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SCIENCE ADVICE ON VESSEL BIOFOULING AS A VECTOR FOR NONINDIGENOUS SPECIES INTRODUCTIONS IN CANADA

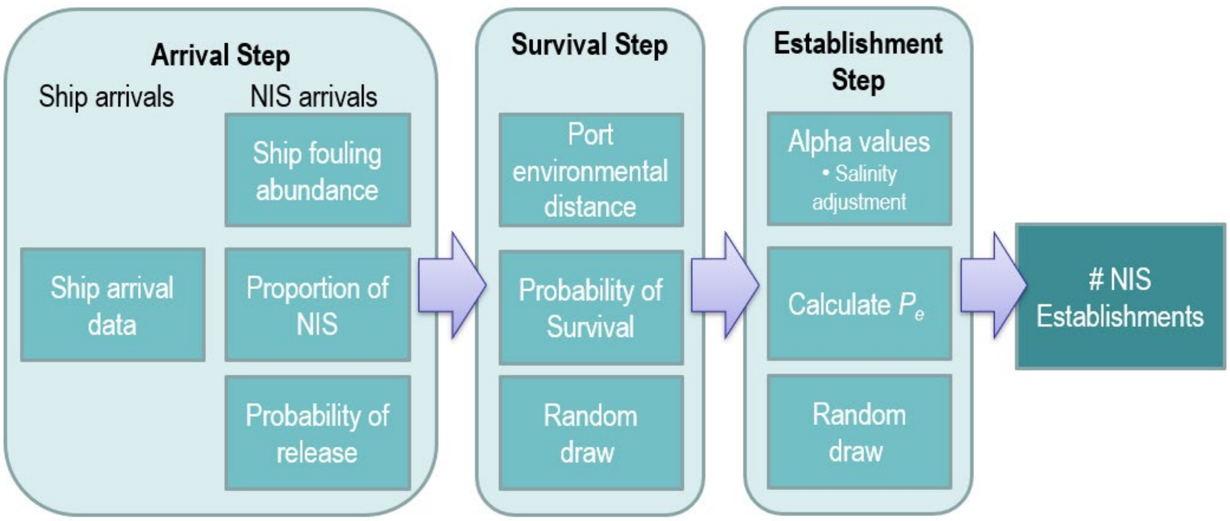

Figure 1. Flow chart outlining the main steps in the model in the arrival, survival, and establishment steps (large bubbles) each with specific steps (smaller squares) to obtain the final number of predicted nonindigenous species establishments

Context:

Nonindigenous species (NIS) are a major threat to aquatic ecosystems. Vessel biofouling is recognized as a dominant vector for the global transport and introduction of NIS, yet is currently unregulated in Canada. Transport Canada requested that Fisheries and Oceans Canada update prior assessments on probability of NIS introduction and establishment via biofouling on vessels. This science advice will inform development of Canadian biofouling management policies.

A national assessment was conducted using advanced modelling methods, incorporating best-available shipping, environmental and biological data to estimate the number of NIS establishments per year across Canadian regions with international shipping activity. Factors affecting rate of NIS establishment via biofouling were examined, such as vessel type and vessel part (main hull vs. niche areas). Scenarios of increased shipping traffic and vessel size in the Arctic region were investigated to explore future risk of NIS establishment in this region.

This Science Advisory Report is from the January 10-14, 2022 national advisory meeting on biofouling as a vector for aquatic invasive species introduction. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule]() as they become available.

SUMMARY

- Vessel biofouling is a complex process involving a diverse assemblage of aquatic species, which is recognized as an important global pathway for the introduction of NIS.
- This advice is based on a first quantitative estimate of establishment rates of aquatic NIS associated with initial vessel arrivals to Canada, predominantly by foreign-flagged cargo vessels, using a year-long dataset representative of a typical year of ship traffic.
- Domestic transits (not included in this assessment) are likely an important mechanism for both primary and secondary NIS introductions that should be explored in future analyses.
- The probability of NIS establishment by vessel biofouling is considerable. At current rates of shipping, Canada can expect, on average, eight new NIS establishments from biofouling per year in each of the Atlantic and Pacific regions, five in the Great Lakes-St. Lawrence River (GLSLR) region, and two in the Arctic.
- The results indicate that the probability of NIS establishment from niche areas is greater than from the main hull, despite being proportionally smaller in area, highlighting the importance of niche areas for establishment of NIS.
- The probability of NIS establishment was greater for container vessels, bulkers, passenger vessels, and tankers compared to other vessel types (tugs and other special purpose), likely due to the higher frequency of arrivals and greater wetted surface area.
- The lower probability of NIS establishment in the Arctic is largely driven by the currently low level of vessel traffic, while survival and establishment rates are lower in the freshwater GLSLR since NIS associated with vessel biofouling are predominantly marine taxa.
- Regional differences in probability of NIS establishment are associated with patterns of vessel traffic and size, with container vessels and tankers dominating in the Atlantic region, while bulkers and container vessels dominate in the Pacific region, and all three vessel types are of relatively equal importance in the GLSLR. Bulkers, followed by passenger vessels, currently dominate vessel traffic in the Arctic.
- Patterns among regions might also be driven by small sample sizes, though there are likely real differences driven by variation in shipping routes (prior ports-of-call) among the regions that should be more thoroughly explored in any future studies.
- Based on generalized vessel traffic predictions for the Arctic region only, NIS establishments are expected to increase by more than 50%. Predicted habitat suitability is expected to increase across Canadian coasts for selected NIS, and is expected to be greatest in the Arctic region for more cold-tolerant species. However, as a limited number of species have been evaluated (20-30 species per coast), modelling for additional species is needed. Although future establishment rates for all regions could not be modelled at this time, in the absence of intervention, establishments are expected to increase at all Canadian ports with continued ocean warming.
- It was not possible to forecast the effect of projected changes in shipping activity and temperature on the probability of NIS establishments by vessel biofouling across Canada during this CSAS process for a number of reasons, including unavailability of detailed vessel traffic projections and gaps in projected environmental data for inland and riverine ports, so effort to develop such data is critical. Suggestions on how to more broadly forecast the future probability of NIS establishments across Canada using available data sources were provided and could be undertaken with additional effort in the near future.

- Uncertainties in the data and parameters used in the model were identified due to factors such as small sample sizes, poor taxonomic resolution and complexity of the biofouling community dynamics (further described below).
- Other considerations that could not be addressed here, but warrant future attention, include the influence of different antifouling coatings, vessel duration of stay in ports, cumulative effects of multiple vessel arrivals through time and species-specific variability in survival and establishment (further described below).

BACKGROUND

Nonindigenous species (NIS) pose a considerable threat to biodiversity and health of aquatic ecosystems (Clavero et al. 2009; Havel et al. 2015). One of the largest pathways for the transport of aquatic NIS is international commercial shipping (Hewitt et al. 2009; Bailey et al. 2020a), either via vessel ballast water or fouling of organisms on vessel surfaces (Hewitt et al. 2009; Hopkins 2010). Marine biofouling is defined as the accumulation of organisms such as invertebrates, algae, and bacteria on substrates immersed in sea water (Callow and Callow 2002; Yebra et al. 2004). Although the impacts of biofouling are estimated to be high (Bailey et al. 2020a; Hewitt et al. 2011), the process is relatively understudied and unregulated in Canada. With shipping traffic increasing within Canada, specifically in the Arctic region (Dawson et al. 2018; Chan et al. 2019), biofouling is likely to play a major role in the increasing spread of NIS.

The biofouling process is complex and impacted by a variety of factors, leading to transport of diverse communities of organisms. The diversity and abundance of organisms that accumulate can depend on various factors, such as the length of time a vessel stays in a port, and the geographic history of port visits (Davidson et al. 2009; Chan et al. 2022). Many vessels have antifouling coating systems to manage biofouling, however the efficacy of these coatings declines with age and application may not be possible on complex non-hull surfaces of a vessel (i.e., niche areas such as seachests, seachest gratings, propellers, and intake pipes) (Hopkins 2010). The time-since-application of the antifouling coating may also play a role in the amount of biofouling on a vessel (Sylvester et al. 2011; Chan et al. 2022). Environmental factors, such as temperature and salinity, also play a role in the reproduction, survival, and establishment of organisms in a new recipient port (Minchin and Gollasch 2003; Delauney et al. 2010; Bradie et al. 2020).

The International Maritime Organization (IMO) has developed voluntary guidelines for the control and management of vessel biofouling to minimize the transfer of aquatic organisms (International Maritime Organization 2011). These guidelines include implementation of a biofouling management plan and record book, as well as using antifouling coating systems and in-water inspections and cleaning to reduce fouling, including in niche areas where fouling may accumulate at higher levels.

Various regional risk assessments were conducted by the Department of Fisheries and Oceans Canada (DFO) between 2012 and 2017, identifying biofouling via commercial and recreational vessels as important pathways for introduction of NIS to Canadian aquatic ecosystems (Bailey et al. 2012; Chan et al. 2012; Adams et al. 2014; Linley et al. 2014; Simard et al. 2017). Transport Canada is responsible for regulation of shipping activities under the *Canada Shipping Act, 2001*, including those that may result in introduction of NIS (e.g., by ballast water discharges or biofouling). Transport Canada requested science advice from DFO to inform the development of biofouling management policies for vessels over 24 meters in length to protect Canadian aquatic ecosystems against the introduction and establishment of NIS.

Objective

The objective of this study was to build on previous DFO regional risk assessments on the establishments of aquatic NIS via vessel biofouling conducted between 2012 and 2017 (Bailey et al. 2012; Chan et al. 2012; Adams et al. 2014; Linley et al. 2014; Simard et al. 2017), to create an updated comprehensive national biofouling assessment. Using best available data and improved modelling approaches, this study provides insight into the following questions:

1. What are the probabilities of arrival, survival, and establishment of biofouling NIS posed by domestic and international commercial vessels at freshwater and marine ports and anchorages, considering different operational and/or route characteristics and additional factors identified in the scientific literature that could be used to predict the probability of establishment of NIS by biofouling; and
2. What effect will forecasted changes in shipping activity and temperature (as predicted by climate change model(s)) have on the probability of establishment of NIS by biofouling to freshwater and marine ecosystems of Canada (in particular, to the Arctic and other waterways where greater changes are expected)?

ASSESSMENT

The assessment was performed for four regions of Canada: Pacific, Atlantic, Great Lakes-St. Lawrence River, and Arctic. Hull and niche areas were assessed separately to account for potential differences in fouling levels in these areas. A multi-stage mechanistic model (a multiple-step model describing the steps or stages of the invasion process) was utilized for the assessment, which built on previous peer-reviewed approaches for the assessment of species introductions via ballast water (Drake et al. 2020; Bradie et al. 2020; DFO 2020). This model estimated NIS establishment by biofouling using three main components based on real world processes that allow for final NIS establishment: 1) the probability of arrival (biofouling abundance and proportion of NIS); 2) the probability of survival predicted by the environmental similarity (temperature) between the Canadian arrival port and two prior ports-of-call; and 3) the probability of establishment based on a theoretical equation for establishment (Leung et al. 2004) with an adjustment based on a salinity match component between the Canadian arrival port and two prior ports-of-call. Full details on the model and assessment methods are available in Brinklow et al. (In press).

Data sources

This study utilized multiple data sets obtained from a variety of sources as inputs for the multi-stage mechanistic model. One year of shipping data (2018) was obtained from Transport Canada Marine Security Operation Centres (East and West), with an adjustment made for the Arctic region to account for peak operations during the early revenue phase at the Baffinland iron mine in 2019. The shipping data contained information for large commercial vessels first entering Canada , including voyage history (up to 10 last-ports-of-call), arrival/destination port within Canada and vessel type.

Biological data on vessel fouling was obtained from underwater dive surveys conducted by the Canadian Aquatic Invasive Species Network (CAISN) for vessels sampled in the Atlantic (*n = 20*), Pacific (*n = 20*) (Sylvester et al. 2011) and Great Lakes-St. Lawrence River (*n = 19*) regions (Sylvester and MacIsaac 2010), as well as an additional 12 vessels subsequently sampled in the Arctic region (Churchill, MB) (Chan et al. 2015). Data from drydock sampling of vessel seachests were included from vessel sampled in the Pacific (*n = 6*) and Atlantic (*n = 2*) coasts (Frey et al. 2014). Biological data were pooled across regions with each vessel acting as a data point in the calculated abundance distributions. Environmental data (salinity and temperature variables) were obtained for ports from Keller et al. (2011) and World Ocean Atlas 2013 Vol. 3 (Locarini et al. 2013; Zweng et al. 2013), with corrections to salinities for freshwater ports where errors were found (Bailey et al. 2020b).

Model Steps and Outcomes

Arrival of NIS was estimated using probability distributions calculated from the biological data, describing the total abundance of all fouling organisms on a vessel hull or niche area, and the proportion of those individuals that are NIS. Species abundance distributions (the number of species and relative abundance of each species) were assigned randomly to each vessel arrival. A probability of release factor was also applied to estimate the likelihood of an individual being released at the destination port.

Port environmental conditions (mean temperature during the warmest month, mean temperature during the coldest month and annual average temperature) were used to estimate the survival of NIS in the destination port. Using a feature selection analysis, the last two ports-of-call were determined to be most important for predicting the presence of NIS in the fouling community on a vessel. Therefore, environmental distance between the destination port and the last two ports-of-call was calculated, and probability of survival was determined based on a relationship between environmental distance and probability of organism survival already established for aquatic organisms (Bradie et al. 2020).

The likelihood of NIS establishing a viable population in the destination port was determined using an equation relating the probability of establishment to population density (Leung et al. 2004). Alpha values (probability that a single individual will establish a population) were randomly generated, and adjusted based on the salinity match between the destination port and prior ports-of-call. Once final probability of establishment was calculated for each species on each vessel, they were compared to a uniform distribution and a random draw was made to determine if each species establishes or becomes extinct. The total number of unique NIS establishing from each vessel entry into Canada was then calculated as the number of species per year (SpPY). A sensitivity analysis was performed on the model parameters to verify how much influence each of the parameters have on the predicted establishment rates.

The model predicted higher rates of NIS establishing in Canada per year by vessel biofouling via niche areas compared to main hulls. The regions with greatest NIS establishments per year was the Atlantic (7.6 SpPY via niche areas, 2.1 SpPY via hulls) and the Pacific (8.4 SpPY via niche areas, 2.2 SpPY via hulls). The ports in these regions also had the greatest amount of vessel traffic, which likely is the main driver of higher establishment rates. The Great Lakes-St. Lawrence River region had lower rates of establishment (4.7 SpPY via niche areas, 1.5 SpPY via hulls), however, considering that many biofouling organisms are marine species with limited potential to establish viable populations in freshwater environments, these results suggest further model calibration may be needed. The Arctic region had the lowest estimates of NIS establishments (1.7 SpPY via niche areas; 0.6 SpPY via hulls), potentially due to low traffic in the region. However, the Arctic region was often most sensitive to changes made to model parameters in the sensitivity analysis, suggesting that changes such as increased vessel traffic or higher fouling abundances may cause considerable increases in NIS establishment rates in the future.

Vessels with the largest number of entries into Canada per year, as well as largest wetted surface areas, were found to have the highest probabilities of NIS establishment (i.e., container vessels, bulkers, passenger vessels, and tankers). There were some regional differences in NIS establishments associated with each vessel type, particularly that establishments in the Arctic region are mainly associated with bulkers, while other vessels play a larger role in establishment rates in other regions (container vessels and passenger vessels in the Pacific, container vessels and tankers in the Atlantic, and container vessels, tankers, and bulkers in the GLSLR).

Future Scenario

The future probability of establishment of NIS by biofouling into Canada was not able to be examined on a national scale. The initial plan was to rerun the model with forecasted changes in shipping activity and environmental conditions, to result in an estimate for future establishment rates of NIS via biofouling under future shipping activity and climate scenarios. Forecasted shipping data could not be obtained within the timeframe of this process, and future temperature data were missing for approximately 66% of ports, thus the future scenario analysis was not completed as planned.

Instead of completing the above future scenario across Canada, two new scenarios were conducted to investigate potential future changes in the Arctic region only: 1) Increased vessel traffic; and 2) Increased vessel traffic and vessel gross tonnage. Re-running the model under these new conditions revealed an overall increase in NIS establishments. For both scenarios, the rate of NIS establishments per year was estimated at 0.9 SpPY via vessel hulls (compared to current scenario at 0.6 SpPY). This confirms that predicted increases in vessel traffic in the Canadian Arctic (Dawson et al. 2017; Dawson et al. 2018) are likely to result in greater NIS establishments via vessel biofouling, with model predictions increasing by more than 50%. With little difference in the results of the two future scenarios, there does not appear to be a strong effect of increases in vessel gross tonnage. Further investigation on the expected magnitude of increases in vessel gross tonnage, with additional climate change data which may increase the extent of suitable habitat available for NIS establishment in all regions, would better inform model estimates in future studies. With additional effort, more complete temperature data for future scenario assessments might be obtained by extending projections from the closest available point or seeking out smaller scale data sources (e.g., projections for the Great Lakes rather than global).

Sources of Uncertainty

Results presented here represent a reasonable first order approximation of expected rates of NIS establishment; future improvements should be focused on addressing the following areas of uncertainty:

- Patterns among regions might be driven by small sample size, though there are likely real differences driven by variation in shipping routes (prior ports-of-call) among the regions.
- Only a subset of taxa in the available biological data were identified to species level which leads to uncertainty about the total abundance and proportion of NIS associated with vessel biofouling.
- Vessel biofouling communities are complex and highly variable, due to the accumulation of species through time and the diversity of life history strategies of the fouling organisms, such that biological data informing these results may not fully reflect the potential risk of vessel biofouling by all taxa.
- As unique species identifiers were used in the model, the extent of possible NIS establishments was limited by the data that fed the model (i.e., 59 unique taxa via hulls and 179 unique taxa via niche areas) and there is likely a much larger pool of species across the

population of vessels arriving to Canada. The model also may not sufficiently capture multiple establishments of the same species

- Duration of stay at previous ports-of-call and duration of transit are both likely to influence abundance and diversity of vessel biofouling, but were not directly captured in this model. Similarly, the duration of stay of vessels at port in Canada will affect the probability of NIS release and establishment (explored as part of the model sensitivity analysis).
- The relationship between initial population size and establishment success is generally considered to be positive (with larger founding populations having great probability of long-term establishment) but is also highly variable across different taxa and environmental conditions. This model used relationships established for ballast water zooplankton to generate propagule pressure-establishment relationships (alpha values), which may not be representative of biofouling communities. Additional studies to better characterize this relationship for biofouling species are warranted.

CONCLUSIONS

This analysis built on previous DFO regional assessments to estimate relative probability of NIS establishments by vessel biofouling nationally, using advanced modelling methods and best available data. The assessment shows that biofouling is a considerable vector for the establishment of NIS into Canadian coastal regions via shipping. Niche areas are higher risk compared to main hulls, likely due to higher NIS abundance in these areas, and should be a primary focus for biofouling prevention and control methods. Future increases in vessel traffic will likely impact all regions, but particularly the Arctic region, for which an over 50% increase in NIS establishments is predicted based on projected increases in vessel traffic alone. Other factors, such as increased habitat suitability with climate change, fouling abundance and duration of stay of vessels, may also have significant influence on future establishment rates in Canada, with particular concern for the Arctic region.

OTHER CONSIDERATIONS

- This analysis was informed by data from vessels using biocidal antifouling coatings at least 10 months in service and abundance and proportion of NIS could be different for newer coatings, no coating, or different coatings (e.g., foul release).
- Voluntary biofouling management practices recommended by the IMO could reduce vessel biofouling risk, although levels of uptake were low at the time that biological data informing this model were collected. In the same way that time-since-application of antifouling coating systems is a significant predictor of biofouling percent cover and abundance, time-since-cleaning is likely to be an important consideration.
- The results do not take into account the cumulative effect of multiple vessel arrivals in a short period of time, which could increase establishment success. There can also be multiple introductions of the same NIS at different ports across Canada.
- Although the ballast water and biofouling results were based on a similar model structure, the two were parameterized differently and therefore direct comparisons are not recommended.
- Shipping traffic patterns are rapidly changing (e.g., proportionally large increases in the Arctic over the next 5 years), therefore analyses such as these should be revisited frequently.

- Different taxa have different strategies for survival to overcome short-term exposure to unsuitable environmental conditions that may be experienced at different ports and during transit. While the potential implications of these different strategies were explored via a sensitivity analysis by adjusting survival rates for a proportion of taxa based on higher order classifications, species-specific establishment rates may not be well-reflected in this pathway-level model.

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SOURCES OF INFORMATION

This Science Advisory Report is from the January 10-14, 2022 national advisory meeting on biofouling as a vector for aquatic invasive species introduction. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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