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Research Article

Network centrality as a potential method for prioritizing ports for aquatic invasive species surveillance and response in the Laurentian Great Lakes

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Abstract

Ballast water is a leading vector for the introduction of aquatic invasive species worldwide and, once a novel species is established, regional ballast water exchange between ports can accelerate secondary spread. The importance of shipping induced invasions in the Laurentian Great Lakes has resulted in policies that require more stringent ballast water treatment standards for transoceanic shipping than is required of ships operating regionally within the Great Lakes. As a result, ballast water discharges within the Great Lakes are not well regulated, primarily because of the challenge of treating the high volumes of water carried by vessels that are confined to the waters of the Great Lakes. We used a discrete-time Markov chain model on a network with annual time-steps to simulate ballast water management scenarios at high-priority ports in the Great Lakes shipping network for two potential invaders, golden mussel (*Limnoperna fortunei*) and monkey goby (*Neogobius fluviatilis*). We chose high-priority ports by using graph-theoretic network analysis techniques to calculate six network centrality metrics for 151 ports in the network. Ports scoring high in network centrality scores have more ties with other ports or are positioned within the network such that they potentially have greater influence over the secondary spread of aquatic invasive species than other ports. We simulated secondary spread scenarios where hypothetical ballast water treatment was implemented at the top twenty ranked ports in each network centrality metric, as well as the top twenty busiest ports by ship arrivals. The results of each scenario were compared to a scenario where no management action was taken. Simulated secondary spread for both golden mussel and monkey goby resulted in significantly reduced infestation probabilities ($p < 0.001$) under all management scenarios when compared to unmanaged spread scenarios. Management at ports with inwardly directed ties to other ports reduced infestations by the greatest amount compared to other management scenarios; 65.4% for golden mussel and 74.6% for monkey goby. The indegree centrality of ports in the Great Lakes was found to be an important factor in governing secondary spread. Here we show that prioritized management, like high volume shore based treatment systems based on network centrality, is a potentially effective strategy for impeding the secondary spread of new or localized invasive species in the Great Lakes.

Key words: ballast water, species invasions, golden mussel, monkey goby, graph-theory

Introduction

In the Laurentian Great Lakes (Hereafter: Great Lakes), ballast water and residual sediments released from ballast tanks of commercial shipping vessels have been the dominant vectors for unintentional species introductions and dispersal (Holeck et al. 2004; Ricciardi 2006; Sylvester and MacIsaac 2010; Pagnucco et al. 2015). To reduce new introductions, efforts have been made to address the issue of transoceanic ballast water entering the Great Lakes. In 1989 and 1990 ships entering the Great Lakes were asked to flush their ballast tanks with saltwater before entering the St. Lawrence Seaway on a voluntary basis. In 1993 this procedure became mandatory under U.S. law for ships carrying pumpable ballast water volumes and for all vessels, including those reporting no ballast water on board, in 2008.

However, more than a decade following the implementation of mandatory ballast water exchange policies, there is recognition that current policies have probably reduced new invasions but do not provide complete protection (Ruiz and Reid 2007; Briski et al. 2010; Bailey et al. 2011). Furthermore, despite increasing evidence of the importance of shipping in the secondary spread of aquatic invasive species around the Great Lakes (Rup et al. 2010; Briski et al. 2012; Sieracki et al. 2014a, b; Drake et al. 2015), ships operating exclusively within the Great Lakes, colloquially termed “Lakers”, remain largely exempt from ballast water management regulations. Once an oceanic vessel enters the basin it is also not required to treat its ballast water between Great Lakes ports. This is despite the fact that the potential for further introductions remain, not only from shipping, but from numerous other active pathways including accidental or intentional introductions from the live trades (aquarium, ornamental trades, water gardens, live food, biological supplies), illegal stocking, canals, and recreational boating (Padilla and Williams 2004; Johnson et al. 2009; Clarke-Murray et al. 2011; Pagnucco et al. 2015). However, treating ballast water in the domestic Laker Fleet has proved challenging, as they are generally older vessels and their ballast tanks are not designed to handle the biocides most treatment technologies use to purge organisms (Cangelosi and Mays 2006; USEPA Science Advisory Board 2011). As a result, secondary spread of introduced species by shipping can occur, regardless of the initial vector of introduction, and due to limited management in this regional pathway (Rup et al. 2010).

Because shipboard treatment may not be a viable option for the entire Laker Fleet, some interest has been expressed in ballast water treatment at shoreside facilities. An independent report for the Wisconsin Department of Natural Resources concluded that a shoreside ballast water treatment option could be feasible for the port of Milwaukee, WI (Brown and Caldwell 2007). However, transitioning to a management scheme such as this will also require considerable investment in retrofitting treatment facilities with universal deck connectors and updating their capacities to handle greater volumes of water (The Glosten Associates 2002). Nevertheless, the Valdez Maritime Terminal (Prince William Sound, AK) has demonstrated that shoreside ballast water treatment facilities are capable of handling high water volumes likely equivalent to what would be required to enable treatment of the Laker Fleet. The Valdez facility is capable of processing up to 33 million gallons of ballast water per day, and although its current function is only to remove residual hydrocarbons, such a facility could be used for biological sanitation as well (Tsolaki and Diamadopoulos 2010). In the Great Lakes, building a system of shoreside treatment facilities would require significant capital investments, and would be difficult to justify for every Great Lakes port. But it is possible that a network of priority ports within the Great Lakes shipping network could be effective in slowing the secondary spread of incipient populations of invasive species and warrant investment as part of a comprehensive set of management strategies.

Identifying priority ports may not be as simple as focusing on the busiest hubs as there is no guarantee this will have the greatest impact in slowing spread. For example, Floerl et al. (2009) used a stochastic model to predict the spread of a hypothetical invasive organism by hull fouling in a boating network and found that both high traffic hubs and seemingly unimportant "quiet" nodes in networks contributed to the rapid spread of invasive organisms. They noted that high traffic hubs in networks did not always result in faster rates of spread nor more secondary invasion events. Similarly, Banks et al. (2015) showed that in addition to considering the level of traffic between nodes, it was important to consider the arrangement and connectivity of those nodes to understand invasive species spread. Studies of inland lakes and plant invasions have similarly stressed the importance of network connectivity in controlling invasive species spread (Moody and Mack 1988; Muirhead and MacIsaac 2005). Therefore, consideration of node arrangement and connectivity in networks is warranted when modeling invasive species spread and management through largely human-mediated vectors.

A suite of potential invaders to the Great Lakes region with broad environmental tolerances have prompted concern among researchers and managers. Among these potential invaders are two species with contrasting life histories and spread potential, golden mussel *Limnoperna fortunei* (Dunker, 1857) and monkey goby *Neogobius fluviatilis* (Pallas, 1814). Golden mussel is a bivalve with a similar life history to zebra mussel *Dreissena polymorpha* (Pallas, 1771), a high profile Great Lakes invader with a planktonic larval stage and a tendency to form multi-layered aggregations on a variety of substrates (Karatayev et al. 2007). Native to SE Asia, golden mussel was introduced to South America in 1990 through ballast water and has continued to spread, especially in the Rio de la Plata basin. They have had similar economic and ecological impacts as dreissenid mussels have had in North America (Darrigran 2002; Oliveira et al. 2010) and appear capable of establishing at least in the lower Great Lakes

(Kramer et al. 2017). Monkey goby is a Ponto-Caspian species closely related to round goby *Neogobius melanostomus* (Pallas, 1814), a species that has established and become widespread in the Great Lakes. Monkey goby is a benthic generalist which has been recently documented invading inland water systems in Europe (Copp et al. 2005; Grabowska et al. 2009) and has a high likelihood of predicted introduction and establishment in the Great Lakes (Ricciardi and Rasmussen 1998; Stepien and Tumeo 2006; MacIsaac et al. 2015; Pagnucco et al. 2015). They are forecast to have similar impacts on fish and macroinvertebrate communities in the Great Lakes as their established congeners (round goby; Pagnucco et al. 2015), but impacts can be unpredictable and synergistic interaction among and between invaders and other stressors cannot be ruled out (Ricciardi 2001; Yule et al. 2006; Mandrak and Cudmore 2010; Allan et al. 2013; Pagnucco et al. 2015). Both monkey goby and golden mussel have been prioritized by Great Lakes natural resource managers as potential invaders if introduced (Fusaro et al. 2018). Both species have high potential for their invasions to be facilitated by ballast water, and therefore were suitable candidates for modeling ballast water management strategies.

In this study, we use the Great Lakes domestic shipping network to explore the utility of graph-theoretic network analysis techniques for identifying locations where ballast water management efforts can be focused to slow the secondary spread of an incipient invasive species. Specifically, we report our predictions for the hypothetical spread of two potential future Great Lakes invaders, golden mussel and monkey goby, and quantify the effectiveness of targeted ballast water management at ports on each species. We used a discrete-time Markov chain model, parameterized by back-casting against historic zebra mussel and round goby spread through time, to forecast the secondary spread of golden mussel and monkey goby. We then simulated secondary spread under a range of management scenarios where hypothetical shoreside ballast water treatment was in place at select ports in the Great Lakes shipping network. From these model simulations, we propose a method for prioritizing ports in the Great Lakes for future investment in ballast water management systems that have the potential to slow the secondary spread of novel invasive species.

Materials and methods

Study Area

Secondary spread simulations were constrained to the Laurentian Great Lakes and the St. Lawrence Seaway. The St. Lawrence Seaway was defined as the stretch of the St. Lawrence River beginning at the headwaters in Lake Ontario and ending at the westernmost point of Anticosti Island (following Sieracki et al. 2014a). To construct a network of ballast water activity between

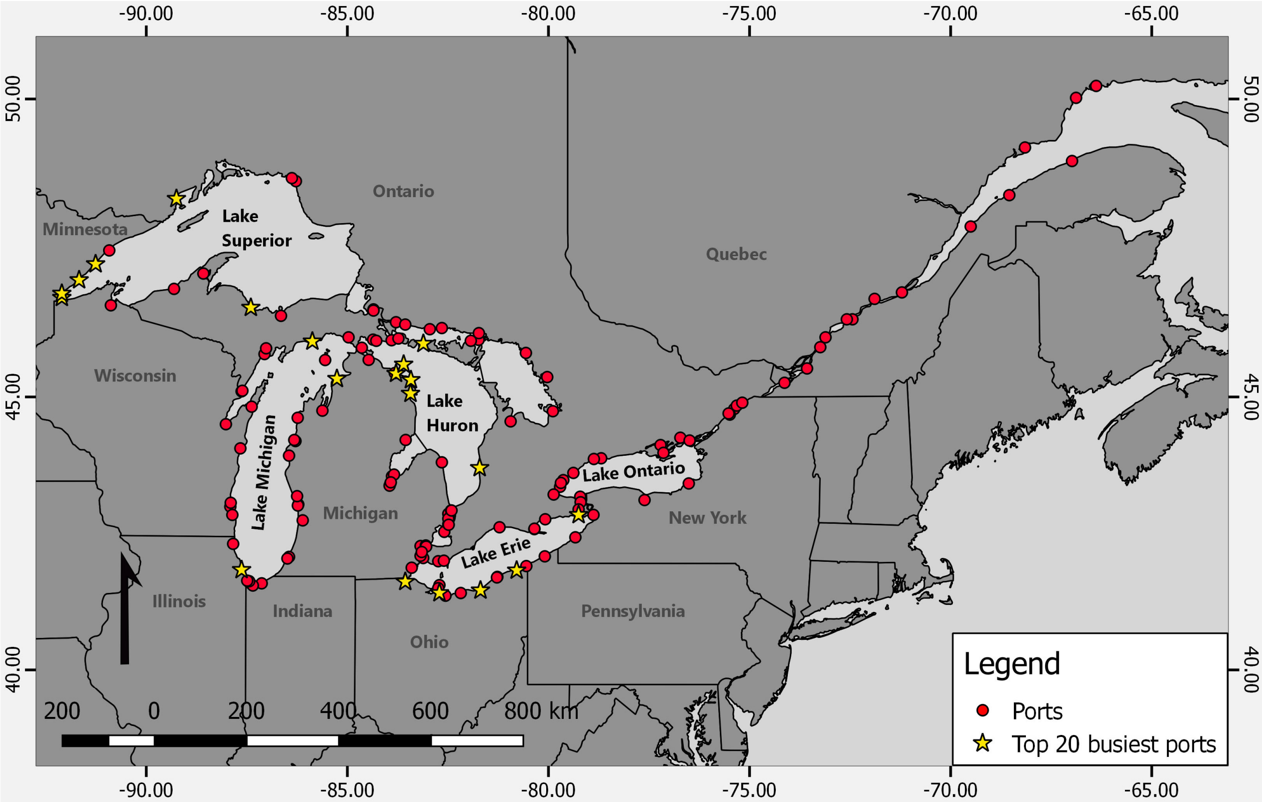

Figure 1. Locations of all 151 ports and the top twenty busiest ports by average number of annual ship arrivals in the Great Lakes–St. Lawrence Seaway regional domestic shipping network identified from ballast water source and discharge records from 2005 to 2015.

Great Lakes ports, we identified ballast tank records in which ballast water was both sourced and discharged at or near a Great Lake or St. Lawrence Seaway port. Ballast tank records with source locations outside of the Great Lakes and St. Lawrence Seaway were omitted from our simulations so our model would approximate secondary spread caused by the domestic Laker Fleet as closely as possible. In total, 151 shipping ports within the confines of Great Lakes and St. Lawrence Seaway were identified and used in our simulations (Figure 1).

Model

Data needs

Empirical data reported for U.S. ballast water source and discharge locations were used to create a matrix of average annual ballast water source and discharge activity between ports on the Great Lakes. Individual records of ballast water source and discharge activity from 2005 to 2015 at each U.S. state bordering the Great Lakes (Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York) were retrieved from the National Ballast Information Clearinghouse (NBIC 2015). Because ships have multiple ballast tanks, water from a single source location could be discharged at multiple destination locations, thus the path a ship takes reflected by their last port and arrival port may not accurately reflect the fate of ballast water. Therefore, individual ballast tank source and discharge records were considered more reliable for predicting patterns of spread than information about ship traffic between ports.

Canadian ballast water data reported to the Canadian Coast Guard Information System on Marine Navigation (INNAV) from 2005–2007 and used in Rup et al. (2010) were obtained from Fisheries and Oceans Canada. Shipping information from the INNAV reporting data did not include information for individual ballast tank source and discharge locations, therefore for these data we assumed that all ballast water discharged at a given destination port was sourced at the last port of call referenced in the dataset. The temporal scale of each dataset also differed, therefore average annual ballast water source and discharge records were used rather than total source and discharge records.

Model structure

Our secondary spread model is a discrete-time Markov chain model where the random variable being predicted is the infestation status of ports, which is a binary status. The form of the model is:

$$Pr\big(X_j(t+1)=1 \,\big|\, X_j(t)=0;\ X_i(t)\big)=P_j$$

where the probability of infestation at a destination port at time t + 1 is conditional on the destination port not already being infested at time t and on the infestation status of its source ports at time t.

The probability of an infestation occurring at a destination port (Pj) is determined by summing the average annual number of times ballast water is sourced at infested ports and discharged at receiving ports (T_{ij}, where i denotes source locations, j denotes discharge locations, and s denotes a subset of source ports (i) which are designated as infested) multiplied by a scalar (x) which scales the average of the ballast water activity occurring between ports represented by the T_{ij} matrix (ranging from 0 to 975.9) into probabilities of infestation:

$$P_j=\sum_{i=s}^{n}T_{ij}x$$

If a port receives ballast water from an infested source, its new status as either infested or uninfested, is determined using a binomial trial. This model assumes that each ballast water discharge event carries some probability of causing a new infestation to occur given that the source port is infested. Therefore, the probability of an infestation occurring at a given port is a function of the average annual number of ballast water discharges received from one or multiple infested ports. The probability of infestation can be modified through the scalar (x), which might correspond to any number of factors including, for example, differences in how rapidly species with contrasting life histories would spread.

A natural spread function was also built into the model to account for infestations that may occur by movement of invasive organisms to nearby ports in the network. The natural spread function is a simple deterministic function in which ports within a specified distance of an infested port are also designated as infested. Distances between ports was estimated from a least-cost path analysis to find the shortest paths between all origin and destination ports using Great Lakes shipping routes in the U.S. Army Corps of Engineers Navigable Waterways network. The distance threshold which determines infestations at nearby ports was modified based on natural spread capabilities of the organisms being modeled. For this study, we assigned a standard natural spread distance of 10 km for both golden mussel and monkey goby. Because our model can only account for infestations occurring in the network of 151 identified shipping ports in the Great Lakes, the natural spread function does not reflect natural spread over time, but rather whether ports within a specified distance from each other could become infested from the same introduction event.

Model parameterization

We parameterized our model by back-casting against historic spread patterns of two current invasive species in the Great Lakes, zebra mussel and round goby. Both species have widespread presences in the Great Lakes basin and their long-distance dispersal has been mostly attributed to ballast water transport rather than natural spread (Griffiths et al. 1991; Kornis et al. 2012). Zebra mussels were considered a good surrogate for modeling the secondary spread of many highly productive invertebrates with a planktonic veliger stage, including golden mussels. Round goby was chosen as a second species for parameterization because they are likely to more accurately reflect spread patterns for many fish species with primarily benthic distributions, including monkey goby.

Zebra mussel and round goby presence data by year, from initial reporting date to present, were obtained through the U.S. Geological Survey Nonindigenous Aquatic Species (NAS) database. We considered ports with species presences within 10 km to be infested. All species presences outside of our chosen distance bin were not considered to be an infestation event in the network of shipping ports. We chose a 10 km distance buffer because ships often conduct ballasting activities at a range of distances offshore before arriving at a port and without a reasonable distance buffer, infestations at ports may be underestimated in our model.

To find parameters that maximized agreement between model predictions and observed zebra mussel or round goby presences in the NAS database, a Cohen's kappa statistic (k) was used:

$$k = \frac{p_o - p_e}{1 - p_o}$$

The Cohen's kappa is commonly used to evaluate levels of agreement on categorical data between two independent observers while taking into account that sometimes two independent observers will either agree or disagree by chance (Viera and Garrett 2005). Thus for our purposes, p_o is the observed agreement (i.e accuracy) between the model predictions and the reported presences and absences and p_e is the hypothetical probability that the agreement between those presences and absences was obtained by random chance. Because our model predicts infestations stochastically and the Cohen's kappa is designed to take into account randomness in the observed agreement of categorical data, the Cohen's kappa was determined to be an appropriate statistic for properly parameterizing our model. To most accurately reflect the pace of invasion, from first recorded presence in the Great Lakes to almost complete saturation within the Great Lakes basin, we compared the zebra mussel presences in 1993 to the output of the 7th year of simulated spread and round goby presences in 2006 to the output of the 15th year of simulated spread.

We chose initial infestation ports for each of our back-casting species based on estimates from the NAS presence data and accounts from the literature. Zebra mussels were first recorded in waters of Lake Erie's north shore in 1986 at a water treatment plant in Union, ON about 4.8 km east of Kingsville, ON and in 1987 four zebra mussel specimens were discovered on the hull of a commercial fishing vessel drydocked in Kingsville (Carlton 2008). Based on these historical accounts and the fact that Kingsville is a shipping port in the Great Lakes network, we chose Kingsville as an initial infestation port for our zebra mussel back-casting exercise. Round goby were discovered in the St. Clair River in 1990 near Sarnia, ON and St. Clair, MI. Although adult goby are benthic organisms and do not possess a swim bladder, their larvae migrate vertically in the water column and that behavior likely allowed for lake freighters to facilitate their dispersal within the Great Lakes via ballast water (Hensler and Jude 2007). We chose St. Clair, MI as a starting port for our back-casting exercise because it receives the most ship traffic of all ports on the St. Clair River, making it a likely contender for an initial location for the secondary spread of round goby in the Great Lakes.

Values for the parameterizing scalar (x) were randomly chosen for each model trial on uniform distributions between 0.001 and 0.05 for zebra mussels and 0.0001 and 0.02 for round goby, corresponding to differences in how rapid dispersal in the Great Lakes occurred for each species. We ran the model for 1000 trials at 10 years and 20 years for zebra mussel and round goby, respectively, and compared the model results to the observed presence data using the Cohen's kappa statistic.

Finally we used a piece-wise linear regression model to fit each value of x where the Cohen's kappa values were maximized for each species, which

Table 1. Agreement levels corresponding to each range of possible Cohen's kappa values (Landis and Koch 1977).

Cohen's kappa range	Level of agreement
< 0.00	Poor
0.00–0.20	Slight
0.21–0.40	Fair
0.41–0.60	Moderate
0.61–0.80	Substantial
0.81–1.00	Almost perfect

occurs at the change-point (φ) in the piece-wise linear regression. The values at each φ were considered the best-fit values for x for modeling the spread of potential invasive species of similar taxa. The φ values can be interpreted as the per-ballast-tank-discharge probability of causing a new infestation at a destination port given that the source port is infested. We then assigned an agreement level to the maximum average kappa values (Table 1; Landis and Koch 1977).

Network analysis

To select potentially influential ports within the Great Lakes shipping network to test for hypothetical management focus, we used concepts from graph theory to quantitatively rank ports based on their degree of connectedness within the network. In graph theory, graphs are mathematical objects consisting of nodes which represent individual actors in the network and edges which represent a value of interaction occurring between actors. The Great Lakes shipping network can be thought of in these terms where each port represents a node and the edges of the graph represent the connections between ports, or whether ballast water originating at any given source port travels to and is discharged in any given destination port. Nodes in a network that are more central than others have three distinct advantages: they have more ties to other nodes, they can reach other nodes faster, and they control the flow of information or materials between other nodes (Freeman 1978; Opsahl et al. 2010). By considering the Great Lakes shipping network in graph mathematics terms and identifying ports that act as central actors in the network, we can then apply that information to a model of invasive species spread to test the potential effectiveness of shoreside ballast water treatment at those locations.

Centrality metrics are useful for quantifying the connectedness of individual nodes in a network and their importance to the whole network. In total six unweighted network centrality scores were calculated: Freeman's, or total, degree centrality, outdegree centrality, defined by the number of outgoing connections to other ports, indegree centrality, defined by the number of incoming connections from other ports, betweenness centrality, defined by the number of times a node acts as a bridge along the shortest paths between nodes, closeness centrality, which is the inverse sum of the shortest distances between each node and all other nodes, and Eigenvector centrality which assigns high centrality scores to nodes based on connections to other highly connected nodes.

The ways in which particular nodes rank in different centrality metrics can give different insights into how they might control patterns of spread within the network. For example, degree centrality scores (Freeman's, indegree, and outdegree centrality) are general measures of node connectivity. They are roughly analogous, in this system, to the general flow of shipping traffic between ports but instead of describing how many ships a port receives or distributes to, degree centrality scores describe how many other nodes a node is connected to and the directions of those connections, either toward or away. By contrast, betweenness and closeness scores are based on identifying shortest paths between nodes in a network. Rather than using their connectivity as a measure of importance, these scores are based on the positions of nodes within the network. Finally, Eigenvector centrality assigns scores dependent on the scores of others in the network. This measure of centrality is useful for identifying nodes that rapidly saturate a network with information or materials because nodes scoring high in Eigenvector centrality will be connected to other highly connected nodes, which are in turn connected to highly connected nodes, and so on. Depending on the behavior of the network and its configuration, different groups of nodes categorized by network centrality metrics may have more or less influence over the spread of information or materials within the network. Which measurement of network centrality is more important is always dependent on the context of the network and can change as the configuration and activity within the network change.

We calculated correlations among network centrality metrics using Spearman's rank correlation to assess whether individual metrics provide novel information on relative connectedness. Graph-level density was calculated to provide a global metric that measures how densely connected the network is and is defined as the sum of the actual connections in the network divided by the number of all possible connections that exist in the network. Finally, we calculated the graph-level centralization index of the Great Lakes shipping network which is also a global centrality measurement of the network that defines the extent to which the network is centered on one or few actors. The graph-level centralization is defined as the sum of the absolute deviation from the most central point to that of all other points defined by their respective Freeman's degree centrality scores.

Management scenarios

Golden mussel and monkey goby spread were forecast using the previous prediction models validated by their current invasive counterparts, zebra mussel and round goby. The forecasting models differed from the back-casting models in that the initial point of introduction was changed to reflect likely points of introduction for the initial infestation sources for each species.

We used Bay City, MI as the point of introduction for golden mussel to test the model, because this port receives a number of ships that take up ballast water from international ports where golden mussel is present. We assumed that golden mussels could potentially be introduced to this site, even if untreated ballast discharge is prohibited, through sediment in anchor chain lockers or sea chests. Since monkey goby is closely related to round goby and they share similar native geographic ranges we chose to model monkey goby spread from ports in the Saint Clair River, where both round goby and tubenose goby were first reported in the 1990s. The initial infestation ports for monkey goby were Sarnia, ON, Marine City, MI, and Saint Clair, MI. These scenarios are meant to be for illustrative purposes; not that these are the most likely scenarios, simply that they are convenient for demonstrating the potential utility of the model.

We ran the model for 1000 trials at 10 and 20 years in each trial for golden mussel and monkey goby spread respectively to obtain the most likely infestation scenarios based on the results of numerous trials and account for differences in the pace of spread related to differences in life histories. After each year of simulated spread, the status of each port was recorded as either “infested” or “uninfested”. Once a port was designated as infested, it remained infested for the remaining number of years until a new trial began. We assigned an infestation probability to each port calculated by the percentage of times in 1000 trials each port was designated as infested by our model.

We used the model to test several potential scenarios where the top 20 ports identified by each network centrality metric were selected for hypothetical ballast water management. We ran the model 1000 times at 10 years to generate infestation probabilities for each port in the shipping network as well as the average number of ports that became infested at least once in all 1000 trials. We first ran the model under a “no management” scenario where no ports were managed as a control scenario.

After selecting the management scenario that resulted in the greatest reduction in infestations relative to the “no management” scenario, we then simulated various levels of management effort ranging from 0% effort (effectively no management) up to 100% effort (100% of boats entering managed ports were assumed to have no chance of causing an infestation) in 10% increments. We also compared the effects of various management effort levels on the median infestation probability of each lake by separating the simulation results by the lake in which each port is located. To determine the relative importance of management effort versus management extent (i.e. the number of ports being managed), we compared the mean number

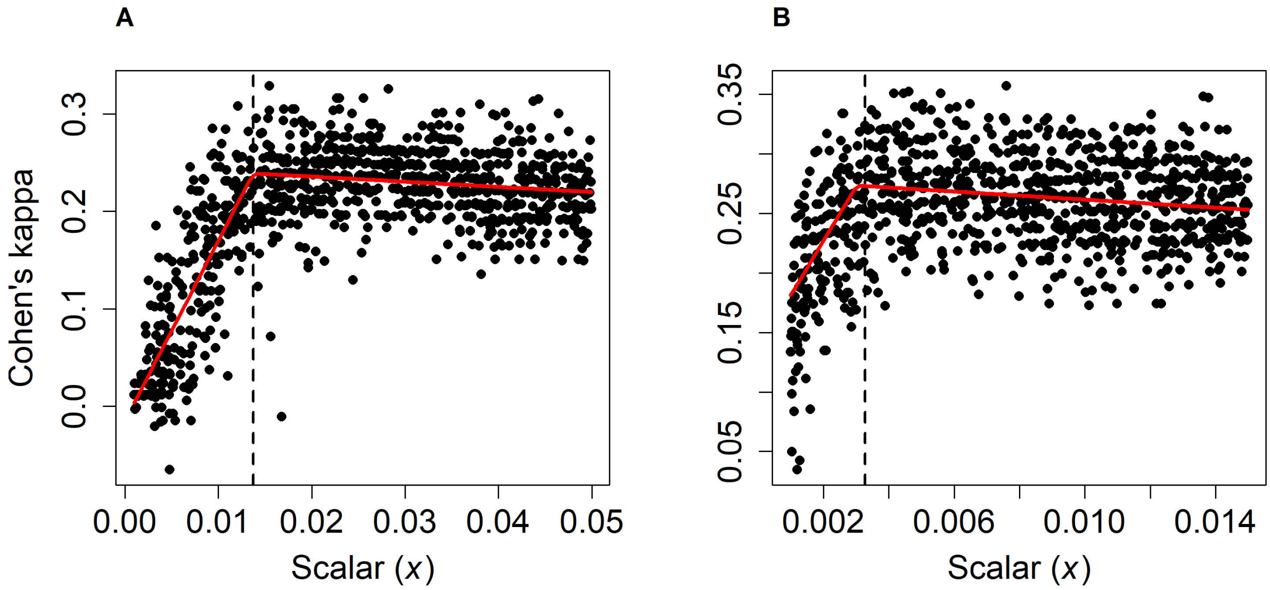

Figure 2. Unweighted Cohen's kappa results of 1000 model simulations for the scaling parameter (x) used in zebra mussel (a) and round goby (b) simulations. The change-point in each graph (vertical dashed lines) were at 0.014 (a) and 0.003 (b). The piece-wise linear regression models for each graph are shown with solid red lines.

of ports infested at 50%, 65%, 80%, and 95% effort for scenarios where the top 20, 15, 10, and 5 ports in the chosen metric were being managed.

We calculated median infestation probabilities at different management effort levels by multiplying the infestation probability of the targeted ports given no management by the percent chance that an infestation would occur at a given level of management. Thus a 100% management effort would correspond to a 0% infestation probability at the ports selected for management. We used a non-parametric Mann-Whitney U test to compare the infestation probability distributions of the managed and unmanaged scenarios, excluding the ports we selected for direct management. Differences in the average number of ports infested across management scenarios were tested using a one-way analysis of variance (ANOVA) and a post-hoc Tukey's honest significant differences (HSD) test.

All statistical analyses and model simulations were performed in R version 3.2.0 (R Development Core Team 2015).

Results

Model parameterization

Best-fit φ values for each of the piece-wise linear regressions on the Cohen's kappa back-casting results were 0.014 for zebra mussel and 0.003 for round goby (Figure 2a, b). The φ values represent the relative probability that an individual infested ballast tank discharging at a given port will cause a new infestation at an uninfested port. The average Cohen's kappa values based on 1000 trials at each φ were 0.22 for zebra mussel and 0.27 for round goby, indicating fair agreement (Table 1).

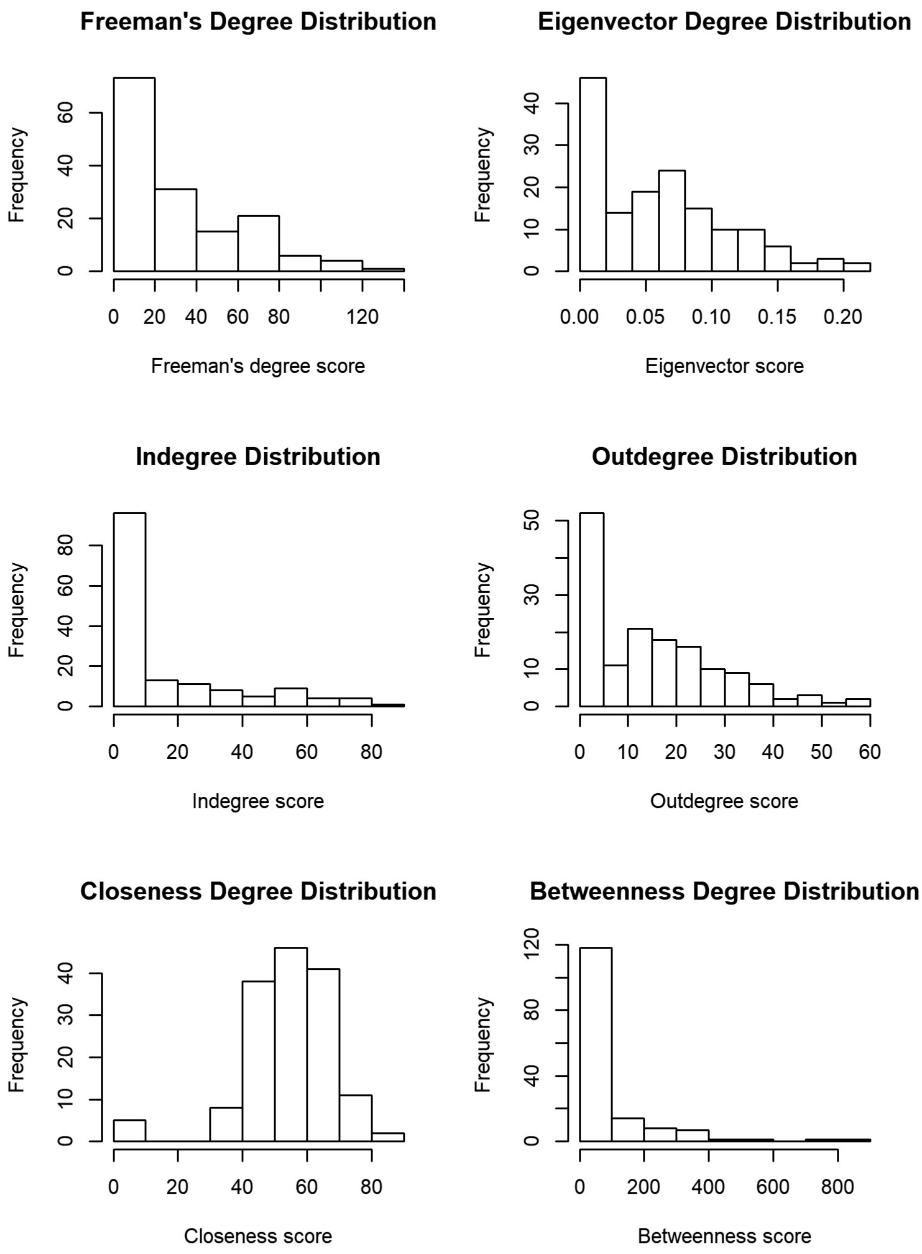

Figure 3. Distributions of values in all six network centrality scores among 151 ports in the Great Lakes commercial shipping network.

Network analysis

The degree distributions for all six degree centrality metrics are shown in Figure 3. In general, the distribution of degree centrality was positively skewed for all but the closeness centrality scores, for which its distribution was negatively skewed. The top ten most central ports by Freeman's (total) degree centrality were Superior, WI, Cleveland, OH, Detroit, MI, Two Harbors, MN, Sandusky, OH, Toledo, OH, Marquette, MI, Calcite, MI, Duluth, MN, and Ashtabula, OH. The top twenty ports in all six centrality measurements are shown in Table 2. All six centrality metrics were highly correlated with each other (Table 3) and overlap in high scoring ports between centrality metrics was common. Across all six centrality metrics

Table 2. Top twenty scoring ports and corresponding values for each centrality metric calculated in the network analysis of the Great Lakes domestic shipping network. The range of values in each metric for all 151 ports in the network is given. The rank of each port in each respective metric is shown in parentheses.

Port	Indegree (0–81)	Outdegree (0–58)	Freeman's (1–135)	Betweenness (0–895.6)	Closeness (0–81.8)	Eigenvector (0–0.214)
Alpena, MI	–	–	–	201 (19)	–	–
Ashtabula, OH	–	45 (7)	93 (9)	296.5 (12)	74.8 (7)	0.174 (6)
Burns Harbor, IN	–	32 (18)	–	–	–	–
Calcite, MI	70 (6)	–	98 (7)	274.1 (13)	–	0.133 (17)
Cedarville, MI	56 (12)	–	–	–	–	–
Chicago, IL	54 (15)	50 (4)	104 (5)	527.9 (3)	77.2 (4)	0.173 (7)
Cleveland, OH	61 (7)	58 (1)	119 (2)	758.6 (2)	81.8 (1)	0.214 (1)
Conneaut, OH	–	39 (10)	75 (15)	–	71.7 (10)	0.154 (8)
Detroit, MI	56 (12)	50 (4)	106 (4)	335.3 (6)	76.8 (5)	0.184 (5)
Drummond, MI	50 (19)	–	–	–	–	–
Duluth, MN	77 (3)	–	99 (6)	395.9 (5)	–	–
Erie, PA	–	32 (18)	–	–	–	–
Essexville, MI	48 (20)	–	–	–	–	–
Fairport, OH	–	36 (14)	–	–	69.8 (14)	0.136 (15)
Gary, IN	–	35 (15)	–	–	69.0 (18)	0.135 (16)
Goderich, ON	–	32 (18)	75 (15)	255.9 (16)	–	–
Green Bay, WI	–	42 (8)	–	257.6 (15)	72.8 (8)	0.152 (11)
Hamilton, ON	–	53 (3)	–	405.1 (4)	80.2 (2)	0.201 (2)
Indiana Harbor, IN	–	38 (11)	75 (15)	–	70.8 (12)	0.154 (8)
Lorain, OH	–	35 (15)	–	–	69.2 (16)	–
Marquette, MI	61 (7)	–	78 (12)	–	–	–
Meldrum Bay, ON	58 (10)	–	75 (15)	187.9 (20)	–	–
Milwaukee, WI	–	38 (11)	–	–	70.8 (12)	0.142 (13)
Montreal, QC	–	–	–	319.3 (7)	68.3 (19)	0.131 (18)
Nanticoke, ON	–	37 (13)	–	–	71.5 (11)	0.15 (12)
Port Dolomite, MI	61 (7)	–	74 (19)	–	–	–
Port Inland, MI	54 (15)	–	–	208.8 (17)	–	–
Presque Isle, MI	56 (12)	–	76 (14)	–	–	–
Quebec City, QC	–	–	–	310.5 (8)	68.2 (20)	–
Sandusky, OH	52 (18)	–	77 (13)	204.3 (18)	–	–
Sarnia, ON	–	46 (6)	83 (11)	305.3 (10)	76.2 (6)	0.192 (4)
Sault Ste. Marie, ON	–	34 (17)	–	–	69.3 (15)	0.139 (14)
Silver Bay, MN	73 (4)	–	86 (10)	–	–	–
Stoneport, MI	73 (4)	–	97 (8)	304.4 (11)	–	–
Superior, WI	81 (1)	–	112 (3)	305.9 (9)	–	0.13 (19)
Thunder Bay, ON	54 (15)	–	–	–	–	–
Toledo, OH	79 (2)	56 (2)	135 (1)	895.6 (1)	79.8 (3)	0.195 (3)
Toronto, ON	–	–	–	–	69.2 (16)	0.129 (20)
Two Harbors, MN	57 (11)	–	–	–	–	–
Windsor, ON	–	40 (9)	73 (20)	273.4 (14)	72.7 (9)	0.154 (8)

calculated, three ports: Superior, Cleveland, and Toledo typically had the highest measures of centrality. The top twenty busiest ports based on average annual ship arrivals from other Great Lakes ports are shown in Table 4. Although most of the busiest ports also scored high in various network centrality scores, two ports, Port Colborne, ON and Charlevoix, MI, ranked high in general ship traffic but did not rank in the top twenty of any centrality metric. The graph-level density of the network was 0.104, suggesting that the Great Lakes domestic shipping network is sparsely connected, meaning that the number of actual connections between ports is low compared to the number of potential connections. The graph-level centralization index was 0.351, indicating a somewhat decentralized network.

Table 3. Spearman's rank correlations for each network centrality metric calculated in the Great Lakes domestic shipping network.

	Betweenness	Indegree	Outdegree	Eigenvector	Freeman's
Closeness	0.76	0.61	0.98	0.99	0.86
Betweenness		0.92	0.77	0.79	0.90
Indegree			0.63	0.65	0.89
Outdegree				0.99	0.87
Eigenvector					0.88

Table 4. Average annual ship arrivals from Great Lakes ports, regardless of whether ballast water was discharged, for the top twenty busiest ports in the network.

Rank	Port	Lake	Average annual arrivals from GL ports
1	Superior, WI	Superior	581.7
2	Sandusky, OH	Erie	329.3
3	Two Harbors, MN	Superior	298.5
4	Calcite, MI	Huron	277.4
5	Marquette, MI	Superior	262.9
6	Toledo, OH	Erie	237.7
7	Duluth, MN	Superior	227.9
8	Port Inland, MI	Michigan	212.3
9	Thunder Bay, ON	Superior	207.3
10	Stoneport, MI	Huron	190.2
11	Alpena, MI	Huron	180.9
12	Silver Bay, MN	Superior	167.9
13	Cleveland, OH	Erie	159.6
14	Presque Isle, MI	Huron	156.8
15	Chicago, IL	Michigan	154.1
16	Meldrum Bay, ON	Huron	150.7
17	Goderich, ON	Huron	149
18	Ashtabula, OH	Erie	138.2
19	Charlevoix, MI	Michigan	129.6
20	Port Colborne, ON	Erie	112

Management scenarios

In general, incorporating management at the 20 most central ports for each of the six network centrality metrics in our simulated spread scenarios reduced the average numbers of new infestations basin-wide in all our simulations (Figure 4).

A one-way ANOVA yielded significant variation among management strategies in both the golden mussel [$F(7, 7992) = 9925$, $p < 0.0001$] and monkey goby scenarios [$F(7, 7992) = 9597$, $p < 0.0001$]. A post-hoc Tukey's HSD test additionally showed that most of the six centrality approaches produced significantly different average numbers of new infestations between all groups with the exception of the closeness and Eigenvector centrality comparison for both species. Managing for high scoring indegree ports (i.e. those ports with the greatest number of incoming connections from other ports) reduced average infestations and infestation probabilities by the greatest amount. Indegree management resulted in a 65.4% and 74.6% decrease in new infestations for golden mussel and monkey goby, respectively. However, focusing on the top 20 busiest ports produced comparable reductions in new infestations. Management at

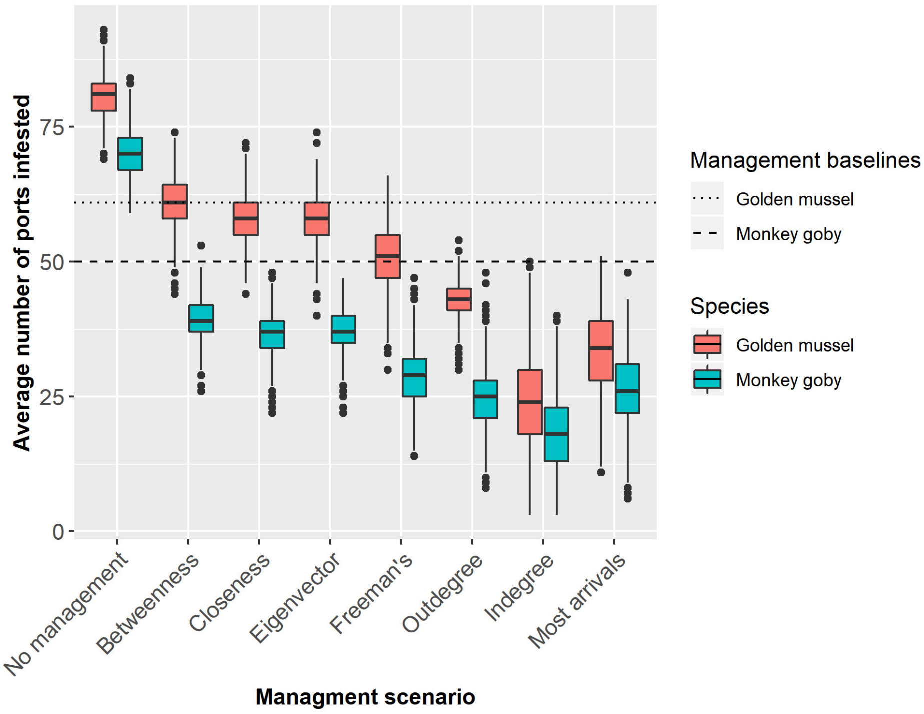

Figure 4. Average number of ports infested during different ballast water management scenarios for both golden mussel and monkey goby. Dashed lines are set at 20 minus the average values in each "no management" scenario because all other scenarios include 20 ports that were prevented from becoming infested.

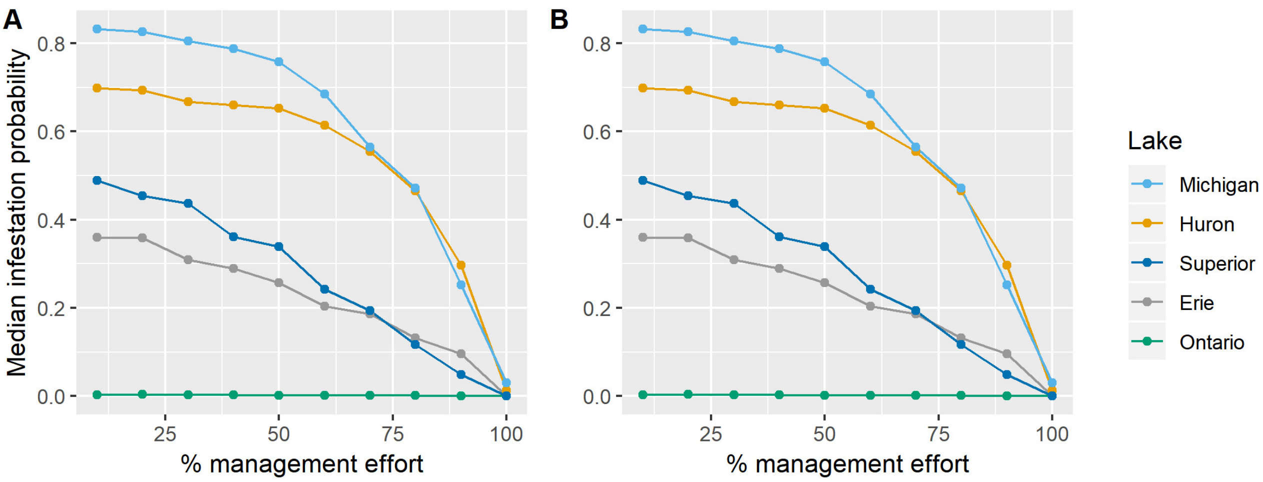

Figure 5. Median infestation probabilities for ports located in each of the five Great Lakes and management in effect at the top 20 indegree ports (across all lakes) under different levels of effort, ranging from 0% to 100%, for golden mussel (a) and monkey goby (b) scenario.

the top 20 busiest ports resulted in a 58.5% and 62.9% average reduction in new infestations for golden mussel and monkey goby, respectively.

Management effort

We tested different levels of management effort with consideration to the indegree management scenario, because this measure decreased average infestations by the greatest margin. Median infestation probabilities reduced differently depending on the lake (Figure 5). Lakes Erie and Superior's median

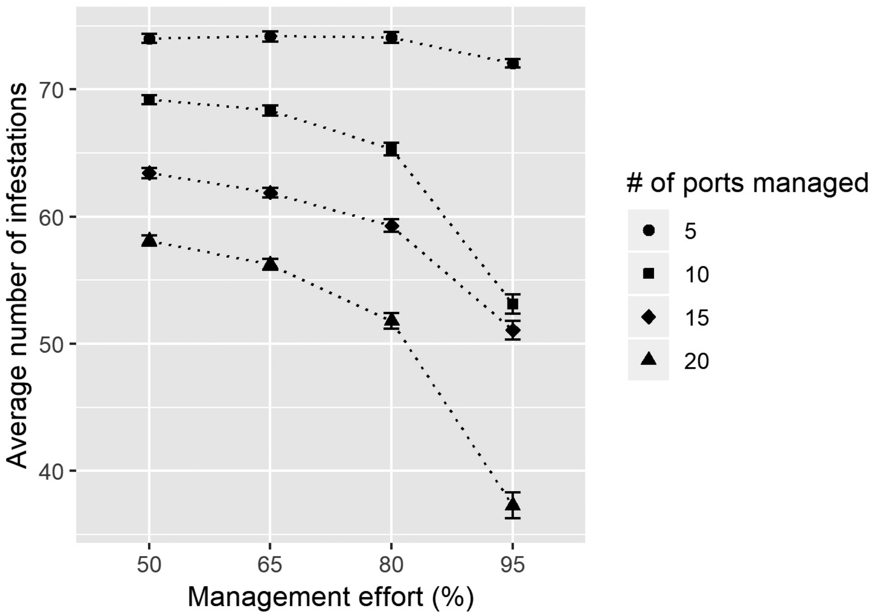

Figure 6. Average number of infestations (± SE) after 1000 simulations with ballast water management at the top 5, 10, 15, and 20 indegree ports at 50%, 65%, 80%, and 95% management effort.

Table 5. The differences in median infestation probabilities from "no management" scenarios for both species. The significance levels from a Mann-Whitney U test are reported as codes. Significance level codes are defined as follows: *** is p < 0.0001, ** is p < 0.001, * is p < 0.05, – is p > 0.05.

	Management effort			
Species	*100%*	*90%*	*85%*	*80%*
Golden mussel	0.308, ***	0.189, **	0.172, *	0.113, –
Monkey goby	0.149, ***	0.085, *	0.055, –	0.053, –

infestation probabilities reduced linearly as management effort increased. Median infestation probabilities for Lake Huron and Lake Michigan decreased the sharpest when ballast water management effort was between 70% and 100%. Median infestation probabilities for Lake Ontario remained close to 0 at all levels of management effort.

The relative importance of the management effort level versus the number of ports being managed is shown in Figure 6. Similar to Figure 5, the trends in Figure 6 showed dramatic reductions in mean infestations when management effort rose from 80% effort to 95% effort. This trend was retained even when fewer ports were selected for management. However, at only 5 ports selected for management the trend appeared to break down and a much smaller reduction in mean infestations was seen even when management effort rose to 95%. For 10 and 15 ports, a 95% management effort produced similar reductions in average infestations as managing 20 ports at 80% management effort.

The Mann-Whitney U test results ($p < 0.0001$) showed that managing the top 20 indegree ports during both golden mussel and monkey goby spread simulations significantly reduced infestation probabilities throughout the Great Lakes basin when managed with at least 85% effort for golden mussel and 90% effort for monkey goby (Table 5).

Discussion

Our simulations of ballast water management at potentially influential ports, quantified by network centrality scores and shipping traffic, resulted in significantly fewer infestation events in all cases when compared to the current scenario of no requirement for ballast water treatment for all vessels within the Great Lakes (Figure 4). Specifically, management at either highly connected ports (as measured by indegree centrality) or a similar number of the busiest ports in the Great Lakes domestic shipping network has the potential to significantly reduce secondary spread probabilities. Further, our simulations suggest that management at only a fraction of the total ports in the network, 13% of ports in our case, can have a worthwhile impact as far as reducing secondary spread probabilities ten or more years after an initial infestation. We note however, that the number of ports we chose for management (top 20 in each category) was chosen purely for illustrative purposes; our objective was to demonstrate that network centrality can be used to prioritize ports for surveillance and management. Future studies should seek to determine the number of locations necessary to achieve a range of objectives. For example, it would be useful to know the number of ports necessary to achieve the maximum reduction in spread probability or the number required to achieve the highest cost to benefit ratio.

In general, we found that the extent of management in the network was more important than the intensity of management effort. However, we did see some instances in which a lower number of ports being managed intensely could produce similar results as a high number of ports being managed with lower efficiency. For example, we found that managing only 10 or 15 ports at 95% management effort produced similar results as managing 20 ports at 80% effort in our simulations (Figure 6). While it is ideal to manage a large number of ports at high levels of effort, constraints on resources and challenges with intergovernmental cooperation often necessitate compromises. Our simulations suggest that tradeoffs between the extent of management and the intensity of management can still produce desirable regional outcomes.

The low graph-level density score (0.104) suggests that the number of actual connections, compared to the total number of possible connections, between nodes is small. However, ports on average scored high for closeness centrality, indicating that each port is only a few steps removed from any other given port in the network. Therefore, even if there is a low probability of spread from an initial infestation location due to low shipping traffic, only a small number of successful secondary invasions are necessary to dramatically increase the probability of spread to the rest of the basin.

Our results suggest that network centrality may be an effective means of prioritizing effort for invasive species management in the Great Lakes.

Although focusing management at the busiest ports produced similar reductions in new infestations, shifting focus to high indegree centrality ports significantly reduced new infestations even more (65.4% *vs.* 57.2% for golden mussel and 74.6% *vs.* 62.7% for monkey goby). Thus based on our simulations, using ship traffic as a surrogate for ballast water pathways in the Great Lakes may be adequate for prioritizing ports for invasive species management, but consideration of network centrality can add information that might otherwise be overlooked and increase effectiveness in invasive species management plans.

These findings are consistent with suggestions from Floerl et al. (2009) that infestations can spread through networks quickly from both "quiet" and "busy" nodes although there is often a greater lag time between the initial infestations of "quiet" nodes and when infestations begin to spread through the rest of the network. Floerl et al. (2009) also stressed the importance of "hub" nodes, which they defined as both high volume and highly connected nodes, in governing secondary spread. Our results also correspond strongly with suggestions from Drake et al. (2015) in which the importance of anthropogenic connectivity between ports in the Great Lakes shipping network is stressed. We used centrality (i.e. connections), irrespective of actual ship visits, to define importance and yielded similar conclusions. Therefore, invasive species management plans should not only focus on reducing per-ship-visit infestation probabilities (Drake and Lodge 2004), but also consider the total number and the direction of connections between ports.

The directionality of connectivity between nodes in the Great Lakes shipping network had important implications on management during our secondary spread simulations. The fact that indegree port management reduced infestations by the greatest amount (Figure 3) may suggest that few ports in the network serve as hubs for ships traffic. In turn, those hub ports appear to be distributing traffic, thus secondary invasions, widely throughout the basin, a scenario which is suggested in the distribution of indegree and outdegree centrality scores shown in Figure 4. Ports that scored high in indegree centrality tended to be cities with large population centers or they had some major economic draw for commercial shipping, such as limestone quarries or iron ore deposits. The distribution of those goods may be directed to many different ports in the basin which facilitates the rapid secondary spread of invasive species through ballast water as has been seen with past cases of invasive species spread such as zebra mussel. In this study we suggest that the secondary spread of invasive organisms in the Great Lakes is highly facilitated by ports that score high in indegree centrality. In addition, we propose that focusing management at high indegree ports can be effective for slowing the secondary spread of a species and prevent it from becoming broadly distributed in the Great Lakes basin.

Network centrality has been previously demonstrated as a useful technique in invasion biology. Our findings are consistent with a previous study examining the role of trade networks in invasive bird distributions in which it was found that bird invasions are more likely to occur in countries with high indegree centrality as measured by the diversity of imports they receive in the global trade network (Reino et al. 2017). Network centrality has also been used to study the mating behavior in invasive red palm weevils (*Rhynchophorus ferrugineus*) which revealed the importance of individual weevils in mating networks (Inghilesi et al. 2015). Our study helps demonstrate the potential for network centrality to be used in decision-making contexts, where limited resources to conduct surveillance and control efforts must be allocated in an optimal way.

The geographic distribution of ports selected for management were unevenly shared among states and provinces; 9 out of the 20 ports selected for management were in Michigan (Table 2). The costs of implementation would therefore likely fall unevenly across the Great Lakes state and provincial jurisdictions. However, ballast water management would be more effective if there was full participation among state, provincial, and the federal governments of both the U.S. and Canada and this would be consistent with the regional binational commitments to preventing and controlling the spread of invasive species (National Research Council of the United States and Royal Society of Canada 2012).

Our model validations only reached "fair agreement" with the Cohen's kappa statistic, 0.22 and 0.25 for zebra mussel and round goby respectively, thus were likely limited by the data we used to back-cast our model with. One problem is that a species invasion is the singular result of a random event determined by a given probability whereas our model estimates the most likely outcome based on many trials. Therefore, if what we observe is a low probability event, some disagreement between actual events and what the model simulates will be expected. In addition, invasive species monitoring data will inevitably include many false negatives by the very nature of how these data are collected. The USGS NAS database, for example, relies on reported species detections and many ports are not subject to active monitoring effort thus it is likely that invasions occurred at ports predicted by our model during back-casting but were not reflected in the presence data. By choosing the scalar that maximizes the Cohen's kappa statistic and generating infestation probabilities through many stochastic trials, our model is able to produce useful results while taking uncertainty into account.

Early detection and rapid response is a cornerstone approach of most invasive species management plans (Lodge et al. 2006; Vander Zanden and Olden 2008). While prevention of new invaders is the most desirable scenario, it is acknowledged that even the best prevention plans cannot always prevent new introductions in the Great Lakes (Pagnucco et al. 2015) and an effective early detection and rapid response strategy is a complementary management approach to preventing further ecological and economic harm (Vander Zanden et al. 2010). Ports with high centrality scores would be priorities for surveillance monitoring. Furthermore like Sieracki et al. (2014a, b), our models have the potential to identify potential source and recipient ports following the detection of novel a population of invasive species and hence direct delimitations surveys necessary to inform response determination processes.

This study assumes a framework for an intraregional ballast water management plan that would rely on the concept of shoreside deballasting, offloading ballast to a shoreside treatment facility. Offloading ballast water to shoreside treatment facilities in the Great Lakes would require a non-trivial investment in constructing or updating existing shoreside treatment plants at the desired locations as well as updating ballast pump connectors to a universal standard. Shoreside treatment has been recommended as a viable ballast water treatment option in several major shipping regions, including in the Great Lakes (The Glosten Associates 2002; Brown and Caldwell 2007; Pereira and Brinati 2012). Investing in shoreside treatment facilities could overcome industry inertia or inability to adopt onboard treatment systems. It would also have the benefit of shifting the burden of cost of ballast water treatment systems away from the shipping industry and Laker Fleet that may not have been responsible for the original introduction and would also recognize the broader regional economic contribution of the industry. Additionally, the costs associated with investing in shoreside treatment facilities are likely easily offset by the cost avoided by preventing or slowing the spread and cumulative impacts of future invasive species introductions to the Great Lakes (Brown and Caldwell 2007).

The region has seen substantial investment in the response efforts to prevent the introduction or spread of silver (*Hypophthalmichthys molitrix* Valenciennes, 1844), bighead (*H. nobilis* Richardson, 1845) and grass carp (*Ctenopharyngodon idella* Valenciennes, 1844). For example, in 2015 alone, approximately $44.2 million was spent in the Chicago Area Water System and Upper Mississippi River on actions to protect the Great Lakes from silver and bighead carp invasions (USFWS 2015). By contrast, the estimated upfront capital investments for on-site treatment and storage options at shipping ports in the Great Lakes range from $1.3 million to $6.6 million per port, depending on the type of treatment system (Brown and Caldwell 2007). Thus, the estimated one-time cost to implement shoreside treatment at a small number of highly influential ports would be similar to the annual costs of current invasive species control programs. Additionally, since the annual costs of operation and maintenance of shoreside treatment facilities would be substantially lower than the initial investment, there is potential to save money for the region in the long-term compared to the potential costs of new or expanded invasive species control programs.

Our simulations suggest that implementation of shore-based treatment at a small number of ports relative to the total number of ports in the network would effectively impede the secondary spread of introduced species. Furthermore, our results could also be used to refine existing invasive species management efforts in the region, such as the Aquatic Invasive Species Interstate Surveillance Framework for the U.S. Waters of the Great Lakes (Chadderton et al. 2019) which identifies priority sites for monitoring based on simple surrogates of all major invasion pathways including the number of port ship visits as a proxy for the ballast water pathway. We believe the results of this study offer a novel approach to identifying high priority areas for aquatic invasive species management.

Trade networks are dynamic and trade patterns can shift over time. Therefore, a re-evaluation of the centrality scores should be performed after any event that results in changes in shipping patterns. In addition, because an infestation can occur anywhere in the shipping network, new secondary spread simulations should be run and a re-analysis of management strategies should be considered whenever a new species is discovered near a shipping port. However, since focusing on the busiest ports in our simulations produced similar reductions in secondary invasions, a management approach that emphasizes some combination of the busiest ports and most central may provide the most practical and reliable way to impede invasive species spread. This would help buffer against the fact that individual trade routes can easily change, but high traffic ports tend to maintain their status due to their regional economic importance and the infrastructure already in place at those ports to handle high ship traffic.

Management at the chosen ports in our simulations did not have equal impacts in all lakes (Figure 5) but had the greatest effect on spread when at least 90% of ships entering and discharging ballast at a port were treated (Table 5). Management effort levels lower than 90% may therefore indirectly put other places at risk of infestation. Together these results suggest that inconsistent inter-jurisdictional management effort can result in unequal outcomes for ports in the network. Thus an adherence and adoption of consistent management approaches across the Great Lakes will produce the best regional outcome and be consistent with existing regional commitments to aquatic invasive species management.

Finally, the Great Lakes are and continue to be at risk of new species introductions (Ricciardi 2006; Pagnucco et al. 2015). Recent policy changes in the Great Lakes have reduced, but not eliminated the risk of ship-mediated introductions (Bailey et al. 2011). Furthermore, the live trades, illegal stocking, recreational boating and canals continue to have potential to introduce new species to the basin (Padilla and Williams 2004; Johnson et al. 2009; Clarke-Murray et al. 2011). Yet efforts to manage secondary spread of invasive species around the Great Lakes have stalled seemingly over the cost and ability to implement treatment on the Laker Fleet, even though Lakers continue to have potential to facilitate rapid secondary spread of novel invasive species. Our models suggest that shore-based treatment at a small number of sites has the potential to offer an alternative management approach that would provide regional benefits by targeting one of the most important vectors for invasive species spread. Furthermore, we can inform where to intervene in the network by not only considering overall shipping activity but the relative connectivity of ports in order to best disrupt secondary spread by ship movement within the Great Lakes as part of a regional ballast water management strategy.

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