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Commentary

Are the Great Lakes at risk of new fish invasions from trans-Atlantic shipping?

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ABSTRACT

The 180+ invaders established in the Great Lakes include three fishes introduced by ballast water. Using previously published and new data, Snyder et al. (2014) identified a total of 10 possible 'high risk' fishes from Eastern Europe and assessed their respective abilities to survive open-ocean, ballast-water exchange during a trans-Atlantic voyage. Their study predicted that a subset of four species would not only survive ballast-water exchange but also invade and disrupt Great Lakes ecosystems. We have reassessed these results by incorporating information regarding opportunities for potential ballast water discharge by ships (i.e. propagule pressure) and a more robust requirement for salinity tolerance imposed by current ballast-water regulation. Our analysis reveals that only one species within the candidate group is likely to potentially pose a 'high risk' to the Great Lakes.

Introduction

Biological invasions by non-indigenous species have been one of the principal stressors in the Great Lakes over the past century (Mills et al. 1993), with discharge of contaminated ballast water accounting for at least 55% of new established species since the modern St. Lawrence Seaway opened in 1959 (Ricciardi, 2006). Identifying and reducing invasion threats is a top management priority in the Great Lakes (Carlton et al., 2011; Bailey et al., 2013; Pagnucco et al., 2015). Several studies have addressed the risk of future invasions to the Great Lakes using different approaches. Keller et al. (2011) examined the global network of commercial vessels linked to the Great Lakes and the environmental similarity of source ports linked to Great Lakes' destination ports. Ports in Europe and the eastern seaboard of North America had the most direct connections and highest environmental similarity to the Great Lakes (Keller et al. 2011). Ricciardi and Rasmussen (1998) considered invasion history, opportunities for ballast-water transport, and inherent salinity tolerance to identify a suite of 17 species from the Ponto-Caspian region expected to invade the Great Lakes. The U.S. Environmental Protection Agency (2008) used a combination of expert knowledge and literature review to identify a suite of 158 potential invaders, including 49 from the Black or Caspian Seas, that could be introduced by ballast water. Although fish invasions associated with ballast water are relatively uncommon and involve a limited number of taxa (Wonham et al. 2000), three Eurasian fishes have invaded the Great Lakes via ballast-water discharge (Mandrak and Cudmore, 2010). Kolar and Lodge (2002) assessed life history and other differences among 45 fish species that either established or failed to establish viable populations after being introduced to the Great Lakes. They also identified 22 Ponto-Caspian species, each identified by two different modeling approaches, that posed an establishment risk to the Great Lakes if introduced by ballast water. Five of these species (Big-Scale Sand Smelt, Monkey Goby, Black and Caspian Sea Sprat, European Perch, Eurasian Minnow) were expected to spread and cause harm (Table 1).

New ballast-water regulations were implemented between 2006 and 2008 to ensure that all ships entering the Great Lakes had treated ballast water or had conducted open-ocean, ballast-water exchange for all tanks to be discharged into the lakes. A high rate of compliance combined with pre- versus post-regulation sampling of biota in ballast water led Bailey et al. (2013) to conclude that the risk of invasion from ballast water discharged to the lakes has been greatly reduced. However, Snyder et al. (2014) extended the approach of Kolar and Lodge (2002) with additional data (largely from unpublished reports in Russian) and new establishment, spread and impact models to identify 28 of 42 examined species that could become established if introduced, based upon their life history characteristics, invasion histories, and thermal and salinity tolerances. Of these, five species (Black Sea Shad, Caspian Tyulka, Volga Dwarf Goby, Caspian Bighead Goby, and Black-striped Pipefish; Table 1) were predicted to spread and cause

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Table 1
Ten Ponto-Caspian fish species identified in Kolar and Lodge (2002) or Snyder et al. (2014) as being at high risk of invading, spreading and disrupting the Great Lakes. Number of discharge events describes the number of ballast tanks discharged between 2009 and 2014 inclusive into the Great Lakes by ships arriving from Eurasian ports inhabited by the species. Probability of Introduction refers to Snyder et al.'s (2014) (Table 5) assessment regarding lack of effectiveness of ballast-water exchange. All fish in the table are believed capable of reproducing in fresh water.

Common name[a]	Scientific name[a]	Salinity tolerance (ppt)	Number of discharge events[b]	Study source[i]	Probability of introduction
Big-Scale Sand Smelt	*Atherina boyeri*	77[c]	6397	1	High
Black-Striped Pipefish	*Syngnathus abaster*[d]	60[e]	2288	2	High
Monkey Goby	*Neogobius fluviatilis*	46[f]	237	1	High
Black and Caspian Sea Sprat	*Clupeonella cultriventris*	34[g]	217	1	Moderate
Black Sea Shad	*Alosa maeotica*	16[f]	165	2	Moderate[j]
European Perch	*Perca fluviatilis*	10[h]	6953	1	Low
Eurasian Minnow	*Phoxinus phoxinus*	7[f]	6714	1	Low
Caspian Tyulka	*Clupeonella caspia*	36[e]	0	2	Low
Volga Dwarf Goby	*Hyrcanogobius bergi*	14[f]	0	2	Moderate
Caspian Bighead Goby	*Ponticola gorlap*	14[f]	0	2	Moderate

[a] Kottelat and Freyhoff, 2007.
[b] S.A. Bailey, DFO (pers. comm).
[c] Palmer et al., 1979.
[d] Synonym = *S. nigrolineatus*.
[e] Freshwater fishes of Iran website (www.briancoad.com).
[f] Snyder et al., 2014.
[g] Food and Agriculture Organization website (FAO.org).
[h] Bein and Ribi (1994).
[i] Study sources: 1 indicates Kolar and Lodge (2002), while 2 refers to Snyder et al. (2014).
[j] Most tolerant life stage was used.

harm in the Great Lakes. Snyder et al. (2014) then combined results for the 10 high-risk species identified in their study with those of Kolar and Lodge (2002) and considered the predicted effectiveness of ballast-water exchange at preventing their successful introduction to the Great Lakes. Species were expected to withstand open ocean ballast-water exchange if they could tolerate exposure to 40–50% (14–17 ppt) seawater (Snyder et al. 2014). Their analysis highlighted four species (Monkey Goby, Big-Scale Sand Smelt, Caspian Tyulka, Black-striped Pipefish) that would likely survive ballast-water exchange and, thus, constitute the greatest risk of invasion, spread, and harm (Snyder et al., 2014).

We are concerned by a number of aspects regarding this analysis, particularly the probable introduction effort (i.e. propagule pressure) for each species, definition of salinity tolerance with application to ballast-water exchange, and differences in acute versus chronic exposure to saline water. Burgeoning research indicates that the more propagules introduced to an ecosystem, the higher the likelihood that a species will successfully establish (e.g. Carlton et al., 2011; Blackburn et al., 2015). The total number of propagules introduced consists of both the number of introduction events and the number of individuals introduced per event. Previous work on salmonid introductions revealed that both factors affect establishment success (Colautti, 2005). Therefore, the number of propagules loaded at the source port by a ship and the number of ballast water discharge events by ships potentially carrying propagules to a new habitat (i.e. number of events) from that port are critical to the outcome of invasion success. Snyder et al. (2014) acknowledged that abundance data were important but not available for ballast water, while Kolar and Lodge (2002) did not include introduction effort in their modeling study. We utilized data from Transport Canada's regulatory ballast water database to identify all transoceanic vessels carrying ballast water that entered the St. Lawrence Seaway between 2009 and 2014 and recorded source ports from which their ballast water is reported to have originated. We then summed the number of ballast water tank discharge events possibly carrying each of the high-risk fish species from ports in Eurasia where the fishes are known to occur (Table 1). As information on fish abundance in ballast tanks of these vessels was not available, we assumed that each port would potentially contribute a similar number of individuals of a particular species. Our approach is conservative in that we assume that our target species are present in every ballast tank filled at a port where the fishes are known to occur. In reality, the probability that our target species are taken into ballast tanks is likely much lower since larval and juvenile fishes, which are most likely to be transported (Wonham et al., 2000), may exhibit strong spatial and temporal variation in abundance in coastal environments, including ports (e.g. Azeiteiro et al., 2006). We classified potential propagule pressure as low (0–3476 events—below the midpoint), or high (3477–6953 events—above the midpoint) based upon the number of ballast tanks discharged (= events) by vessels potentially carrying that species.

Furthermore, we considered the reported salinity tolerance for each of the top ten species, obtained either from Snyder et al. (2014) or from published literature. We simplified Snyder et al.'s approach by assuming that the life stage with the highest reported salinity tolerance is being transported (i.e. worst-case scenario) for the Black and Caspian Sea Sprat, the one species identified with life-stage-specific salinity tolerances. We also employed a binary classification system for salinity tolerance (<30 ppt; ≥30 ppt) of these fishes, because all ships entering the Great Lakes with foreign ballast water are inspected by USA or Canadian government officials and required to demonstrate that ballast-water salinity is at least 30 ppt if the vessel intends to discharge the water within the system (see Bailey et al., 2013). In fact, all of the species in the category <30 ppt have salinity tolerance <17 ppt and, thus, should

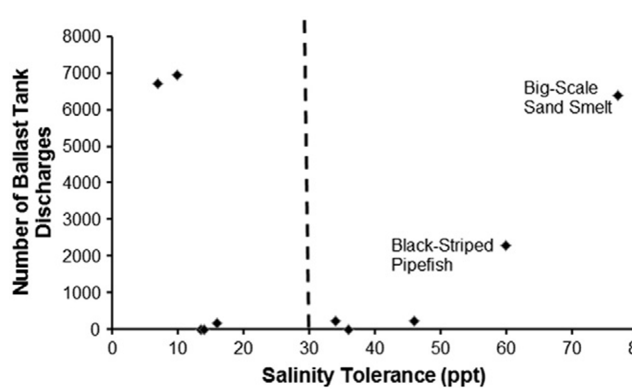

Fig. 1. Number of ballast tank discharges into the Great Lakes between 2009 to 2014 inclusive with water originating from European ports inhabited by ten perceived 'high risk' invaders (see Table 1) versus salinity tolerance of the species. Vertical dotted line represents legal minimum salinity requirement for foreign ballast water discharged into the Great Lakes. The two highest risk species are labeled. Overlapping points at 14 ppt salinity tolerance have been slightly offset.

not tolerate open ocean ballast-water exchange. Given that all ships are inspected, our salinity tolerance requirement for 'high risk' designation is more realistic and stringent (i.e. ≥30 versus ≥14 ppt; Fig. 1) than that applied by Snyder et al. (2014).

When potential propagule pressure and salinity tolerance are jointly considered, the probability of survival (in ballast water) and arrival to the Great Lakes (which we equate with introduction) may be classified as either low or high. We considered probability of introduction to be low when either potential propagule pressure and/or salinity tolerance was low and high only when both factors were high. As the overall biological risk of a potential invasive species is a product of probability of introduction and the magnitude of predicted undesirable consequences (Mandrak et al., 2012), nine of the 10 species with low probability of introduction would have an overall risk of 'low', regardless of potential impact (Table 1). Five species identified as 'high risk' by Snyder et al. (2014) and two species identified by Kolar and Lodge (2002) are considered 'low risk' here as a result of low potential propagule pressure (Table 1). For example, of the seven species in the low propagule pressure category, only one (Black-striped Pipefish) may have had more than 237 potential introduction events into the Great Lakes over the six years from ports within its known range, and three species appear to have had null propagule pressure, with no ballast water discharges originating from ports occupied by the species (Table 1). Two additional 'high risk' species (European Perch, Eurasian Minnow) highlighted in Kolar and Lodge (2002) occur in ports frequented by many vessels carrying ballast water to the Great Lakes, though neither species can tolerate open-ocean, ballast-water exchange and thus should pose low risk (Fig. 1).

Of the original ten 'high risk' fish species, only one—Big-Scale Sand Smelt (*Atherina boyeri*)—has a high risk of introduction and high salinity tolerance (Fig. 1). This species was identified as a potential nuisance by Kolar and Lodge (2002), an assessment with which we agree. It has invaded central European lakes, and its planktivory is thought to exert cascading effects in the food web (Kücük et al., 2012).

A second species, the Black-striped Pipefish, has high salinity tolerance but a 'low' number of ballast-water discharge events that could introduce it to the Great Lakes based on our binary classification (Table 1). A more conservative approach would suggest that this species poses a moderate risk considering that 2288 ballast-tank discharges could have delivered this species between 2009 and 2014. Although the Black-striped Pipefish has an invasion history in central Europe, largely related to colonization of newly created reservoirs and accidentally introduction with mysids in the Volga River basin (Kiryukhina, 2013), and is hypothesized to have been introduced to the Danube River by ships from the Black Sea (Cakić et al., 2002), it has no verified history of ship dispersal (Wonham et al., 2000). Moreover, it has no documented impacts in invaded waterbodies, possibly due to low abundance (Gavlena, 1974; Cakić et al. 2002; Kiryukhina, 2013). Thus, this species seems an unlikely candidate to invade and disrupt ecosystems in the Great Lakes.

Our analysis of risk is subject to change if species distributions expand to key trade ports in Europe or if trade patterns shift to include areas where these species occur. While some of the aforementioned species are abundant in source ports, thus increasing the likelihood of uptake of a large(r) number of individuals, open-ocean ballast-water exchange should strongly diminish potential propagule pressure by purging most entrained taxa at sea (see Bailey et al., 2013). It is for individuals remaining in ballast tanks after exchange that salinity tolerance becomes a relevant issue.

Current models of salinity tolerance often depend on literature reports of extant salinity values in natural ecosystems where species occur. It is not clear whether these reports, which essentially assess chronic exposure to salinity, provide realistic assessments of species' adaptive capabilities experienced during ballast-water exchange. Two types of exchange are possible depending on a vessel's stability requirements and stress limits. The first, flow-through method, involves replacement of ballast water in tanks by pumping through at least three times the volume of the ballast tank, gradually increasing salinity to the extant ocean value. The second method, sequential exchange, is more akin to acute exposure as it involves emptying and then refilling ballast tanks to achieve at least a 95% volumetric exchange. For any organisms that remain in a ballast tank during and after exchange, the former method would provide an enhanced opportunity for physiological adjustment to the influx of high salinity water, while the latter would pose a major challenge to all but the most adept osmoregulators. Nevertheless, given that ballast-water exchange procedures take from a few hours to ~2 days to complete (depending on the number of tanks being managed simultaneously, pumping rate, and tank volumes), the time available for acclimation may be brief and abundance of original organisms left alive in the tanks may be sharply reduced.

Bailey et al. (2013) explored differences in invertebrate species richness and abundance in ballast water before and after mandatory ballast-water exchange was implemented for the Great Lakes and concluded that the procedure provided strong but incomplete protection. Comparable studies have not been conducted for fish species carried in ballast water; however, the lack of reported invasions of fish species in the Great Lakes in the last 25 years provides circumstantial, although admittedly inconclusive, evidence that opportunities for trans-Atlantic invasions have been reduced by ballast-water policies enacted for full tanks in 1993 and for partial or 'empty' tanks in 2006 by the USA and Canada, respectively. Fish invasion risks associated with other vectors (e.g. live trade, canals) remain substantial (Mandrak and Cudmore, 2010; Pagnucco et al., 2015), and we argue that these need to be addressed with greater urgency. Based on our assessment of the results of previous studies, the absence of recent fish invaders, and mandatory ballast-water exchange/flushing for all foreign vessels, the Great Lakes are currently likely at low risk of new fish invasions from trans-Atlantic shipping.

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