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Climate change, non-indigenous species and shipping: assessing the risk of species introduction to a high-Arctic archipelago

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ABSTRACT

Aim Anticipated changes in the global ocean climate will affect the vulnerability of marine ecosystems to the negative effects of non-indigenous species (NIS). In the Arctic, there is a need to better characterize present and future marine biological introduction patterns and processes. We use a vector-based assessment to estimate changes in the vulnerability of a high-Arctic archipelago to marine NIS introduction and establishment.

Location Global, with a case study of Svalbard, Norway.

Methods We base our assessment on the level of connectedness to global NIS pools through the regional shipping network and predicted changes in ocean climates. Environmental match of ports connected to Svalbard was evaluated under present and future environmental conditions (2050 and 2100 predicted under the RCP8.5 emissions scenario). Risk of NIS introduction was then estimated based on the potential for known NIS to be transported (in ballast water or as biofouling), environmental match, and a qualitative estimate of propagule pressure.

Results We show that Svalbard will become increasingly vulnerable to marine NIS introduction and establishment. Over the coming century, sea surface warming at high latitudes is estimated to increase the level of environmental match to nearly one-third of ports previously visited by vessels travelling to Svalbard in 2011 ($n = 136$). The shipping network will then likely connect Svalbard to a much greater pool of known NIS, under conditions more favourable for their establishment. Research and fishing vessels were estimated to pose the highest risk of NIS introduction through biofouling, while ballast water discharge is estimated to pose an increased risk by the end of the century.

Main conclusions In the absence of focused preventative management, the risk of NIS introduction and establishment in Svalbard, and the wider Arctic, will increase over coming decades, prompting a need to respond in policy and action.

Keywords

Arctic, biological invasions, climate change, climate matching, shipping network, vector-based analysis.

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INTRODUCTION

Many marine non-indigenous species (NIS) have been introduced into tropical and temperate zones in or on ships (Minton *et al.*, 2005; Molnar *et al.*, 2008). These have included economically and environmentally harmful species, difficult or impossible to eradicate (Bax *et al.*, 2003). Management approaches to help prevent the introduction of marine NIS target regional vectors (i.e. ships) (Hewitt & Campbell, 2007), although the magnitude and type of risk is unknown for many regions, particularly where changing patterns of shipping or climate change are likely to occur. Global changes in climate, and patterns of trade and travel, may promote or inhibit the introduction and establishment of new NIS by altering port environment conditions and regional shipping intensity. Given that preventing the introduction of NIS remains the most effective course of management (Sylvester *et al.*, 2011), identifying existing and potential biological introduction risks is a priority for environmental managers.

Marine vector-based risk assessment methodology is well established in the scientific literature (Campbell & Hewitt, 2011; Keller *et al.*, 2011; Chan *et al.*, 2012; Floerl *et al.*, 2013) and in management arenas (Clarke *et al.*, 2003; Gollasch, 2006). This approach commonly uses environmental matching to quantify vulnerability to the negative impacts of NIS, whereby a high degree of environmental match is taken to mean high risk (Floerl *et al.*, 2013). Risk is also a function of the number and rate at which NIS are introduced to a region (i.e. propagule pressure – Lockwood *et al.*, 2009). By coupling environmental matching data to ship arrivals as a proxy for propagule pressure, vector-based assessments can identify potential high-risk introduction pathways. In this way, recent studies have estimated current invasion risk associated with global (Keller *et al.*, 2011; Seebens *et al.*, 2013) and regional shipping networks (Chan *et al.*, 2012; Floerl *et al.*, 2013).

While these methods are able to assign meaningful risk ratings in the absence of direct measures of ship-associated biota, they are not without limitation. Principally, a number of studies have demonstrated that vessel arrival details are a poor proxy of propagule pressure, usually leading to overestimates (Verling *et al.*, 2005; Lawrence & Cordell, 2010; Ruiz *et al.*, 2013). The alternative of directly measuring ship-associated propagule pressure is logistically challenging and resource intensive. Ships predominately transfer marine species in ballast water tanks (in ballast water, attached to tank walls, or within tank sediment), or on the wetted surface of hulls as biofouling. The task of representatively sampling ship biota is difficult because of the number and variety of ships, the number of shipping routes and the number of connected potential source NIS that exist within even the simplest network. For example, Keller *et al.* (2011) demonstrated that Laurentian Great Lakes orts were indirectly connected to over 2000 global ports by 716 ships during 2005–2006. Adding to this, complexity is the need to adequately account for the myriad influences on propagule loads, such as the potential for inoculation (e.g. port layover period, antifouling paint age: Coutts, 1999; Coutts & Taylor, 2004; Davidson *et al.*, 2009a,b; Sylvester *et al.*, 2011), *en route* survivorship (Gollasch *et al.*, 2000; Coutts *et al.*, 2010), and management measures intended to mitigate propagule pressure (e.g. ballast water exchange: McCollin *et al.*, 2008; Bailey *et al.*, 2011; Briski *et al.*, 2012). In the face of uncertainty surrounding, the exact conditions under which potentially invasive species are introduced; however, decisions must be made about how and when to limit risk (Keller *et al.*, 2011). Qualitatively characterizing the processes affecting propagule pressure may guide these decisions.

Here, we develop a temporal framework for estimating change in vulnerability to NIS introduction based on relative estimates of propagule pressure and climate matching. As a case study, we analyse the shipping network linked to the high-Arctic Svalbard archipelago to evaluate whether this region will become increasingly vulnerable to NIS establishment under future predicted environmental conditions. The archipelago remains one of the most pristine marine environments in the world with no known NIS (although sampling effort in port environments is low). Svalbard extends from 74° to 81°N and 10° to 35°E, with a mean annual sea surface temperature of 3°C (mean range: −2 to 8°) reflecting warm inflow of Atlantic water towards the Arctic and, thus, salinities approaching 35 psu. To the north of the islands, temperatures are low and salinity affected by the fresher polar mixed layer. Consistent with other polar regions, shipping to the archipelago has increased markedly over the past 40 years (Governor of Svalbard, 2012), and evidence of sea surface warming is apparent (Berge *et al.*, 2005; Bjørklund *et al.*, 2012). We expect that, as with much of the wider Arctic, long-term barriers to species introduction and establishment may be breached (de Rivera *et al.*, 2011) and that the region will become vulnerable to impacts caused by NIS.

This study builds upon the approach of Floerl *et al.* (2013) who predicted effects of climate change on potential sources of NIS. Our method involves three major steps. First, we identify shipping connections that present higher risks of NIS introduction based on environmental matching and relative estimations of propagule pressure. Second, we determine how climate change will affect the vulnerability of regions to NIS introduction using environmental data projected for 2050 and 2100. Third, we consider the potential effect of regional management interventions. Our aim is to evaluate the potential change in vulnerability of a region to NIS introduction as a means to direct further research and the development of targeted preventative management.

METHODS

Shipping network characteristics

Details of ship visits and ballast water discharges were obtained from port authorities and individual vessels, respectively, for the year 2011. To identify potential biofouling donor pools that may contribute to ship biofouling, the last three ports visited by vessels prior to visiting Svalbard were identified from the FleetMon database (www.fleetmon.com). FleetMon provides information on present and historical vessel itineraries through coverage of 5531 of the world's ports together with technical information for most of the world's ships. These data were not available for recreational vessels. Because biofouling organisms can be acquired at any port, and may persist on a vessel for several ports (or years) thereafter, we also include secondary and tertiary potential source ports visited by vessels in our analysis.

Only bulk carriers transporting coal from Svalbard discharge ballast water in the region (Port Master, Longyearbyen pers. comm.). Ships travelling to Norway carrying ballast water sourced from an area outside of the Norwegian Exclusive Economic Zone, or Norwegian territorial waters including Svalbard, are required to manage ballast water under the Norwegian Ballast Water Regulation (Norwegain Ministry of the Environment, 2009). The primary management option currently employed under the regulation is ballast water exchange (BWE). This requires that vessels replace port-sourced ballast water with open ocean water as a means to limit the number of coastal organisms discharged at the destination which are assumed to be of greater invasion risk. The following data were collected from eight of these vessels: last port of ballasting, date of most recent ballasting, whether or not BWE was undertaken and if so where, and the date and volume of ballast water discharge in Svalbard. For the remaining bulk carriers discharging ballast water in Svalbard, we estimated discharge based on discharge from a known vessel of the same size and class (e.g. sister ships) (Rup *et al.*, 2010; Chan *et al.*, 2012). For these vessels, we assumed that ballast water was sourced from the last port of call.

Environmental matching

We examined present-day and future (2050 and 2100) environmental match between Svalbard and potential NIS ports connected by the shipping network. We restricted our analysis to the northern hemisphere as we consider it unlikely that biofouling organisms sourced in the southern hemisphere and transported to the Arctic would survive (Sylvester *et al.*, 2011). Environmental match was based on sea surface temperature (SST) and sea surface salinity (SSS) for each port, evaluated for the upper 10 m surface layer. This depth is characteristic of coastal ports, and other shallow water environments associated with marine NIS (Floerl *et al.*, 2013). We base our analyses solely on SST and SSS as both variables have been shown to substantially restrict species distributions (Van den Hoek, 1982) and have been identified as the most appropriate for marine environmental match assessments (Barry *et al.*, 2008; Floerl *et al.*, 2013). We incorporated maximum and minimum values for each variable in addition to mean values to better characterize variability of port environments.

Environmental data were modelled using the EC-Earth climate model participating in CMIP5. Present-day SST and SSS values were obtained, as were predictions for the years 2050 and 2100 based on the RCP8.5 emissions scenario (see Appendix S1 in Supporting Information). From this coarse resolution model archive, we extracted minimum, maximum and mean annual values for the years 2011, 2050 and 2100 for the nearest model grid point of all ports in the study. We examined changes for a more managerially meaningful time period (2050), and a date at which predicted environmental change for higher latitudes relative to temperate regions is maximal (2100). Data were extracted for all coastal regions and inland waterways for which data were available (n = 3189 global ports; 60% of all study ports) (see Appendix S1).

Following Floerl *et al.* (2013), data were processed prior to calculations to remove correlation and scaling errors (see Appendix S1). Environmental match was estimated by calculating the Euclidean distance (d) between data points (network ports) over the three time periods. To determine the relative importance of each environmental variable in environmental distance calculations, we conducted a sensitivity analysis (Keller *et al.*, 2011; Chan *et al.*, 2012). In addition, we also compared environmental distances when based on environmental data predicted under a different emissions scenario (see Appendix S1).

Potential donor pool

For ports within the Svalbard shipping network, we compiled lists of known NIS for ecoregions within which ports were located. Lists were extracted from the Nature Conservancy's Marine Invasive Database (Molnar *et al.*, 2008), which reports NIS occurrences by marine coastal ecoregions (Spalding *et al.*, 2007; Molnar *et al.*, 2008). As current port-specific lists of NIS are typically not available, this database is the most current and comprehensive compilation of marine NIS.

Evaluating risk

Environmental match between ports visited by vessels within the 2011 Svalbard shipping network was filtered to ports with an environmental match of $d < 1.0$ for the time periods present and 2050, and $d < 2.2$ for 2100. Minimum SST and SSS of ports separated by less than these distances fell within the range of values characterizing Svalbard. When cross-checked with the environmental tolerances of a number of NIS established in port ecoregions separated by greater environmental distances, NIS were found to be filtered out appropriately (data not shown). The appropriate cut-off increased over time as predicted Svalbard SSTs overlapped with the tolerances of NIS found in port regions separated by greater distances. This method of filtering environmental distances gives the distance metric an increased biological relevance suggested to be necessary by several authors (e.g.

Barry *et al.*, 2008; Campbell & Hewitt, 2011; Floerl *et al.*, 2013). To evaluate whether secondary or tertiary source ports could also act as potential biofouling source pools, we filtered secondary and tertiary potential donor ports according to whether they were environmentally matched to Svalbard (as per the above values of *d*) and between steps (e.g. between a tertiary port and a secondary port) as a measure of *en route* survivorship.

Lists of known NIS were matched to those ports which exhibited high environmental match ($d < 1.0$ for the present and 2050; $d < 2.2$ for 2100). We then applied a qualitative model to derive relative estimates of low, medium or high propagule pressure associated with each vector. Our model makes assumptions about: (1) the probability of a vessel entraining or providing habitat for an NIS; (2) the probability of an organism surviving transport; (3) the effect of ballast water management practices; and (4) the probability of repeat inoculations based on data published in the scientific literature. Current understanding of processes affecting propagule pressure does not permit the formal modelling of propagule pressure for an 'unknown' vessel along a particular pathway of potential introduction in the absence of biological sample data; therefore, we do not attempt to predict propagule pressure, but characterize the process of propagule inoculation, transport and introduction to estimate relative levels of propagule pressure (see Appendix S2 in Supporting Information).

RESULTS

Shipping network characteristics

We identified 90 ships making 155 visits to Svalbard. Twenty-two ships visited Svalbard more than once during 2011. Including the previous three ports vessels had visited, Svalbard was connected to 136 global ports, 46 of which were primary ports. Ports visited by vessels were concentrated in Western Europe (Fig. 1a), while primary ports of departure were concentrated in Scandinavia (34%). The majority of ships visited the largest settlement on the archipelago, Longyearbyen (Fig. 2a), and the tourism sector accounted for the majority of ship visits (Fig. 2b). The composition of vessel types at any port was strongly spatially dependent: the port of Longyearbyen received the full range of vessel types visiting Svalbard, while no cruise or tourist ships visited the port of Svea. There was a strong seasonality in ship arrivals, with 77% between June and September. Vessels' mean duration in ports prior to visiting Svalbard was 12.6 ± 2 days (mean ± SE), although substantial differences existed between vessel classes. For example, bulk carriers and cruise ships spent a mean of 2.3 ± 0.9 and 3 ± 1 days in port, respectively, whereas fishing and research vessels spent a mean of 19.3 ± 9.5 and 20.4 ± 2.3 days in port, respectively.

During 2011, 13 ships made 31 fully ballasted trips collectively to Svalbard, discharging ballast water upon each arrival. We estimate the volume of ballast water discharged by the entire fleet to be 653,000 m^3 (mean = 21,060 m^3 ± 2070 m^3). Vessels all sourced ballast water from one of 16 European ports (Fig. 3). Five of the eight ships for which we have data reported having exchanged ballast water mid-ocean, while three reported no form of exchange. The age of ballast on these ships upon discharge varied (range: 1–22 days). From all vessels, ballast water discharged in Svalbard was mostly sourced from marine waters (92%), with the remainder sourced from brackish ports (14–19 psu). Both Longyearbyen and Barentsburg ports received modest quantities of unexchanged ballast water, while the port of Svea received substantial quantities of exchanged ballast water. Thus, coastal organisms are being transferred to two ports, whereas predominately oceanic organisms are likely being transferred to a third (Svea).

Environmental similarity

Sensitivity analysis revealed that temperature variables explained the majority of variation in environmental distance about the mean (linear regression with only temperature variables: $R^2 = 0.64$). Both temperature variables (see Appendix S1) were independently important, reflecting the higher

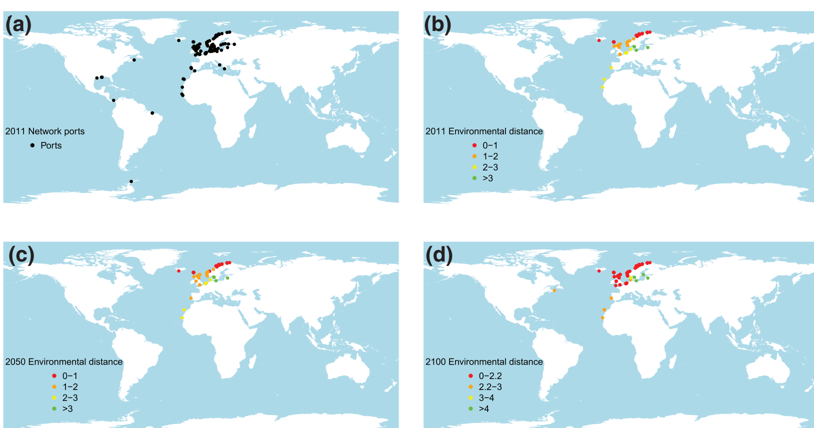

Figure 1 Ports connected to Svalbard through the 2011 shipping network and environmental distances from Svalbard. Environmental distance (*d*) is based on temperature and salinity with lower values of d indicate higher environmental match. Panel (a): all primary, secondary and tertiary ports connected to Svalbard during 2011. Panel (b): environmental distances from primary ports of call for the year 2011 and also environmentally matched ($d < 1$ for b–c; $d < 2.2$. for d) secondary and tertiary ports.

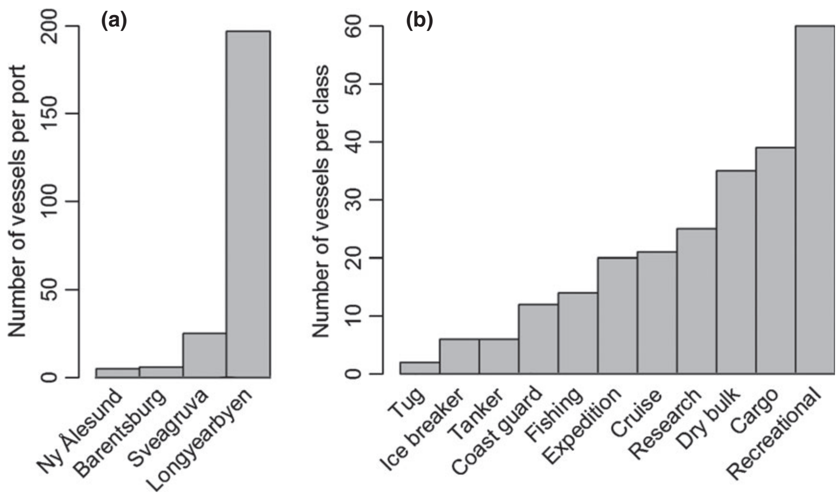

Figure 2 (a) Vessel arrival by Svalbard port during 2011. (b) Vessel arrivals by type across all Svalbard ports during 2011.

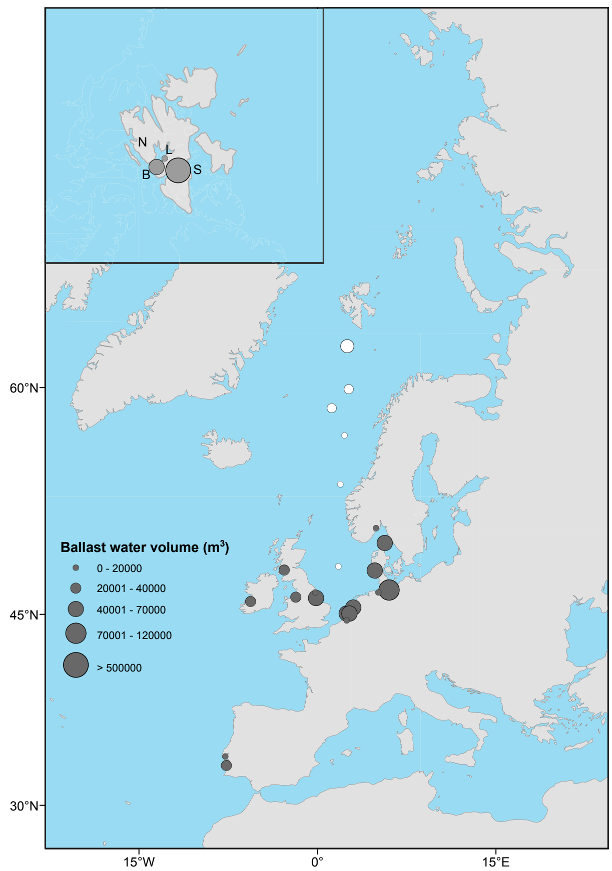

Figure 3 Regions from which ballast water was sourced by vessels prior to discharge in Svalbard in 2011: grey circles – original ballast water source estimated for all vessels; open circles – mid-ocean exchanged ballast water reported by eight vessels. Inset: ballast water discharged in Svalbard. S, Svea; B, Barentsburg; L, Longyearbyen; N, Ny Ålesund: no ballast water was discharged in Ny Ålesund.

proportion of global ports that are more saline (e.g. similar to Svalbard, more than one half of global ports have salinities > 30 psu) compared with the overall low number of global ports with similar temperature characteristics to Svalbard. Nonetheless, removing salinity from the calculations increased deviance significantly between the full and reduced linear models (ANOVA: $F = 22{,}352$, $P < 0.001$, 12 d.f.). Based on this result, salinity data were retained in environmental distance calculations.

The current environmental distance between ports where ballast water was sourced and Svalbard ranges from 2.1 to 2.6 (Fig. 1b). Environmental distances between all primary ports of departure and Svalbard ranges from 0.8 to 5.0 under present conditions (Fig. 1b). Twenty-eight vessels connect Svalbard to primary ports of departure (six different ports) with $d < 1.0$ presently (range: 0.8–1.0). These same vessels connect Svalbard to a further five secondary and tertiary ports of high environmental match ($d < 1$) to Svalbard.

Considering present shipping network connections, Svalbard would be connected to seven ports with $d < 1.0$ by 2050 and 16 ports with $d < 2.2$ by the end of the century (Fig. 1c–d). Considering secondary and tertiary ports, five and 22 further ports of high environmental match would be connected to Svalbard under the same shipping network by 2050 and 2100, respectively.

No ballast water source ports are predicted to be environmentally matched ($d < 1.0$) to Svalbard by 2050, yet two current ballast water source ports will become matched ($d < 2.2$) to Svalbard by 2100.

By 2100, predicted environmental distances < 2.2 to Svalbard are characterized by maximum temperatures in the range 7.9–20.9°C and salinity levels > 32 psu.

Environmental match using data modelled under the A1B scenario (see appendix S1) estimated only marginally smaller degrees of environmental match between ports (mean = 0.2 ± 0.2).

Potential donor pool

Under present conditions, the shipping network connects Svalbard to four ecoregions with similar environmental conditions ($d < 1.0$). Sixteen NIS are known from these regions (Molnar *et al.*, 2008), including one species indigenous to Svalbard (the soft-shelled clam *Mya arenaria*) (see Appendix S3 in Supporting Information). Of the remaining 15 species, 14 are suited to transport as biofouling on ships (see Appendix S3) (Molnar *et al.*, 2008).

Assuming climate change predictions and the same shipping network, by 2050, Svalbard will remain connected to the three same highly environmentally matched port ecoregions. By 2100, the number of highly matched port ecoregions is estimated to increase to nine. The pool of current NIS in these nine regions is 640% greater (see Appendix S3) (Molnar *et al.*, 2008) than that in the four regions currently connected to Svalbard. Therefore, while it is impossible to know the number of NIS that will be present in these regions in coming decades, it is likely that an increase in connected regions of high environmental match will expose Svalbard to a larger number of NIS.

Evaluating risk

Ballast water discharged in Svalbard waters was not estimated to pose a risk currently, or by 2050. By the end of the century, two ballast water sourced ports will be environmentally matched to Svalbard ($d < 2.2$). Propagule pressure associated with ships currently sourcing ballast water from these ports is estimated to be low for those vessels currently performing BWE, and high for those not.

Risk associated with biofouling is estimated presently to be limited to the 28 ships connecting Svalbard to six highly environmentally matched ports. Of these, 11 were estimated to pose high propagule pressure, and six low. All cruise ships are estimated to pose low propagule pressure, while those posing high propagule pressure include vessels from all other classes with the exception of bulk carriers which are estimated to pose low or medium propagule pressure.

DISCUSSION

Regulatory mechanisms, ship operations, trading patterns, the distributions of NIS and ecological values need to be taken into account when assessing the potential risks for NIS transfers. In the first such assessment for the European Arctic, we have demonstrated an efficient means to do this. Our assessment of the Svalbard shipping network indicates an increasing vulnerability to NIS introduction and establishment over coming decades. Risk is differentiated by vector, shipping routes, recipient location and time. All Svalbard ports are estimated to be at high risk of biofouling introductions mediated by a small number of vessels; yet the NIS donor pool is small (15 species) owing to the small number of ports environmentally matched to Svalbard. Vulnerability to biofouling introductions is likely to increase towards the end of the century, however, due to the increasing diversity of the potential NIS donor pool and moderating SSTs. Ballast water introductions are not estimated to pose a risk presently, or by 2050. By the end of the century, however, two ports will be matched to current ballast water source ports. These results suggest that the values for which Svalbard is managed will come under threat as the region becomes increasingly vulnerable to the effects of NIS.

Densities of organisms in ballast water sourced from the same ecoregions have been reported to be high (although varied) in other studies (5×10^3–8×10^5 organisms m^3 – McCollin *et al.*, 2008; Simard *et al.*, 2011). While mortality is known to increase with time, the short voyages in our analysis are likely to maintain some level of survivorship (Simard *et al.*, 2011). BWE heavily reduces the number of coastal NIS transferred in ballast water (McCollin *et al.*, 2007, 2008; Simard *et al.*, 2011) and was undertaken by the majority of ships discharging ballast water in Svalbard. Nevertheless, BWE efficacy varies according to the method of BWE, source port and taxa (McCollin *et al.*, 2007, 2008; Simard *et al.*, 2011) and has been shown to increase propagule diversity (McCollin *et al.*, 2008) and even survivorship of ballast water organisms (Briski *et al.*, 2012).

Ballast discharge in Svalbard is restricted to bulk carriers that travel to Svalbard from European ports to collect coal. One of the two coal mining companies on Svalbard has recently expanded (Store Norske, 2013), while the other has access to considerable reserves of coal on Svalbard (Arktikugol, 2013). Therefore, ballast water sourced from European ports is likely to continue to be discharged in Svalbard in the foreseeable future. Subject to the ratification and phasing in of the International Ballast Water Convention in 2016, and modifications to the Norwegian Ballast Water Regulation to mandate ballast water treatment (currently optional), ships will be required to install ballast water treatment systems with strict discharge limits (IMO, 2004; Norwegain Ministry of the Environment, 2009). These systems would substantially reduce any risk of NIS introduction associated with ballast water transfer to Svalbard. Yet, there is some non-compliance with the current Norwegian Ballast Water Regulation among Svalbard shipping operators; our results press the need to improve this over coming years.

Vessel traffic in 2011 included movement that could be expected to differ little from year to year (e.g. cargo and local tourism associated shipping) and movement that may change from year to year (e.g. cruise and bulk shipping, and recreational vessel traffic). Due to the seasonality of shipping, the geographical range of ports vessels visited prior to arrival in Svalbard is wide (Fig 1a). Durations spent in ports visited by vessels prior to Svalbard were related to vessel class: cruise ships typically spent < 1 day in port, while research and cargo ships routinely spent periods between 1 week and 1 month in port. No cruise ships connected ports with a high environmental match to Svalbard, whereas all research and cargo ships repeatedly visited ports (primary, secondary and tertiary) of high environmental match to Svalbard. Propagule pressure associated with these vessels was therefore estimated to be high. Under present conditions, fishing, research, expedition and cruise ships connected Svalbard to the most distant ports with a high environmental match (Torshavn and Vestmanna – Faroe Islands; Vestmannaeyjar – Iceland), with the former two estimated to pose low-medium propagule pressure. The size of the potential NIS donor pool from these ports, however, is low (six species).

Some of the increase in estimated vulnerability to NIS introduction and establishment by the end of the century is attributable to our increase in the environmental distance cut-off beyond which assumed risk is considered to be low (i.e. to $d < 2.2$). The rationale behind this increase lies in the thermal reproductive requirements of a number of NIS. Conditions under which species can reproduce are more relevant in estimating establishment potential than physiological tolerances. By the end of the century, maximum SSTs in Svalbard are predicted to rise beyond 10°C (12.5°C). A number of NIS (e.g. the European shore crab *Carcinus maenas,* the edible crab *Cancer pagrus* and the green algae *Codium fragile* ssp. *tomentosoides*) have been shown to be able to reproduce at temperatures between 10° and 12°C. As the maximum SST in Svalbard poses a clear barrier to species invasion, we accordingly align estimates of risk to corresponding values of environmental distance (i.e. $d < 2.2$ by 2100). This cut-off also eliminated low salinity (< 15 psu) ports from our analysis.

Over coming decades, our analysis indicates that vessel biofouling is likely to pose a greater risk of NIS transfer than ballast water discharge. While transfer suggests the potential for introduction, there are distinct differences in the way introduction is mediated. Whereas most organisms transported in ballast water are actively discharged at the recipient port, biofouling dispersal is a passive process that occurs when organisms reproduce in port, when an environmental cue triggers an organism to leave a ship hull in port (especially for mobile fouling organisms such as amphipods or isopods) or through dislodgement (for example during ship berthing) (Minchin & Gollsch, 2003). Despite the stochastic nature of the process, several studies have indicated that biofouling likely accounts for more NIS introductions than ballast water (Fofonoff *et al.*, 2003; Davidson *et al.*, 2009b; Hewitt & Campbell, 2010). Thus, this vector should be included in a marine NIS risk assessment regardless of an inability to predict inoculation rates. Whereas ballast water discharge in Svalbard is regulated under the Norwegian Ballast Water Regulation (Norwegain Ministry of the Environment, 2009), no comparable regulation exists for the management of biofouling.

The importance of biofouling in the spread of NIS is further exemplified by the recent adoption of the '2011 Guidelines for the Control and Management of Ship's Biofouling to Minimize the Transfer of Invasive Aquatic Species' by the International Maritime Organisation (IMO, 2011). The degree to which the voluntary guidelines will affect levels of propagule pressure associated with ships identified as high risk in this study presently remains unknown. Our study, however, underscores the need for high standards of biofouling management practices. We expect similar vulnerability to NIS introduction and establishment to evolve in other Arctic destinations, and in destinations receiving increasing vessel traffic. Increasing shipping traffic along the Northern Sea Route, for example, provides more rapid connections between Western Europe and East Asian ports (compared with travelling via the Suez Canal) and subjects potential biofouling to a range of different environmental conditions. These factors may promote or inhibit survivorship of biofouling, the extent of which will likely alter with climate change. Substantial increases in marine vessel traffic are expected in the wider Arctic region associated with tourism (Eger, 2011) and resource exploitation (Arctic Council, 2009). Vessels are likely to travel frequently to, from and between Arctic regions and operate under a range of different profiles. These movements will entail diverse and dynamic risk profiles. While the focus of this analysis has been on risks posed by vessels travelling to an Arctic location, vessels travelling from Arctic locations may also acquire biofouling and pose a return risk. The type of analysis used in our present study can be readily adapted and applied to increasing and evolving shipping networks to estimate changes in vulnerability to NIS introduction and indicate vessel-related risk.

Limitations of our approach should be noted. Our analyses necessarily excluded recreational vessels as voyage histories are not readily available for these craft. However, the potential for recreational vessels to mediate species transfer is high (Floerl & Inglis, 2005; Davidson *et al.*, 2010; Clarke Murray *et al.*, 2011). Our use of environmental distance assumes that the ranges of organisms will be limited to their current realized niche. A more full evaluation of the biological relevance of environmental distance metrics would be welcomed and would aid and improve risk assessment. Furthermore, while we identified NIS in potential source regions connected to Svalbard, our analysis does not identify species indigenous to source regions that may also pose a threat of impact if introduced.

Finally, assumptions we made in our qualitative model of propagule pressure were necessarily basic and would benefit from better characterizations of the different influences on propagule pressure. In particular, determining the relative contributions of each factor to overall propagule pressure would improve accuracy, as would the incorporation of the age of antifouling paints on vessels which is positively related to the diversity and abundance of biofouling (but see Sylvester & MacIsaac, 2010). Preliminary data collected from ships in this study ($n = 20$) indicate that the age of antifouling paint varies greatly between ships (range: 1–36 months). Despite these limitations, we believe our estimates of propagule pressure, while heuristic, provide meaningful indications of broad levels of risk associated with individual vectors. Our objective for characterizing propagule pressure was to improve the sensitivity of the risk assessment process, reducing overestimates of risk. However, we emphasize that our focus was on estimating relative, as opposed to absolute, risks.

CONCLUSION

By spatially and temporally characterizing a regional shipping network, and by examining present and future environmental conditions and NIS pools in both donor and recipient regions, we have been able to identify biological introduction risks warranting management attention. These data present the first forecast of changing biological introduction risks associated with a regional shipping network. Similar increased vulnerability to species invasion can be expected in other Arctic locations.

International Maritime Organisation regulations provide a vital international context within which to position regional management. The recent adoption of biofouling guidelines signals an important move towards improving the management of this vector. Despite these layers of international governance, biological introduction risks are likely to persist and increase as a result of climate change. The Svalbard shipping network does not constitute a large shipping network: the number of connected ports is one order of magnitude lower than for the Laurentian Great Lakes (Keller *et al.*, 2011). In the absence of more comprehensive data, the method we used provides an efficient means of combining shipping, environmental and biological data to identify current and future risks, prioritize further research and identify management gaps in Svalbard, the wider Arctic, and for ports connected by regional shipping networks.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Environmental data.

Appendix S2 Characterizing propagule pressure.

Appendix S3 NIS connected to Svalbard through the shipping network.

BIOSKETCH

Chris Ware is a PhD candidate at the University of Tasmania and research technician at the Tromsø University Museum. His research focus is on developing and applying methods to quantify and manage invasive species threats in both terrestrial and marine polar regions. The author team's collective interests are: (1) understanding responses of biota to changing climates; (2) the changing bioinvasion threat due to expanding polar shipping; and (3) the efficacy of management tools to reduce invasion threat.

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