectors in their daily operations to inform prioritization of ships for regulatory compliance inspections.

3. This science-based tool combines information on the two primary pathway-level predictors of species establishment success: environmental matching between source and recipient locations and propagule pressure (introduction effort), to generate risk estimates and relative rankings using data taken directly from ballast water reporting forms submitted by arriving ships.

4. This tool thus packages the best available scientific knowledge in such a way as to be readily accessible for day-to-day decision-making. While this tool was developed for Canada, it could be applied in any country with very little, if any, modification. This tool can also be updated in the future to incorporate advances in scientific understanding of ballast-mediated introductions of non-indigenous species.

5. Synthesis and applications. Partnerships between scientists and managers are essential for ensuring that best-available science translates into effective adaptive management. Recognizing a need to inform ballast water management compliance inspections, a tool was created that automatically estimates relative risk of establishment of non-indigenous species for arriving ships. This information can be used by ballast water inspectors developing priorities for resource-limited regulatory compliance inspections.

Keywords
ballast water, decision support tool, environmental similarity, establishment probability, invasive species, non-indigenous species, propagule pressure, risk assessment tool
1 | INTRODUCTION

Non-indigenous species are recognized as a leading cause of biodiversity loss (Cambray, 2003; Didham et al., 2005; Pyšek & Richardson, 2010). The global movement of non-indigenous species is hastened by international trade, which facilitates the movement of species around the world (Bailey, 2015; Seebens et al., 2013, 2016). Ballast water, which is used to control ships’ trim and stability, has historically been one of the most important vectors for the movement of aquatic non-indigenous (NIS) around the world. In response, the International Maritime Organization (IMO) developed ballast water standards to reduce the movement of harmful aquatic organisms and pathogens by shipping. The Ballast Water Management Convention came into force on 8 September 2017 and requires that ships exchange, and eventually treat, their ballast water in accordance with the Regulation D-2 discharge standards. Signatories to the Convention have a duty to monitor ships in their jurisdiction for compliance, but time and personnel limitations restrict the number of ships that any one maritime authority can inspect. To maximally protect waters, compliance monitoring should be prioritized for those ships that pose the greatest likelihood of introducing species that may establish.

The establishment success of NIS is attributed to three main factors: (a) environmental similarity between a species’ source and introduced ranges (Gaston, 2009; Peterson, 2003; Wiens et al., 2010); (b) introduction effort (i.e. the number of individuals and the number of species that are being introduced, hereafter propagule pressure and colonization pressure, respectively; Lockwood et al., 2005, 2009) and (c) species’ traits (e.g. rapid growth rate; wide temperature tolerance; behavioural flexibility; Kolar & Lodge, 2002; Pyšek et al., 2009; Sol & Lefebvre, 2000). Each of these factors should be considered when predicting the likelihood of NIS establishments. Species’ traits typically can only be considered for single-species assessments (except where species are being purposefully imported; see Bradie & Leung, 2015), but both environment and propagule pressure can inform risk of species movements at the pathway or vector level (e.g. multiple species in ballast water).

Despite the need for risk-based prioritization of ballast water monitoring and the availability of scientific knowledge to enable risk predictions, there is no simple way for managers to incorporate this knowledge in their day-to-day operations. Indeed, there is commonly a disconnect between scientific knowledge and its direct use by managers (Hillman & Brierley, 2002). Decision support tools provide an effective means to package scientific knowledge in a way that allows its simple incorporation into daily decision-making. To this end, Globallast (Clarke et al., 2003) was an early attempt at providing a decision support tool for ballast water risk assessment based on the concept of environmental distance (Hilliard et al., 1997). This tool focused on predicting high-risk shipping pathways using environmental similarity between port pairs, and it has been applied globally to direct management decisions (e.g. International Maritime Organization [IMO], 2009, 2010; Stocks, 2006). However, the Globallast software is now incompatible with modern computer operating systems, has large data requirements and is scientifically out-of-date, requiring data on nearly 40 environmental variables to generate predictions. Recent work determined that environmental distance calculations used for risk assessment performed best when computed using a small number (2–4) of most-relevant variables (Bradie et al., 2015).

Herein, a decision support tool, known as a ballast water invasion probability tool, is developed to automatically quantify the risk of NIS associated with individual ships, using information readily available on ballast water reporting forms that ships are required to submit to Transport Canada prior to arrival in Canadian waters. In contrast to Globallast, this tool provides ship-specific predictions by including both environmental distance and propagule pressure information. Environmental data informs one of the main factors affecting NIS establishment success: capacity to survive in the introduced environment (Rahel, 2002). Introduced species have a greater chance of establishing in regions that are similar to their native (or source) range, and by extension, regions that are more similar are more likely to exchange species. Environmental distance is used to quantify environmental similarity between a ship’s ballast water source and discharge ports. Propagule pressure information is used to inform the other main pathway-level predictor of establishment probability. Much evidence supports a strong, quantitative relationship between propagule pressure and establishment success (Bradie et al., 2013; Duncan et al., 2001; Hee et al., 2000; Leung et al., 2004; Ruesink, 2005). For ballast water introductions, propagule pressure is known to vary temporally during the course of a voyage (Chan et al., 2015), regionally (Briski et al., 2013) and based on ballast volume. The joint effects of ballast water age and ballast water volume on propagule pressure are quantified, and combined with environmental data to rank the overall probability of invasion for incoming ships. Since this tool pulls required data from ballast water reporting forms, it can quickly allow managers to prioritize ship inspections based on NIS risk.

2 | MATERIALS AND METHODS

2.1 | Environmental distance

A global list of 8,392 ports was compiled based on Keller et al. (2011), with additions from Transport Canada. Port environmental data for four variables (i.e. salinity, maximum, minimum and average temperature) were obtained from Keller et al. (2011) and World Ocean Atlas 2013 Vol. 2 (Locarnini et al., 2013; Zweng et al., 2013). Salinities of inland freshwater ports modelled by Keller et al. (2011) were corrected where better information was available, and Canadian port data were verified and updated where necessary through literature search or personal communication with local experts. Euclidean distance between ports was calculated using all four variables after they were standardized to mean = 0 and standard deviation = 1 (Barry et al., 2008). Methodology in Bradie et al. (2015) was followed to empirically validate the distance metric. Briefly, using NIS presence data for 98 species downloaded from the Global Invasive Species Information
Network (GISIN; accessed October 22nd, 2014), environmental distance was calculated between presence points in disparate ranges separated by at least 1,000 km and between a given range and pseudo-absence background points. As the three temperature variables are interrelated, two potential methods for calculating distance were explored: (a) using all four environmental variables equally (unweighted method) and (b) providing equal weighting to salinity (50% weighting) and temperature variables (each 16.6% weighting). One-way t tests with Welch’s correction for unequal variance (Welch, 1951; Zar, 1999) were used to test whether environmental distance values were indeed lower between disparate ranges occupied by a given species as compared to distances between their ranges and ‘background’ environmental conditions. If environmental distances are generally lower between regions where a species is known to exist, then that indicates that the environmental distance metric has predictive value. Fisher’s z-scores were calculated from t values as a standardized measure of effect size (Fisher, 1921; Zar, 1999).

2.2 | Propagule pressure

Following Briski et al. (2013), existing ballast water data were used to quantify the effect of ballast water age on propagule pressure. Biological and shipping data used for Fisheries and Oceans Canada’s peer-reviewed National Risk Assessment for the Introduction of Aquatic Nonindigenous Species to Canada by Ballast Water (Casas-Monroy et al., 2014) were used, which included data from previous Canadian research (Adebayo et al., 2014; Bailey et al., 2011; Briski, Bailey, et al., 2012; Briski, Wiley, et al., 2012; Casas-Monroy, 2012; DiBacco et al., 2012; Humphrey, 2008; Klein et al., 2009; Roy et al., 2012). The data included information on invertebrate, dinoflagellate and diatom abundance in ballast tanks of a sample of ships entering Canada as well as corresponding residency time since mid-ocean exchange. Negative binomial generalized linear mixed models were used to characterize the changes in propagule pressure that occurred throughout a voyage based on residency time for each group. Outlier points were identified using Cook’s distance, but ultimately none were removed from the models as they were biologically reasonable and did not change the general conclusions when the model was run without these values. The models relating propagule pressure to residency time were based on concentrations of plankton (i.e. abundances per L or cubic metre) from ballast tanks, so total tank abundances (i.e. abundances per ship) were calculated by multiplying tank concentrations predicted from the models by ballast volumes.

2.3 | Risk tool

The components of invasion probability (i.e. propagule pressure and environment) were combined to inform an overall invasion risk for each ship. Since environmental distance is a relative metric, pairwise environmental distance values were calculated for all global ports to gain an understanding of which environmental distance between ports signified a high environmental similarity and thus should be considered high risk. Percentiles were used to partition environmental distance values into risk categories: the lowest 20% of environmental distance values (i.e. the most similar environments) were classed as ‘very high risk’, 20–40 percentile were ‘high risk’, 40–60 percentile were ‘moderate risk’, 60–80 percentile were ‘low risk’ and 80–100 percentile were ‘very low risk’. Risk cut-offs were compared to environmental distance values obtained between presence ranges in the empirical validation to confirm suitability.

Similarly, using empirical data on ballast water discharges in Canada between August 2018 and July 2019 obtained from Transport Canada, the propagule pressure model results were used to calculate the range of expected number of individuals being discharged at Canadian ports for each ballast water discharge over the course of a year. Calculations summed total abundances for all groups considered herein (i.e. invertebrates, diatoms and dinoflagellates) and these data were used to characterize relative risk of propagule pressure. Percentile groupings matched those listed above for environmental distance. If, for any reason, the shipping data to define these thresholds is not broadly representative of traffic patterns since July 2019, it is possible that predicted propagule pressure would not be spread out equally across the defined risk levels. The relative risk assigned to each ship, however, would still be ordered correctly.

Finally, a risk matrix was generated to combine the risk from propagule pressure and environmental distance into one overall risk rating (Yoe, 2016; Table 1). ‘Overall risk’ was assigned as the

| Environmental distance risk | Very Low | Low | Moderate | High | Very High |
|-----------------------------|---------|-----|----------|------|----------|
| Propagule pressure risk     |         |     |          |      |          |
| Very high                   | Very low (5) | Low (9) | Moderate (12) | High (14) | Very high (15) |
| High                        | Very low (4) | Low (8) | Moderate (11) | High (13) | High (14) |
| Moderate                    | Very low (3) | Low (7) | Moderate (10) | Moderate (11) | Moderate (12) |
| Low                         | Very low (2) | Low (6) | Low (7) | Low (8) | Low (9) |
| Very Low                    | Very low (1) | Very low (2) | Very low (3) | Very low (4) | Very low (5) |
lower of either propagule pressure risk or environmental distance risk, resulting in the same risk categories used for each measure separately (i.e. very low, low, moderate, high, very high). A numeric value, herein termed the ‘differential risk’, was also computed to further differentiate the risk categories to enable easier selection of vessels for inspection (Table 1). The minimum possible differential risk score is determined from the ‘overall risk’ as follows: ‘very low’ = 1, ‘low’ = 6, ‘moderate’ = 10, ‘high’ = 13 and ‘very high’ = 15. If both propagule pressure and environmental distance have the same risk, the differential risk score is equal to the minimum. However, if one metric has a higher risk (i.e. either propagule pressure or environmental distance), the differential risk score is increased by 1 point for each level increase in risk of the second metric. For example, if propagule pressure risk is ‘moderate’ and environmental distance risk is ‘very high’, then the overall risk for that discharge would be ‘moderate’. The minimum possible differential risk score for a moderate risk discharge is 10, but since environmental distance risk is ‘very high’ which is 2 risk levels about ‘moderate’, 2 additional points would be added to obtain a differential risk score of 12. All numeric values in each differential risk category rank lower than the category above (i.e. 1–5 very low risk, 6–9 low risk, 10–12 moderate risk, 13–14 high risk and 15 very high risk). The differential risk rating provides seamless integration of best available knowledge of the likelihood of AIS establishment via ballast water into monitoring.

All analyses were completed in the R programming environment (R Core Team, 2019).

3 | RESULTS

The environmental distance analysis supported the use of the unweighted metric to inform the risk of species establishments between regions. More specifically, species establishments generally occurred between regions that had low environmental distance relative to presence-background distances. The metric calculated using all variables (unweighted method) performed marginally better than the weighted scenario (1/2 salinity; 1/6 maximum temperature; 1/6 minimum temperature; 1/6 mean temperature; Figure 1). For unweighted Euclidean distance, 96% of species showed significantly lower distances between points in their established ranges as compared to presence-background distances, the mean Fisher’s z-score across species was 1.55 (SD = 0.70) and 71% of species had Fisher’s z scores >1.2 which corresponds to an R² of 0.7.

To assign risk based on relative environmental relatedness, an unweighted Euclidean distance was calculated between all port pairs in the port dataset (n = 8,392 ports). The top 20% of port pairs had environmental distance values below 1.25, and these values are considered ‘very high’ risk (Figure 2). Port pairs with environmental distance values between 1.25 and 2.11 spanned the 20th–40th percentile and are considered ‘high risk’. Moderate risk port pairs had distance values between 2.11 and 3.08, whereas low-risk port pairs had values between 3.08 and 4.3. All port pairs with distances >4.3 are considered very low risk. These cut-off values were compared to environmental distance values calculated for established aquatic invasive species from the GISIN database. Approximately 70% of presence–presence distances were below 1.25, 78% of distances were below 2.11 and 97% of distances were below 3.08. In contrast, over 80% of presence–absence distances were >3.08.

A significant negative relationship was found between residency time in ballast tank (in days) and organism abundance for invertebrates, diatoms and dinoflagellates (p < 0.001, p < 0.05, p < 0.005, respectively; Figure 3). Invertebrates showed the strongest decline in abundance with residency time (slope = −0.196) followed closely by dinoflagellates (slope = −0.185). Diatoms had the highest expected abundances at uptake as compared to dinoflagellates...
The relative propagule pressure risk per tank was characterized based on the number of individuals expected to be released in a given discharge, with risk groupings based on expected tank discharges using one full year of shipping data (Figure 4). To qualify as 'very high' risk (i.e. top 20 percentile), $1.87 \times 10^{10}$ individuals would need to be released in a given discharge. Discharges above $6.74 \times 10^9$ individuals were classified as 'high' risk, whereas discharges over $2.89 \times 10^9$ individuals were classified as 'moderate risk'.

Within this sample data of 1 year of shipping traffic, overall risk attributed to discharges based on their combined environmental distance and propagule pressure indicated that a very low proportion of discharges are considered 'very high' risk (<1%; Figures 5 and 6). Approximately 10% of discharges are classified as 'high' risk and ~30% of discharges are classified as 'moderate' risk. The majority of discharges in Canada are considered low risk (Figures 5 and 6; ~60%
of transits are either ‘low risk’ or ‘very low risk’), due to high environmental distance, low propagule pressure or both. The differential risk ratings (Figure 6) further inform relative priority for inspections within these groups.

4 | DISCUSSION

Many researchers undertake projects designed to inform environmental management issues, yet much of the knowledge gained from these projects is not directly applicable in practice (Hillman & Brierley, 2002). This presents a missed opportunity to present research in such a way that it can be readily incorporated into decision-making. Recognizing a need to inform ballast water management compliance inspections, a tool was created that automatically calculates relative risk of establishment of non-indigenous species for arriving ships to inform ballast water inspectors of biological risk when developing priorities for regulatory compliance inspections.

To ensure the smooth adoption of the tool, the end user, Transport Canada, was consulted during development to ensure that the end product was suitable for their needs, could be readily integrated into their workflow, and provided a metric that was easily understood by day-to-day decision-makers. To this end, during tool development, a prototype was created in the R package shiny (Chang et al., 2020) that was available online for testing (code is available online at https://github.com/johannabradie/BWRA_Tool). Transport Canada inspectors and managers were able to access the tool for testing, to explore its capabilities and to provide feedback for its improvement. One such feedback was that the general risk categories were too broad, since depending on port of call, some inspectors would have many incoming ships with the same risk level. This feedback motivated the inclusion of the second, numeric ‘differential’ risk rating to give inspectors more differentiation between ships. After the initial testing phase, the tool was built in to Canada’s Ballast Water Reporting Form Information System (where data from Canadian Ballast Water Forms is recorded) so that risk ratings are automatically populated when Ballast Water Reporting Forms are received for ships arriving to Canada. This is very beneficial as it requires no additional effort in the day-to-day operations to produce the risk report.

This risk tool uses information on the primary pathway-level predictors of invasion risk to inform monitoring priorities: environmental matching and propagule pressure. While environmental matching has been widely used, it has only been recently validated (Bradie et al., 2015). In this application of environmental distance, methodology developed by Bradie et al. (2015) was used to test and contrast two ways of calculating environmental distance for this tool. This provided confidence in the utility of environmental distance as formulated for use in the tool, and also allowed verification of the risk levels prescribed to different distance levels. While risk levels were determined based on relative relatedness of global port pairs (split into equally spaced categorical risk values), these distances were comparable to distances calculated between ranges of known invaders (e.g. 70% of presence–presence distances fall in ‘very high’ risk category and 97% of presence–presence distances were ranked ‘moderate risk’ or higher).

The second main driver of this risk assessment is propagule pressure. The relationship between propagule pressure and establishment success has been examined in a multitude of studies (Drake & Lodge, 2006; Lockwood et al., 2009; Simberloff, 2009). While there is clear agreement that increased propagule pressure leads to a higher chance of invasion success (Cassey et al., 2018), establishment success is stochastic in nature and contingent on a suite of variables. As a result, it is not certain what level of propagule pressure is biologically risky, hindering the development of a numeric standard with quantified efficacy. Indeed, even for ballast water, which is a relatively well-studied topic in invasion ecology, and for which discharges are regulated by the International convention for the control and management of ships’ ballast water and sediments (International Maritime Organization [IMO], 2004), the numeric discharge limits were determined with emphasis mainly on risk reduction, rather than acceptable risk levels, because the actual risk associated with a specific discharge size is unknown (Gollasch et al., 2007). To understand this relationship better, more research is needed to understand the likelihood for each individual and species to establish (Leung et al., 2004); how likely discharged individuals are to be able to interact with each other after water disperses in a port (particularly important for sexually reproducing species; Wells et al., 2011) and how the balance of colonization pressure and propagule pressure impact invasion risk (e.g. while higher colonization pressure may increase the chance that one species will be able to successfully establish, for a given propagule pressure, greater diversity equates to lower propagule pressure of each species which would decrease establishment likelihood for...
individual species; Lockwood et al., 2009). Owing to the unknowns involved in the relationship between propagule pressure and establishment, risk categories were determined by mirroring the approach taken for environmental distance. More specifically, using a 1-year iteration of ship traffic data, the expected ballast water volume associated with each discharge was calculated and divided into equal bins representing five levels of risk. Thus, this risk tool is built with best available current knowledge, which simply indicates that higher propagule pressure equates to higher invasion risk. Since the purpose of this tool is to provide risk ratings that allow inspectors to easily target the most risky ships for inspection, the tool will provide appropriate risk ordering to accomplish this task regardless of the nominal label assigned to the risk from a specific discharge.

Alternative ways to define propagule pressure risk categories were considered, including, for example, relating the expected discharge to allowable discharge levels as defined by IMO’s D-2 discharge standards (International Maritime Organization [IMO], 2004). More specifically, for taxa considered herein, the D-2 standard stipulates that organisms greater than or equal to 50 µm in size are limited to a maximum of 10 individuals discharged/m³ of ballast water (herein, this size class includes invertebrates) and discharges of organisms greater than or equal to 10 µm but <50 µm (herein, diatoms and dinoflagellates) must not exceed 10 individuals/mL which is equivalent to 10 million individuals/m³. With an average discharge of 1,781 m³ per ship, this equates to an allowable discharge of 17,810 invertebrates and 17.8 billion diatoms and dinoflagellates, combined. In comparison, the average expected discharge for invertebrates was 7.9 million individuals (median = 1.6 million) and for 10–50 µm organisms was 12.0 billion individuals (median = 4.5 billion). Thus, even with the staggering number of 10–50 µm organisms released, the average expected release is in line with the allowable limit, as compared to invertebrates where average expected releases are ~450 times higher than allowable. More emphasis could be placed on the risk associated with zooplankton, but since the discharge standards were not determined based on biological risk, there is no strong rationale to do so. Furthermore, since similar relationships were determined for each taxa versus ballast age (Figure 3), the number of invertebrates, diatoms and dinoflagellates in the expected discharge for each risk bin would be proportionally very similar whether risk bins were divided for each taxa separately or based on overall abundances. Nonetheless, if more information becomes available in regard to ‘biologically risky’ levels of propagule pressure, it would be beneficial to update the propagule pressure risk categorization to reflect this new knowledge. The same applies to new information on either colonization pressure or regional variation in propagule pressure: neither were considered herein, but more knowledge on either of these aspects of propagule pressure could constitute beneficial next steps to improve this tool.

This tool was developed in collaboration with Transport Canada, but it has potential utility for any country looking to prioritize monitoring of arriving ships based on the biological risk posed by ballast water. To use the tool, countries would need to obtain information on ballast water source location, ballast water discharge location, discharge volume and ballast age (in days) from arriving vessels. Very little, if any, modification to the tool itself would be required to adapt the tool for use globally since the environmental distance risk ratings are based on global port environmental distances. Propagule pressure risk ratings were calculated based on discharge volumes from 1 year of Canadian data, so these values could be updated to reflect the volumes of ballast water discharged in the country of application. However, if this information was not available, the tool could be used by relying on Canada’s propagule pressure risk ratings, with the caveat that if expected propagule pressures do not span a similar range, propagule pressure risk ratings may not be as evenly distributed.

The effective translation of scientific research into management practice is a significant challenge (Ryder et al., 2010) that can be greatly aided by the creation of decision support tools. This risk tool integrates the best scientific knowledge into a tool that gives managers the ability to assess risk ratings in their decision-making with no additional effort. This eliminates the need to interpret scientific literature and ascertain how this knowledge could be used in practice. This tool has been incorporated directly into Canada’s Ballast Water Information System and could easily be provided to other countries either as a stand-alone tool or similarly incorporated into their ballast water data warehousing structure. This tool provides an excellent example of how the gap between scientific research and management can be bridged so that research can be readily applied in day-to-day decision-making without the continual need for scientific consultation.

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AUTHORS’ CONTRIBUTIONS

J.N.B. and S.A.B. conceived the ideas and designed methodology; J.N.B. collected and analysed the data, and led the writing of the manuscript. Both authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The code for the prototype decision support tool created in the R package shiny is available online at https://github.com/johannabra/die/BWRA_Tool. The global port environmental data used for the environmental distance calculations are available via the Dryad Digital Repository https://doi.org/10.5061/dryad.69p8cz906 (Bailey et al., 2020).

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REFERENCES

Adebayo, A. A., Zhan, A., Bailey, S. A., & MacIsaac, H. J. (2014). Domestic ships as a potential pathway of nonindigenous species from the Saint Lawrence River to the Great Lakes. *Biological Invasions*, 16(4), 793–801. https://doi.org/10.1007/s10530-013-0537-5

Bailey, S. A. (2015). An overview of thirty years of research on ballast water as a vector for aquatic invasive species to freshwater and marine environments. *Aquatic Ecosystem Health & Management*, 18(3), 261–268. https://doi.org/10.1080/14634398.2015.1027129

Bailey, S. A., Bradie, J. N., Ogilvie, D., & Mudroch, P. (2020). Data from: Bailey, S. A., Deneau, M. G., Jean, L., Wiley, C. J., Leung, B., & MacIsaac, H. J. (2013). Taxon- and vector-specific variation in species richness of introduced Australian birds: A role for climate. *Journal of Animal Ecology*, 70(4), 621–632. https://doi.org/10.1046/j.1365-2656.2001.00517.x

Fisher, R. A. (1921). On the probable error of a coefficient of correlation and its probable error. *Biometrika*, 13(3–4), 455–462. https://doi.org/10.1093/biomet/13.3-4.455

Didham, R. K., Tylianakis, J. M., Hutchison, M. A., Ewers, R. M., & Gemmell, N. J. (2005). Are invasive species the drivers of ecological change? *Trends in Ecology & Evolution*, 20(9), 470–474. https://doi.org/10.1016/j.tree.2005.07.006

Drake, J. M., & Lodge, D. M. (2006). Allee effects, propagule pressure and the probability of establishment: Risk analysis for biological invasions. *Biological Invasions*, 8(2), 365–375. https://doi.org/10.1007/s10530-004-8122-6

Duncan, R. P., Bomford, M., Forsyth, D. M., & Conibear, L. (2001). High predictability in introduction outcomes and the geographical range size of introduced Australian birds: A role for climate. *Journal of Animal Ecology*, 70(4), 621–632. https://doi.org/10.1046/j.1365-2656.2001.00517.x

Fisher, R. A. (1921). On the probable error of a coefficient of correlation deduced from a small sample. *Metron*, 1, 3–32.

Gaston, K. J. (2009). Geographic range limits of species. *Proceedings of the Royal Society B: Biological Sciences*, 276(1661), 1391–1393. https://doi.org/10.1098/rspb.2009.0100

Gollasch, S., David, M., Voigt, M., Dragsund, E., Hewitt, C., & Fukuyo, Y. (2007). Critical review of the IMO international convention on the management of ships’ ballast water and sediments. *Harmful Algae*, 6(4), 585–600. https://doi.org/10.1016/j.hal.2006.12.009

Hee, J. J., Holway, D. A., Suarez, A. V., & Case, T. J. (2000). Role of propagule size in the success of incipient colonies of the invasive argentine ant. *Conservation Biology*, 14(2), 559–563. https://doi.org/10.1046/j.1523-1739.2000.99040.x

Hilliard, R. W., Walker, S., Vogt, S., Belbin, L., & Raaymakers, S. (1997). Stage 3B environmental similarity analyses. Ports Corporation of Queensland.

Hillman, M., & Brierley, G. (2002). Information needs for environmental-flow allocation: A case study from the Lachlan River, New South Wales, Australia. *Annals of the Association of American Geographers*, 92(4), 617–630. https://doi.org/10.1111/1467-8306.00307

Humphrey, D. B. (2008). Characterizing ballast water as a vector for nonindigenous zooplankton transport (MSc thesis). Faculty of Graduate Studies (Oceanography), The University of British Columbia. https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0052742

International Maritime Organization [IMO]. (2010). Ballast Water Management Programme, India (BAMPi), (Risk Assessment). Submitted

nonindigenous species to Canada by ballast water. DFO Canadian Science Advisory Secretariat Research Document, 2013/128, pp vi + 73. https://www.dfo-mpo.gc.ca/cas-scas/Publications/ResDocs- DocRec/2013/2013_128-eng.html

Cassey, P., Delean, S., Lockwood, J. L., Sadowski, J. S., & Blackburn, T. M. (2018). Dissecting the null model for biological invasions: A meta-analysis of the propagule pressure effect. *PLoS Biology*, 16(4), e2005987. https://doi.org/10.1371/journal.pbio.2005987

Chan, F. T., Bradie, J., Briski, E., Bailey, S. A., Simard, N., & MacIsaac, H. J. (2015). Assessing introduction risk using species’ rank-abundance distributions. *Proceedings of the Royal Society B: Biological Sciences*, 282(1799), 20141517. https://doi.org/10.1098/rspb.2014.1517

Chang, W., Cheng, J., Allaire, J. J., Xie, Y., & McPherson, J. (2020). Shiny: Web application framework for R package version 1.4.0.2. Retrieved form https://CRAN.R-project.org/package=shiny

Clarke, C., Hayes, T., Hilliard, R. W., Kayvanrad, N., Parhizi, A., Taymourtash, H., Yavari, V., & Raaymakers, S. (2003). Ballast Water Risk Assessment: Port of Khark Island, Islamic Republic of Iran. August 2003: Final Report. Globalballast Monograph Series No. 8, IMO. https://www.imo.org/en/OurWork/PartnershipsProjects/Pages/GlobBallastPublications.aspx

DiBacco, C., Humphrey, D. B., Nasmith, L. E., & Levings, C. D. (2012). Ballast water transport of non-indigenous zooplankton to Canadian ports. *ICES Journal of Marine Science*, 69(3), 483–491. https://doi.org/10.1093/ICESJMS/FSR133

Didham, R. K., Tylianakis, J. M., Hutchison, M. A., Ewers, R. M., & Gemmell, N. J. (2005). Are invasive species the drivers of ecological change? *Trends in Ecology & Evolution*, 20(9), 470–474. https://doi.org/10.1016/j.tree.2005.07.006

Drake, J. M., & Lodge, D. M. (2006). Allee effects, propagule pressure and the probability of establishment: Risk analysis for biological invasions. *Biological Invasions*, 8(2), 365–375. https://doi.org/10.1007/s10530-004-8122-6

Duncan, R. P., Bomford, M., Forsyth, D. M., & Conibear, L. (2001). High predictability in introduction outcomes and the geographical range size of introduced Australian birds: A role for climate. *Journal of Animal Ecology*, 70(4), 621–632. https://doi.org/10.1046/j.1365-2656.2001.00517.x

Fisher, R. A. (1921). On the probable error of a coefficient of correlation deduced from a small sample. *Metron*, 1, 3–32.

Gaston, K. J. (2009). Geographic range limits of species. *Proceedings of the Royal Society B: Biological Sciences*, 276(1661), 1391–1393. https://doi.org/10.1098/rspb.2009.0100

Gollasch, S., David, M., Voigt, M., Dragsund, E., Hewitt, C., & Fukuyo, Y. (2007). Critical review of the IMO international convention on the management of ships’ ballast water and sediments. *Harmful Algae*, 6(4), 585–600. https://doi.org/10.1016/j.hal.2006.12.009

Hee, J. J., Holway, D. A., Suarez, A. V., & Case, T. J. (2000). Role of propagule size in the success of incipient colonies of the invasive argentine ant. *Conservation Biology*, 14(2), 559–563. https://doi.org/10.1046/j.1523-1739.2000.99040.x

Hilliard, R. W., Walker, S., Vogt, S., Belbin, L., & Raaymakers, S. (1997). Stage 3B environmental similarity analyses. Ports Corporation of Queensland.

Hillman, M., & Brierley, G. (2002). Information needs for environmental-flow allocation: A case study from the Lachlan River, New South Wales, Australia. *Annals of the Association of American Geographers*, 92(4), 617–630. https://doi.org/10.1111/1467-8306.00307

Humphrey, D. B. (2008). Characterizing ballast water as a vector for nonindigenous zooplankton transport (MSc thesis). Faculty of Graduate Studies (Oceanography), The University of British Columbia. https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0052742

International Maritime Organization [IMO]. (2010). Ballast Water Management Programme, India (BAMPi), (Risk Assessment). Submitted
by India to the Marine Environment Protection Committee as MEPC 60/INF.11. IMO.

International Maritime Organization [IMO], (2004). International convention for the control and management of ships’ ballast water and sediments, 2004; International Conference on Ballast Water Management for Ships, BWM/CONF/36. IMO.

International Maritime Organization [IMO], (2009). Project on control and management of harmful organisms transferred by ballast water. Submitted by Turkey to the Marine Environment Protection Committee as MEPC 59/INF.14. IMO.

Keller, R. P., Drake, J. M., Drew, M. B., & Lodge, D. M. (2011). Linking environmental conditions and ship movements to estimate invasive species transport across the global shipping network. Diversity and Distributions, 17(1), 93–102. https://doi.org/10.1111/j.1472-4642.2010.00696.x

Klein, G., Kaczmarska, I., & Ehrman, J. M. (2009). The diatom Chaetoceros in ships’ ballast waters-survivorship of stowaways. Acta Botanica Croatia, 68(2), 325–338.

Kolar, C. S., & Lodge, D. M. (2002). Ecological predictions and risk assessment for alien fishes in North America. Science, 298(5596), 1233–1236. https://doi.org/10.1126/science.1075753

Locarnini, R. A., Mishonov, A. V., Antonov, J. I., Boyer, T. P., Garcia, H. E., Cavalieri, D. J., & Rudnick, R. A., NOAA. https://rda.ucar.edu/datasets/ds285.0/docs/woa13/woa13_vol1.pdf

Lockwood, J. L., Cassey, P., & Blackburn, T. (2005). The role of propagule pressure in explaining species invasions. Trends in Ecology & Evolution, 20(5), 223–228. https://doi.org/10.1016/j.tree.2005.02.004

Lockwood, J. L., Cassey, P., & Blackburn, T. M. (2009). The more you introduce the more you get: The role of colonization pressure and propagule pressure in invasion ecology. Diversity and Distributions, 15(5), 904–910. https://doi.org/10.1111/j.1472-4642.2009.00594.x

Peterson, A. T. (2003). Predicting the geography of species’ invasions via ecological niche modeling. The Quarterly Review of Biology, 78(4), 419–433. https://doi.org/10.1086/378926

Pyšek, P., Jarolík, V., Pergl, J., Randall, R., Chytrý, M., Kühn, I., Tichý, L., Danilhka, J., Chrtkoven, J., & Sádlo, J. (2009). The global invasion success of Central European plants is related to distribution characteristics in their native range and species traits. Diversity & Distributions, 15(5), 891–903. https://doi.org/10.1111/j.1472-4642.2009.00602.x

Pyšek, P., & Richardson, D. M. (2010). Invasive species, environmental change and management, and health. Annual Review of Environment & Resources, 35, 25–55. https://doi.org/10.1146/annurev-environ-030309-095548

R Core Team. (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Rahel, F. J. (2002). Homogenization of freshwater faunas. Annual Review of Ecology & Systematics, 33, 291–315. https://doi.org/10.1146/annurev.ecolsys.33.010802.150429

Roy, S., Parenteau, M., Casas-Monroy, O., & Rochon, A. (2012). Coastal ship traffic: A significant introduction vector for potentially harmful dinoflagellates in eastern Canada. Canadian Journal of Fisheries & Aquatic Sciences, 69(4), 627–644. https://doi.org/10.1139/t2012-008

Ruesink, J. L. (2005). Global analysis of factors affecting the outcome of freshwater fish introductions. Conservation Biology, 19(6), 1883–1893. https://doi.org/10.1111/j.1523-1739.2005.00267.x

Ryder, D. S., Tomlinson, M., Gawne, B., & Likens, G. E. (2010). Defining and using ‘best available science’: A policy conundrum for the management of aquatic ecosystems. Marine & Freshwater Research, 61(7), 821–828. https://doi.org/10.1071/MF10113

Seebens, H., Gastner, M. T., Blasius, B., & Couchamp, F. (2013). The risk of marine bioinvasion caused by global shipping. Ecology Letters, 16(6), 782–790. https://doi.org/10.1111/ele.12111

Seebens, H., Schwartz, N., Schupp, P. J., & Blasius, B. (2016). Predicting the spread of marine species introduced by global shipping. Proceedings of the National Academy of Sciences of the United States of America, 113(20), 5646–5651. https://doi.org/10.1073/pnas.1524427113

Simberloff, D. (2009). The role of propagule pressure in biological invasions. Annual Review of Ecology, Evolution, & Systematics, 40(1), 81–102. https://doi.org/10.1146/annurev.ecolsys.110308.120304

Sol, D., & Lefebvre, L. (2000). Behavioural flexibility predicts invasion success in birds introduced to New Zealand. Oikos, 90(3), 599–605. https://doi.org/10.1034/j.1600-0706.2000.900317.x

Stocks, D. T. (2006). Ballast water risk assessment for ships entering Canada. BMT Fleet Technology.

Welch, B. (1951). On the comparison of several mean values: An alternative approach. Biometrika, 38(3/4), 330–336.

Wells, M. G., Bailey, S. A., & Ruddick, B. (2011). The dilution and dispersion of ballast water discharged into Goderich Harbor. Marine Pollution Bulletin, 62(6), 1288–1296. https://doi.org/10.1016/j.marpolbul.2011.03.005

Wiens, J. J., Ackerly, D. D., Allen, A. P., Anacker, B. L., Buckley, L. B., Cornell, H. V., Damschen, E. I., Davies, T. J., Gryniewicz-J.A., Harrison, S. P., Hawkins, B. A., Holt, R. D., McCain, C. M., & Stephens, P. R. (2010). Niche conservatism as an emerging principle in ecology and conservation biology. Ecology Letters, 13, 1310–1324. https://doi.org/10.1111/j.1461-0248.2010.01515.x

Yoe, C. (2016). Principles of risk analysis: Decision making under uncertainty. CRC Press. https://doi.org/10.1201/b11256

Zar, J. H. (1999). Biostatistical analysis (4th ed.). Prentice Hall.

Zweng, M. M., Reagan, J. R., Antonov, J. I., Baranova, O. K., Boyer, T. P., Garcia, H. E., and Seidov, D. (2010). The Global Sea Ice and Sea Surface Temperature Data Sets. NOAA Atlas NESDIS, 74, p. 39. https://rda.ucar.edu/datasets/ds285.0/docs/woa13/woa13_vol2.pdf

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