ARCTIC
VOL. 71, NO. 3 (SEPTEMBER 2018) P. 269–280
https://doi.org/10.14430/arctic4732

Arctic Sea Routes: Potential New Pathways for Nonindigenous Species Spread

Duy Nong,[1,2] Amanda M. Countryman,[1] Travis Warziniack[3] and Erin K. Grey[4]

(*Received 21 September 2017; accepted in revised form 3 May 2018*)

ABSTRACT. This paper evaluates the potential effects of future commercial shipping through the Northern Sea Route and Northwest Passage on the spread of nonindigenous species (NIS) between Europe, the United States, and the Asia-Pacific region. We modeled NIS spread risk as a function of two factors: NIS introduction and NIS establishment. The change in risk of NIS introduction from one region to another is based on the expected commodity trade flow between the two regions given Arctic shipping routes. The risk of NIS establishment is based on current marine climate similarities between regions and projected 2030 terrestrial climate similarities. Results indicate that the United States, China, and Japan are at greatest risk for increased terrestrial and marine NIS spread to and from one another given their relatively high levels of trading activity and terrestrial and marine climate similarities. While increased trade between European and Asia-Pacific countries is expected in the future, only Japan has terrestrial climate similar enough to that of European countries to be considered a substantial terrestrial NIS spread risk, while China has the potential to increase the risk of marine NIS species spread in Europe.

Key words: nonindigenous species; risk; Global Trade Analysis Project (GTAP); trade; Arctic shipping routes; climate matching

RÉSUMÉ. Cet article évalue les effets potentiels de la navigation commerciale future dans la route maritime du Nord et le passage du Nord-Ouest sur la propagation d'espèces allogènes (EA) entre l'Europe, les États-Unis et la région de l'Asie-Pacifique. Nous avons modélisé le risque de propagation des EA en fonction de deux facteurs : l'introduction des EA et l'établissement des EA. La variation en matière de risque d'introduction des EA d'une région à l'autre est basée sur le flux prévu des échanges commerciaux entre les deux régions passant par les routes maritimes de l'Arctique. Le risque d'établissement des EA est fondé sur les similitudes climatiques maritimes actuelles entre les régions de même que sur les similitudes climatiques terrestres projetées pour 2030. Selon les résultats obtenus, les États-Unis, la Chine et le Japon courent les plus grands risques de propagation accrue d'EA marines et terrestres de part et d'autre en raison de leurs degrés relativement élevés d'activités commerciales et de leurs similitudes sur le plan climatique terrestre et maritime. Bien que l'on s'attende à l'augmentation du commerce entre les pays de l'Europe et de l'Asie-Pacifique, seul le Japon compte un climat terrestre suffisamment semblable à celui des pays européens pour être fortement considéré comme un risque de propagation terrestre des EA, tandis que la Chine pourrait accroître le risque de propagation des EA marines en Europe.

Mots clés : espèces allogènes; risque; projet d'analyse des échanges mondiaux (Global Trade Analysis Project – GTAP); commerce; routes de navigation de l'Arctique; étude climatique

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Arctic sea ice has shrunk by 12% per decade since the late 1970s (Stroeve et al., 2012), a trend that is expected to continue in the coming decades (Comiso, 2012; Stroeve et al., 2012). This decline in Arctic ice is likely to allow more frequent use of Arctic sea routes for shipping (Borgerson, 2008; Eguíluz et al., 2016), with fairly reliable year-round use expected by 2030 (Wang and Overland, 2012). This paper investigates the potential impact of increased shipping through the Arctic on the spread of nonindigenous species (NIS) throughout the Northern Hemisphere. NIS, or species transported via anthropogenic means to new areas where they are not native, can become invasive in their new locations, causing substantial environmental and economic harm (Blackburn et al., 2014; Pimentel et al., 2014). Increased NIS spread could therefore represent an unintended cost associated with increased Arctic shipping.

Melting Arctic ice is expected to result in expanded use of two main routes: the Northern Sea Route and the Northwest Passage (Fig. 1). The Northern Sea Route reduces the marine distance between Northwest Europe and Northeast Asia by 40% compared to the passage through the Suez Canal (Liu and Kronbak, 2010; Schøyen and

[1] Department of Agricultural and Resource Economics, Colorado State University, Fort Collins, Colorado 80523-1172, USA
[2] Corresponding author: duy.nong@colostate.edu
[3] Rocky Mountain Research Station, 240 West Prospect, Fort Collins, Colorado 80526, USA
[4] Division of Science, Mathematics and Technology, Governors State University, University Park, Illinois 60484-0975, USA

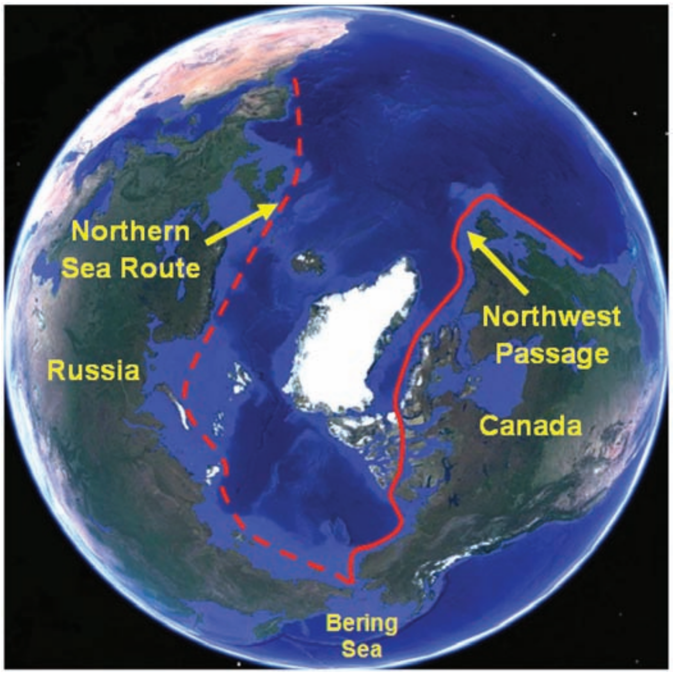

FIG. 1. Map of the Arctic sea routes showing the Northern Sea Route along Russia's mainland and the Northwest Passage through the Canadian Arctic.

Bråthen, 2011). The Northwest Passage reduces the sailing distance between Northeast Asia and the U.S. Atlantic coast by 23% compared to the route via the Panama Canal (Bekkers et al., 2016). The two Arctic routes allow shipping companies to avoid increased tolls in the Suez and Panama Canals (Jervis, 2016) and would allow navigation of super ships that are larger and able to carry greater volumes of cargo. Non-cost advantages of the routes include the ability of ships to avoid politically unstable regions in the Middle East and pirate-infested waters (Hong, 2012), such as the Strait of Hormuz, where an armed attack on cargo ships occurred in 2008 (Borgerson, 2008). As a result, the Arctic sea routes may be used to facilitate international trade (Schøyen and Bråthen, 2011; Faury and Cariou, 2016), thereby increasing trade volumes between the related regions (Kerr, 2012).

Many studies have demonstrated a close relationship between trade and NIS, and shipping is identified as the main vector of NIS in aquatic ecosystems. Olson (2006) reviewed numerous studies of biological invasions and highlighted the importance of international trade as a vector linked to the existence and spread of invasive species internationally. Cook and Fraser (2008) and Perrings et al. (2010) both confirmed a strong relationship between trade and invasive species spread, while Chapman et al. (2017) recently found a strong relationship between a country's NIS invasion risk and its connectivity to global trade networks. Globally, shipping has been found to be responsible for 69% of marine invasive species (Molnar et al., 2008) and 60% of NIS in the freshwater Laurentian Great Lakes (Horan and Lupi, 2005). Risks associated with oceanic shipping come primarily from species' hitchhiking on ship hulls (hull fouling) and in ballast water (Drake and Lodge, 2007; Keller et al., 2011). Of these risk vectors, ballast water has received the most policy attention. Non-voluntary hull fouling policies exist only in Australia and New Zealand, despite the fact that hull fouling is at least equally responsible for shipborne NIS as ballast water (Molnar et al., 2008). Trade-related risks of introduction of terrestrial species come from hitchhiking species on cargo and packing materials (Naylor et al., 2001; Work et al., 2005; Lodge et al., 2006). As a result, ships have been identified as the most common vector of NIS spread around the world (Cook and Fraser, 2008; Keller et al., 2011; Miller and Ruiz, 2014).

Here we focus on the possible changes in NIS risk along the Atlantic coasts of the United States, Europe, and selected countries in the Asia-Pacific region (China, Japan, and South Korea) that may result from expected changes in Arctic shipping. This focus is based on the potential for increased trade volumes in these countries when the Arctic sea routes become available. Our measure of NIS spread risk comprises two components: the changes in the risk of terrestrial and marine NIS introduction and the risk of terrestrial and marine NIS establishment. Our estimation of changes in the risk of introduction, which is described in the next section, is novel in that we use bilateral trade flows of key commodities from a computable general equilibrium modeling framework (Countryman et al., 2016). Our estimation of the risk of establishment is based on climatic similarities between regions. Since we examine the NIS risk only on the east coast of the United States, and China is a relatively large country with a long coastal area in the east, we select only the climate stations on the east coast of these two countries for examination. Other countries in the analysis are relatively small; therefore, we use data from all stations in the remaining countries considered.

METHODS

We combine two independent events, introduction of NIS and establishment of NIS (conditional on being introduced), to examine the risk of NIS spread into a country or region. Establishment of NIS in a region indicates survival of species introduced to that region, while spread of NIS into a country or region in this study means the combination of an initial introduction and subsequent establishment of species in a country or region. Note that we do not specifically address an invasion, which would depend on economic and ecological harmfulness and is beyond the scope of this work, nor do we address secondary spread throughout a country or region.

The combination of these two independent events, NIS introduction and NIS establishment, has been thoroughly investigated in order to determine the risk of spread to a new environment (Drake and Lodge, 2007; Sylvester and MacIsaac, 2010; Seebens et al., 2013). We assume that propagule pressure on a given country of NIS, which includes both the number of individuals released during a single event and the number of discrete release events, depends on import volume to that country or region. Establishment of NIS, which is the survival and reproduction of a species once it has been introduced, is assumed to rely on climate similarities between the new location and the location of origin. Climate similarity has been extensively used to examine how NIS originating from one large environment become established in a similar new location (Bomford et al., 2009; Bacon et al., 2014; Howeth et al., 2016) and also to project potential habitats for non-native species (Howeth et al., 2016; Seebens et al., 2016).

The methods used in this study provide two key extensions in the context of examining the spread of NIS to a specific country or region. First, expected changes in bilateral aggregated trade flows of all commodities used in this study are derived from a global economic model, which provides estimates of trade-related risk that are more comprehensive than those from previous methods that relied mainly on shipping data (Seebens et al., 2013; Ware et al., 2014; Xu et al., 2014). These shipping-based models of risk are not able to predict general equilibrium effects on the global economy and changes in trade volumes, as they consider only changes in shipping traffic. Our trade and corresponding NIS introduction risk results, on the other hand, derive from simulations produced by a computable general equilibrium model, which takes into account the potential economy-wide effects of using the Arctic shipping routes. Second, we use projected 2030 terrestrial climate data (Hijmans et al., 2005) to compare future terrestrial climate similarities between countries or regions affected by opening Arctic sea routes. Previous habitat-matching models of the Arctic have focused either on current climates (Seebens et al., 2013) or on future climates in small geographic areas (Ware et al., 2014).

For this model of NIS risk, we denote $\Delta T_{m,n}$ as the percentage change in country *m*'s real imports (quantity) from country *n* and $C_{m,n}$ as the percentage of meteorological stations in country *m* that match climates projected for 2030 at the stations in country *n* with scores of eight or higher. Our measure of relative risk, $R_{m,n}$ (percentage change), is then described by equation (1). The following sections describe each component of equation (1) in detail.

$$R_{m,n} = \Delta T_{m,n} \times C_{m,n} \tag{1}$$

Note that there is a convention in the Global Trade Analysis Project (GTAP) model: namely, that original levels of prices for commodities are assumed to equal 1. Hence, though data for the model are measured in dollar values, we can still observe changes in quantity units after a shock or change in the model.

We compare the relative changes in risk of NIS introduction to country *m* by comparing real changes in import quantities from country *n* to country *m*. That is,

$$S_{m,n} = \left(\Delta t_{m,n} / \sum_{n \varepsilon N} \Delta t_{m,n}\right) \times 100 \tag{2}$$

where $S_{m,n}$ (percentage) are shares of real increased imports by country *m* from country *n*; $\Delta t_{m,n}$ is the real change in quantity units imported by country *m* from country *n*; and *N* is the set of country *n*.

As a result, we compare the relative percentage changes in risk of NIS spread to country *m* from every country *n*, $r_{m,n}$, according to equation (3):

$$r_{m,n} = S_{m,n} \times C_{m,n} \tag{3}$$

Countries and Regions of Concern

This study considers relevant coastal countries with large trading volumes that are expected to be substantially affected by future Arctic shipping. Trade of many inland countries will also feel the impact of these expanded navigable openings; however, in this study we focus on coastal areas—the environments where NIS would be introduced initially, and from where these species would spread. Three major trading groups were selected: Group 1, in the Asia-Pacific region, consists of China, Japan, and South Korea. Group 2, in Europe, comprises 12 coastal countries with relatively large trading volumes: Finland, Sweden, Norway, the United Kingdom, Germany, the Netherlands, Denmark, France, Ireland, Spain, Portugal, and Poland. Group 3 includes only the east coast of the United States because the opening of the Arctic shipping routes, by decreasing shipping distances from Asia-Pacific countries and the U.S. east coast, is expected to increase trading activities primarily in that eastern region.

Risk of NIS Introduction and the Trade Model

Change in the risk of NIS introduction into a region is based on changes in imports to the region resulting from open Arctic shipping routes, as measured by the modified GTAP model of Countryman et al. (2016). The full description of the standard GTAP model can be found in Hertel (1997); the extended features are provided in Countryman et al. (2016). Briefly, the GTAP model is a global static computable general equilibrium (CGE) model. It involves interactions of representative economic agents and institutions at country and international levels under three common economic assumptions: markets for goods and factors of production are clear, markets are competitive, and firms earn zero profits because of free entry.

The research undertaken by Countryman et al. (2016) meets our specific requirements for estimates of changes in trade flows for several reasons. First, Countryman et al. (2016) is one of the few peer-reviewed papers (if not the only one) to use a global economic model to evaluate the economic effects of the operation of the Northern

Sea Route and Northwest Passage on the United States, Europe, and East Asia. Its general equilibrium simulations provide expected changes in trade for all 16 countries or regions required in our study. Second, the Countryman et al. study implicitly takes into account the marine traveling distance reductions between all relevant countries that will result from the operation of the Northern Sea Route and Northwest Passage compared to the existing routes via the Suez and Panama Canals. Such estimates in distance reductions were not only measured for coastal countries, but also computed for inland countries. Countryman et al. (2016) measured the actual shipping distances (rather than Great Circle distances) that connect an inland country with other countries by evaluating the distance between the capital of that inland country and the closest seaport plus the distance between seaports, or the distance from the closest seaport to the capital of another inland country, or both. Third, given that the United States is included as one country in the economic model and that trade cost reductions vary throughout that country, Countryman et al. (2016) used weighted shipping distances to assess the overall distance reduction between the United States and countries in the Asia-Pacific region. The continental United States has coastal areas on the Pacific and Atlantic Oceans, but the Northwest Passage is likely to substantially affect trading activities on the east coast (the Atlantic Ocean) because it will reduce the marine traveling distance only between that coast and the Asia-Pacific countries. In particular, Countryman et al. (2016) used the marine distances and trade values between three major U.S. ports (Long Beach, California; New Orleans, Louisiana; and Newark, New Jersey) and Asia-Pacific countries to obtain the weighted distance reductions between the United States and trading partners in the Asia-Pacific region. Fourth, the modified GTAP model used in Countryman et al. (2016) is particularly suitable to estimate the effects of distance reductions, measured by transportation and transaction cost reductions, on the global economy. This model is widely recognized as one of the best-suited methods to evaluate the effects of international and regional trade-related policies and facilitation (Dennis, 2006; Hertel, 2013).

Trade networks are interwoven, and models that focus on a single region in isolation generally perform poorly when the driving factor (e.g., a melting Arctic) is global or affects multiple regions. Studies that focus on ships, rather than trade, are able to analyze vector-specific, or technology-specific risk, but are one step removed from the economic forces that affect risk. Open Arctic routes affect relative trade costs, which in turn affect the composition of goods moved round the globe. If we think of the global shipping network, trade acts as the pulse along that network. Trade models like the one used here can tell us the relative size of those pulses and what types of goods will be traded. By analyzing trade directly, we can more accurately describe the types of species likely to be in the vector. This work, in turn, lays the foundation for technology-specific prevention and control policies.

Risk of NIS Establishment via Climate Matching

We estimated the risk of terrestrial NIS establishment on the basis of terrestrial climate similarities between regions by using the weighted Euclidean distance between 16 terrestrial climate variables, as shown in the upper part of Table 1 (Crombie et al., 2008). We applied the same Euclidean method to examine the risk of marine NIS establishment, but using the four current marine climate variables shown in the lower part of Table 1. The Euclidean algorithm developed in our model closely follows the algorithm in the Climatch model (Crombie et al., 2008). Calculations were completed in R (R Core Team, 2014).

Equation 4 calculates the weighted climatic distance $d_{i,j}$ between weather station i in country m and weather station j in country n. That is, every weather station in a country is first compared to every weather station in all of the other countries.

$$d_{i,j} = \sqrt{\frac{1}{k}\sum_{k}\frac{(y_{i,k} - y_{j,k})^2}{\sigma_k^2}} \qquad (4)$$

where $y_{i,k}$ and $y_{j,k}$ are the k^{th} climate variables for the i^{th} and j^{th} stations, and σ_k^2 is the variance of the k^{th} climate variable. Scanning through all weather stations in country n, the minimum distance (i.e., the closest climate match) across all sites in the trading country is assigned to that i^{th} weather station. Then we perform a simple transformation,

$$\hat{d}_{i,min} = floor\left\{(1 - d_{i,min}) \times 10\right\} \qquad (5)$$

The higher values in the equation above indicate better climate matches. The *min* subscript denotes the closest climate match, or least distance. The floor function results in the greatest integer that is less than or equal to its argument, essentially transforming any number in brackets into an integer. For example, the floor of 5.2 is 5, and the floor of 3.8 is 3. We consequently obtain integer values between 0 and 10 for $\hat{d}_{i,min}$. At the final stage, we calculate the measure of climate similarity $C_{m,n}$ as the percentage of meteorological stations in country m with a climate score of eight or higher with country n. We select a climate score of eight as a cutoff for identifying climate similarity between countries or regions since this number has provided moderate to high NIS risk profiles in other studies, such as in Bomford et al. (2009). Also, this number resulted in a larger range of $C_{m,n}$ scores among source countries, allowing for better discrimination of climate similarities. Such climate matching has been widely used to estimate NIS establishment risk (Britton et al., 2010; Kopecký et al., 2013; Kalous et al., 2015).

For the future terrestrial climate, we used 16 terrestrial climate variables from http://www.worldclim.org/ (Hijmans et al., 2005). We obtained terrestrial climate projections

TABLE 1. Terrestrial and marine climate variables used to calculate climate matching between NIS source and destination countries or regions.

Terrestrial climate variables:	
Annual mean temperature (air)	Mean annual rainfall
Temperature – coldest month (air)	Mean rainfall – wettest month
Temperature – warmest month (air)	Mean rainfall – driest month
Annual temperature range (air)	Mean monthly rainfall – Coefficient of variation
Temperature – coldest quarter (air)	Mean rainfall – wettest quarter
Temperature – warmest quarter (air)	Mean rainfall – driest quarter
Temperature – wettest quarter (air)	Mean rainfall – coolest quarter
Temperature – driest quarter (air)	Mean rainfall – warmest quarter
Marine climate variables:	
Minimum sea surface temperature	Salinity of sea surface
Maximum sea surface temperature	
Yearly mean sea surface temperature	

for the year 2030 using "representative concentration pathway 4.5" (RCP45) from the Goddard Institute for Space Studies Russell ModelE version 2 (GISS-E2-R) associated with the Coupled Model Intercomparison Project Phase 5 (CMIP5) downscaled to 10 arc minutes resolution (all of the above information is available on the World Climate [2008] website). Although the projected greenhouse gas concentrations under commonly used RCPs diverge greatly starting around mid-century, the expected concentrations are very similar in 2030 (Meinshausen et al., 2011). Hence, we select the medium concentration pathway 4.5, which peaks in 2040 and decreases thereafter. Current marine climate variables for ports in both destination and source countries, which have been widely used to estimate invasive species risks within the global shipping network, were collected from Keller et al. (2011). Unfortunately, data for marine climate projections in 2030 were not readily available at the appropriate scale for this study.

RESULTS AND DISCUSSION

Risk of NIS Introduction from Trading Results

Table 2 presents the projected bilateral aggregated imports in 2030 for several countries under baseline shipping conditions (no operational Arctic routes), which are derived from Countryman et al. (2016). Relatively large baseline import volumes imply that even a small percentage change in imports ($\Delta T_{m,n}$) could mean a substantial change in import volume ($\Delta t_{m,n}$) and corresponding change in NIS introduction risk. Table 2 shows that potential changes in risk of introduction of terrestrial and marine NIS to European countries from Asia-Pacific countries will not be great because import volumes, with a few exceptions, will be relatively small. For example, Spain, France, Germany, and the United Kingdom import large volumes of commodities from China, while Germany and the United Kingdom have relatively large import volumes from Japan and South Korea. Asia-Pacific countries and the United States may have similarly high potential for increased risk of NIS introduction to each other because of their similar bilateral trade volumes. China and the United States have the highest trading volumes relative to other partners and may therefore be at the greatest risk for terrestrial and marine NIS introduction to each other.

Table 3 provides the expected percentage changes in imports for each country from trading partners ($\Delta T_{m,n}$) resulting from the operation of Arctic sea routes in lieu of the existing canal routes in 2030. The Northern Sea Route reduces the sailing distance between the Asia-Pacific region and Europe by 40%, while the Northwest Passage reduces sailing distance to the U.S. east coast by 23%. However, the weighted distance calculated in Countryman et al. (2016) applies to the total distance reductions for shipping to the United States, where distance is reduced only for the east coast while distances to the west coast remain the same. This fact causes the calculations for cost reductions associated with the volume of trade to be relatively small compared to total trade volume of the whole country. As a result, percentage changes in trade between Asia-Pacific countries and the United States are much lower than those estimated for Asia-Pacific countries and Europe.

The operation of the Northwest Passage may result in relatively low increases (6% to 9%) in total bilateral trade between the United States and China, Japan, and South Korea. On the other hand, trade between Asia-Pacific countries and European countries may increase considerably with the operation of the Northern Sea Route. Total imports by all European countries from the three Asia-Pacific countries may increase at particularly high rates. The large differences in percentage changes in trade between Asia-Pacific countries and Europe compared to those between Asia-Pacific countries and the United States result from differences in the relative reductions in sailing distances when using the Arctic routes.

Table 4 reports the percentage changes in 2030 imports in real terms by comparing the real increases in imports from trading partners ($S_{m,n}$ in equations 2 and 3). For example, the first row of Table 4 indicates that increased U.S. imports are mainly from China (62%), followed by Japan (24%) and South Korea (14%). These figures indicate that the increases in risk of terrestrial and marine NIS introduction to the United States originating from China may be as much as 2.5 times the potential increases in risk from Japan and 4.5 times the potential increases in risk from South Korea.

As noted in Table 3, although percentage changes in imports ($\Delta T_{m,n}$) by each Asia-Pacific country from the United States are relatively small compared to those from European countries, their real import levels ($\Delta T_{m,n}$) from the United States may increase considerably because of the higher baseline trade volumes (from Table 2). In fact, Table 4 shows that real imports from the United States by China, South Korea, and Japan would increase at the highest rates. Chinese imports from the United States would increase by a substantial amount that accounts

TABLE 2. Projected baseline import values (millions of U.S. dollars) for selected countries in 2030 if the Arctic sea routes are not in operation and traditional canal routes are used. Source: Countryman et al. (2016).

	Exporter				Importer		
Importer	China	South Korea	Japan	Exporter	China	South Korea	Japan
Poland	57565	11835	4520	Poland	17008	916	839
Portugal	12775	1051	1944	Portugal	4559	471	756
Spain	110073	11572	9830	Spain	39948	4733	4907
Belgium	78707	6462	12581	Belgium	24017	3816	5094
France	209792	9445	18063	France	40936	10978	12734
Denmark	32773	2790	5461	Denmark	7889	1814	3319
Netherlands	87648	4009	6777	Netherlands	13876	5692	4247
Germany	398449	35100	38300	Germany	115622	24632	25637
UK	268011	23648	30513	UK	38611	10870	18094
Norway	38872	8959	4628	Norway	9168	2107	2854
Sweden	57542	4591	4412	Sweden	14354	3051	3145
Finland	39562	2537	3737	Finland	15068	1876	2477
USA	582060	144812	137298	USA	791020	136606	237708

TABLE 3. Percentage changes in imports ($\Delta T_{m,n}$) in 2030 from the operation of the Northern Sea Route and the Northwest Passage. Increases in imports by countries in the rows (country *m*) from countries in the columns (country *n*). Source: Countryman et al. (2016).

Countries	USA	CHN	JPN	KOR	FIN	SWE	NOR	UK	DEU	NLD	DNK	FRA	BEL	ESP	PRT	POL
United States (USA)		6%	7%	7%												
China (CHN)	9%				23%	24%	26%	20%	25%	24%	26%	11%	22%	7%	6%	30%
Japan (JPN)	8%				33%	28%	38%	32%	39%	33%	32%	19%	29%	17%	14%	32%
South Korea (KOR)	7%				22%	26%	27%	24%	32%	26%	34%	12%	21%	10%	9%	24%
Finland (FIN)		21%	27%	14%												
Sweden (SWE)		21%	28%	18%												
Norway (NOR)		22%	28%	18%												
United Kingdom (UK)		15%	27%	16%												
Germany (DEU)		18%	29%	22%												
Netherlands (NLD)		15%	26%	22%												
Denmark (DNK)		21%	30%	12%												
France (FRA)		5%	15%	13%												
Belgium (BEL)		15%	23%	18%												
Spain (ESP)		2%	12%	8%												
Portugal (PRT)		3%	12%	5%												
Poland (POL)		21%	28%	20%												

for 44% of the total new imports expected with Arctic shipping, whereas increased U.S. imports to Japan and South Korea would account for 29% and 36% of total new imports, respectively. Imports into Asia-Pacific countries from Germany also account for large shares. For example, new imports from Germany would account for 23% of the expected change in total imports for China, 27% for Japan, and 29% for South Korea. Changes in European imports are dominated by increases from China, as nearly three-fourths of the projected new imports to each European country, when Arctic shipping is used, would be from China.

New trade resulting from Arctic shipping (Table 4) indicates that increased risk for terrestrial and marine NIS introduction to China, South Korea, and Japan is primarily from the United States, followed by Germany. Risk for NIS introduction into European countries from China is estimated to be as much as 2 to 9 times as high as the risk from Japan, and 3 to 21 times as high as the risk from South Korea. For some countries, such as Finland, the United Kingdom, Denmark, France, Belgium, and Portugal, the risk for NIS introduction from Japan is twice as high as the risk from South Korea.

Risk of Terrestrial and Marine NIS Establishment via Climate Matching

The potential for terrestrial and marine NIS to become established in a new environment is a function of the similarity of terrestrial and marine climates between trade partners. The climate similarity between regions is indicated by scores ranging from zero to ten. Table 5 shows the percentage of meteorological stations of the countries in the rows with climates that match those at stations of countries in the columns at climate similarity scores of eight or higher ($C_{m,n}$ in equations 1 and 3). High terrestrial climate matches have two key drivers: matches tend to be high if both regions are located within a similar range of northern latitudes and if the altitudes in each region closely resemble each other. The marine climate matching between regions depends mainly on the similarities of fresh water flows from rivers, evaporation, rainfall, and wind (NASA, 2013).

In general, Table 5 shows that marine climate matching is higher than terrestrial climate matching, which is true for two reasons. First, there are fewer marine stations than terrestrial stations. In all countries, the number of marine stations is 3%–60% of the number of terrestrial stations.

TABLE 4. Shares (%) of changes by 2030 in real imports to each country *m* (in the rows) from each relevant country *n* in the columns. $S_{m,n}$ in Equation 2 [$S_{m,n} = (\Delta t_{m,n}/\sum_{n \in N} \Delta t_{m,n}) \times 100$] is assumed to indicate the comparison of increased risks of NIS introduction to country *m* from each country *n* in 2030. Source: Countryman et al. (2016) and calculations by the authors.

Country *m*	USA	CHN	JPN	KOR	FIN	SWE	NOR	UK	DEU	NLD	DNK	FRA	BEL	ESP	PRT	POL
Country *n*																
United States (USA)		62%	24%	14%												
China (CHN)	44%				3%	3%	2%	6%	23%	3%	2%	4%	4%	2%	0%	4%
Japan (JPN)	29%				2%	2%	3%	16%	27%	4%	3%	7%	4%	2%	0%	1%
South Korea (KOR)	36%				2%	3%	2%	9%	29%	6%	2%	5%	3%	2%	0%	1%
Finland (FIN)		86%	10%	4%												
Sweden (SWE)		85%	9%	6%												
Norway (NOR)		75%	11%	14%												
United Kingdom (UK)		78%	15%	7%												
Germany (DEU)		79%	12%	9%												
Netherlands (NLD)		84%	10%	6%												
Denmark (DNK)		78%	18%	4%												
France (FRA)		71%	20%	9%												
Belgium (BEL)		74%	18%	8%												
Spain (ESP)		56%	25%	19%												
Portugal (PRT)		54%	38%	8%												
Poland (POL)		77%	8%	15%												

TABLE 5. Percent of meteorological stations in each region matching climates at scores of eight or higher ($C_{m,n}$ in equations 1 and 3) in 2030. The values in the rows represent the percentage of meteorological stations in that country that match climate (with scores of 8 or higher) with stations of countries in the columns. For the United States and China, only stations on the east coasts were selected to examine the climate matching.

a) Terrestrial climate matching:

Countries	USA	CHN	JPN	KOR	FIN	SWE	NOR	UK	DEU	NLD	DNK	FRA	BEL	ESP	PRT	POL
United States (USA)		43%	87%	10%												
China (CHN)	58%				0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
Japan (JPN)	61%				12%	24%	27%	10%	51%	7%	8%	32%	15%	26%	25%	39%
South Korea (KOR)	6%				0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
Finland (FIN)		0%	100%	0%												
Sweden (SWE)		0%	100%	0%												
Norway (NOR)		0%	87%	0%												
United Kingdom (UK)		0%	93%	0%												
Germany (DEU)		12%	100%	3%												
Netherlands (NLD)		0%	100%	0%												
Denmark (DNK)		0%	100%	0%												
France (FRA)		6%	90%	0%												
Belgium (BEL)		0%	100%	0%												
Spain (ESP)		4%	36%	0%												
Portugal (PRT)		0%	29%	0%												
Poland (POL)		4%	100%	0%												

b) Marine climate matching:

Countries	USA	CHN	JPN	KOR	FIN	SWE	NOR	UK	DEU	NLD	DNK	FRA	BEL	ESP	PRT	POL
United States (USA)		99%	89%	70%												
China (CHN)	100%				4%	10%	11%	7%	13%	13%	8%	76%	10%	90%	42%	4%
Japan (JPN)	100%				0%	11%	12%	13%	11%	13%	9%	89%	12%	79%	36%	0%
South Korea (KOR)	100%				0%	0%	0%	3%	3%	11%	0%	97%	27%	35%	22%	0%
Finland (FIN)		98%	0%	0%												
Sweden (SWE)		95%	22%	0%												
Norway (NOR)		45%	56%	0%												
United Kingdom (UK)		42%	60%	0%												
Germany (DEU)		93%	37%	2%												
Netherlands (NLD)		90%	34%	4%												
Denmark (DNK)		68%	22%	0%												
France (FRA)		79%	59%	41%												
Belgium (BEL)		99%	7%	5%												
Spain (ESP)		81%	75%	67%												
Portugal (PRT)		86%	83%	71%												
Poland (POL)		79%	0%	0%												

Second, while there are correlations between the group of air temperature and rainfall used to measure terrestrial climate, and the group of sea surface temperature and salinity used for marine matching (Barros and Silvestri, 2002; Aldrian and Dwi Susanto, 2003; Xie et al., 2010), only three variables are used in our climate matching exercise to measure sea surface temperature compared to eight air temperature variables used for terrestrial climate matching. Overall, our marine climate matching uses four variables, while terrestrial climate matching uses 16 variables. This difference leads to different standard deviations and Euclidean distances between any pair of variables (in equation 4) and subsequent differences for climate matching between marine and terrestrial environments (in equation 5).

It is worth noting that climate matching between any two countries is not symmetric. That is, the match for country *m* with country *n* is not necessarily the same as country *n*'s match with country *m*. The reason is that the number of stations in each region is different, and the minimum score found by scanning or looping all stations *j* in country *n* for a given station *i* in country *m* is different from the minimum score found if doing the calculation from another direction.

Regarding terrestrial climate matching (Table 5a), the U.S. east coast has 87% of stations matching those in Japan at climate similarity scores of eight or higher, while only 43% of U.S. east coast stations match Chinese east coast stations, and only 10% match South Korea stations at these scores. Stations on the Chinese east coast do not match European stations well, but 58% of Chinese east coast stations match those on the U.S. east coast at climate similarity scores of eight or higher. By contrast, Japan has relatively high climate similarities with all European countries (from 7% to 51%) and the U.S. east coast (61%). South Korea, on the other hand, has very low levels of climate matching with all European countries (from 0% to 1%) and the U.S. east coast (6%). All European countries essentially have no or low climate matching with coastal regions in China (from 0% to 12%) and South Korea (from 0% to 3%), but have very high levels of climate matching with stations in Japan (from 36% to 100%).

Results for terrestrial climate matching indicate that the risk of terrestrial NIS establishment varies between countries. Species from Japan may establish in the U.S. east coast region with relative ease, while species from South Korea have little chance. Similarly, species from the U.S. east coast may establish relatively well in China and Japan, but they are unlikely to become acclimated in South Korea. Species from European countries may not be able to acclimate in Japan, but species from Japan may be able to establish in the European environment. By contrast, species from European countries may be unable to establish in the Chinese east coast and South Korea, and species from these two regions are also unlikely to establish in the European environment because they lack climate similarity.

Marine climate matches between countries are very different from terrestrial matches in many cases (Table 5b).

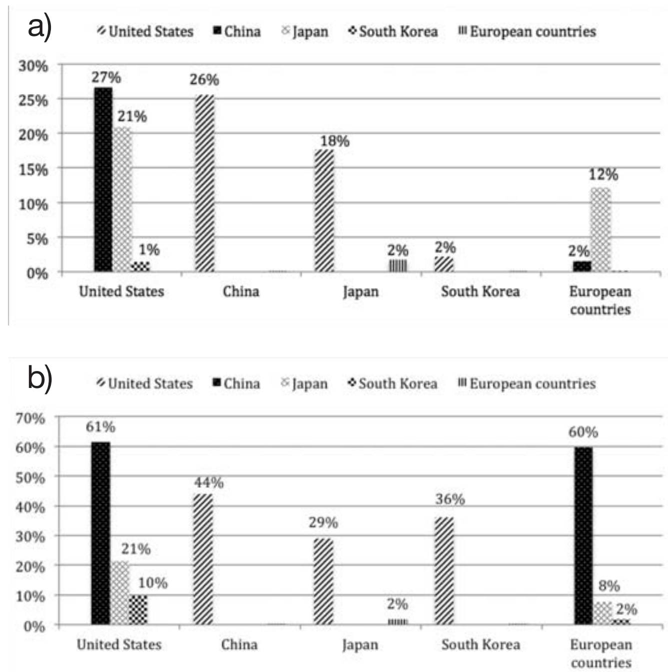

FIG. 2. Comparison of percentage changes ($r_{m,n}$ in equation 3) in relative risk of terrestrial and marine NIS spread from source countries (top of chart) to destination countries (bottom of chart). (a) Risk of terrestrial NIS spread; (b) Risk of marine NIS spread.

Mutual marine climate matchings between the U.S. east coast and China, Japan, and South Korea are extremely high (almost 90% of stations matching with a score of 8 or higher). China and Japan also highly match marine climates in France and Spain (between 75% and 90% matching at a score of 8 or higher). Similarly, most European countries match marine climates with China at high rates, while a subset of Europe matches marine climates with Japan at high rates. South Korea, on the other hand, presents low levels of marine climate matching with most of Europe, and vice versa. This result indicates that marine species are likely to establish in the new environment if they are shipped between the U.S. and China, Japan, and South Korea. Marine species sourced from Europe may acclimate easily in China, but not in Japan or South Korea. However, marine species originating in China and Japan may be established with ease only in France and Spain.

Risk of Terrestrial and Marine NIS Spread

Figure 2 provides the comparison of changes in risk of terrestrial and marine NIS spread to each country from trading partners ($r_{m,n}$ in equation 3). China poses the highest risk of terrestrial NIS spread to the U.S. east coast (27%), followed by Japan (21%), if the Arctic shipping routes become operational (Fig. 2a). The risk from China is relatively high, despite relatively low terrestrial climate similarity, because Arctic shipping is expected to substantially increase U.S. imports from China. The risk of terrestrial NIS spread to the U.S. from South Korea is unlikely to change because Arctic shipping is expected to

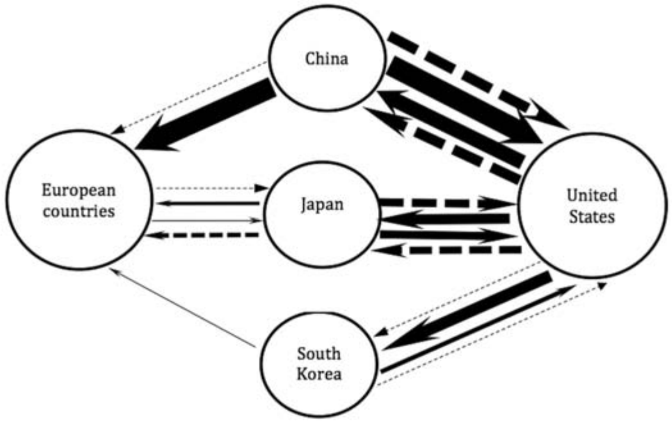

FIG. 3. Diagram of potential spread between countries of terrestrial NIS (solid arrows) and marine NIS (dashed arrows). Thicker arrows indicate greater increases in risk of NIS spread.

have relatively lower impacts on trade, and the U.S. east coast has relatively low levels of terrestrial climate matching with South Korea.

Figure 2a also shows that China is exposed to increased risk of terrestrial NIS spread only from the United States (26%) because its terrestrial climate does not match that of European countries, and Arctic routes are not expected to affect trade between China, South Korea, and Japan. Japan is exposed to risk for spread of terrestrial species primarily from the United States, because of large expected changes in trade and high climate matches, whereas the increase in risk of NIS spread from Europe to Japan is relatively small. Risks for terrestrial NIS spread to South Korea are relatively low overall, as South Korea has low levels of terrestrial climate matching with other regions and low expected changes in trade. The main source of increased terrestrial NIS spread risk to European countries is from Japan (12%), given high terrestrial climate matching, followed by China (2%). There is no change in risk of terrestrial NIS spread from South Korea to European countries because of low levels of terrestrial climate matching.

The change in risk of marine NIS spread to the United States is dominated by China (61%), followed by Japan (21%) and South Korea (10%) (Fig. 2b). This pattern results from a higher increase in U.S. import volumes expected from China compared to Japan and South Korea when Arctic shipping routes are used. Similarly, the United States poses the greatest potential threat of marine NIS spread to China (44%), Japan (29%), and South Korea (36%), because of large expected changes in trade and high climate matches, while marine spread risk from European countries is negligible.

Risk of marine NIS spread to European countries is highest from China (60%), while Japan accounts for only 8% and South Korea only 2% of the expected change in marine NIS spread risk to European countries. This result is explained by the higher level of marine climate similarities between European countries and China compared to similarities with Japan and South Korea and by the expectation that Chinese imports to Europe will increase more than Japanese and South Korean imports. Figure 3 is another visual representation of the results in Figure 2 and outlines the changes in risk of terrestrial and marine NIS spread. As illustrated, China and the U.S. mutually expose each other to relatively high risks of both terrestrial and marine NIS spread compared to the mutual relationships between other trade partners. However, our findings may underestimate the total risk for NIS spread, as we rely greatly on climate matching levels. When two regions have dissimilar climates, we conclude that the risk of establishment is relatively low, but many established NIS are generalist species that are able to thrive in a wide range of climate conditions (Clavel et al., 2011).

This study employs a new method to determine and compare the changes in risk of terrestrial and marine NIS spread, in contrast to previous risk analyses that considered specific transport vectors between ports (Sylvester and MacIsaac, 2010; Seebens et al., 2013; Xu et al., 2014). Rather than focus on specific vectors, we aggregated import vectors by using trade flows to estimate the overall changes in risks of terrestrial and marine NIS introduction between countries. However, our trade-based risk assessment of terrestrial and marine NIS introductions may present several limitations. For example, the method assumes that risks derived from all commodities are equal. This may or may not be the case, as some commodities are sources of higher risks of terrestrial NIS introduction than others. For example, agricultural commodities may contain many terrestrial NIS compared to non-agricultural goods. Nevertheless, focusing on economic drivers, as we have done here, allows us to get closer to the true source of risk than approaches that focus only on ships. We also ignore spatial variability within countries. Specific risks to each port cannot be identified in this study, as trade data are available only at country levels. In future work, we will link changes in trade to the associated ship types and movements specific to different product classifications. Finally, future work should consider shorter voyage durations and adverse weather conditions during Arctic Ocean voyages, as both factors may affect survival rates of species. Despite limitations, this work is an important contribution to the literature and treats a topic area that warrants continued research.

CONCLUSION

This paper compares the potential changes in relative risk of terrestrial and marine NIS spread to a country from relevant trading partners due to the operation of the Northern Sea Route and Northwest Passage in the near future. Before comparing the changes in risk of terrestrial and marine NIS spread, we evaluate the factors that jointly determine NIS spread risk: changes in risk of NIS introduction, which is tied to import vectors, and the risk of terrestrial and marine NIS establishment, which is determined by the levels of terrestrial and marine climate matching. Results indicate that the United States, China, and Japan are mutually exposed to high risks of terrestrial and marine NIS spread from each other. China is a potential source of high marine NIS spread risk to European countries, but is not a threat for terrestrial species. Japan is a relatively important source for terrestrial and marine NIS spread to Europe. South Korea poses negligible to low terrestrial and marine NIS spread risk to the United States and Europe.

These findings have several important policy implications. First, relatively high terrestrial and marine climate matching between the U.S. east coast, European countries, China, and Japan should be taken into account when considering trade policies between these regions because of their high potential for terrestrial and marine NIS establishment. Second, U.S. and European monitoring and policy efforts may be best focused on commodities and ships traveling from China and Japan, and mitigation strategies should target Chinese and Japanese species. Similarly, China, Japan, and South Korea should focus on potential risk from commodities, ships, and species arriving from the United States and Germany. Europe may also need to pay more attention to Chinese marine species, as they will pose the largest risk of spread to the European region if the Arctic routes become operational.

ACKNOWLEDGEMENT

The authors would like to acknowledge the research funding from the National Science Foundation, award number 142 7157.

APPENDIX 1

The following table and figures are available in a supplementary file to the online version of this article at: http://arcticjournalhosting.ucalgary.ca/arctic/index.php/arctic/rt/suppFiles/4732/0

TABLE S1.The number of stations in the former region matching climates in 2030 with the stations in the latter region at each grade/score level.

FIG. S1. Terrestrial climate matching between regions in 2030.

FIG. S2. Marine climate matching between regions in 2030.

REFERENCES

Aldrian, E., and Dwi Susanto, R. 2003. Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. International Journal of Climatology 23(12):1435–1452.
https://doi.org/10.1002/joc.950

Arctic Council. 2009. Arctic marine shipping assessment 2009 report. Oslo: Arctic Council.
https://www.pmel.noaa.gov/arctic-zone/detect/documents/AMSA_2009_Report_2nd_print.pdf

Bacon, S.J., Aebi, A., Calanca, P., and Bacher, S. 2014. Quarantine arthropod invasions in Europe: The role of climate, hosts and propagule pressure. Diversity and Distributions 20(1):84–94.
https://doi.org/10.1111/ddi.12149

Barros, V.R., and Silvestri, G.E. 2002. The relation between sea surface temperature at the subtropical south-central Pacific and precipitation in southeastern South America. Journal of Climate 15(3):251–267.
https://doi.org/10.1175/1520-0442(2002)015<0251:TRBSST>2.0.CO;2

Bekkers, E., Francois, J.F., and Rojas-Romagosa, H. 2016. Melting ice caps and the economic impact of opening the Northern Sea Route. The Economic Journal 128(610):1095–1127.
https://doi.org/10.1111/ecoj.12460

Blackburn, T.M., Essl, F., Evans, T., Hulme, P.E., Jeschke, J.M., Kühn, I., Kumschick, S., et al. 2014. A unified classification of alien species based on the magnitude of their environmental impacts. PLoS Biology 12(5): e1001850.
https://doi.org/10.1371/journal.pbio.1001850

Bomford, M., Kraus, F., Barry, S.C., and Lawrence, E. 2009. Predicting establishment success for alien reptiles and amphibians: A role for climate matching. Biological Invasions 11(3):713–724.
https://doi.org/10.1007/s10530-008-9285-3

Borgerson, S.G. 2008. Arctic meltdown: The economic and security implications of global warming. Foreign Affairs 87(2):63–77.
http://www.jstor.org/stable/20032581

Britton, J.R., Cucherousset, J., Davies, G.D., Godard, M.J., and Copp, G.H. 2010. Non-native fishes and climate change: Predicting species responses to warming temperatures in a temperate region. Freshwater Biology 55(5):1130–1141.
https://doi.org/10.1111/j.1365-2427.2010.02396.x

Chapman, D., Purse, B.V., Roy, H.E., and Bullock, J.M. 2017. Global trade networks determine the distribution of invasive non-native species. Global Ecology and Biogreography 26(8):907–917.
https://doi.org.10.1111/geb.12599

Clavel, J., Julliard, R., and Devictor, V. 2011. Worldwide decline of specialist species: Toward a global functional homogenization? Frontiers in Ecology and the Environment 9(4):222–228.
https://doi.org/10.1890/080216

Comiso, J.C. 2012. Large decadal decline of the Arctic multiyear ice cover. Journal of Climate 25(4):1176–1193.
https://doi.org/10.1175/JCLI-D-11-00113.1

Cook, D.C., and Fraser, R.W. 2008. Trade and invasive species risk mitigation: Reconciling WTO compliance with maximising the gains from trade. Food Policy 33(2):176–184.
https://doi.org/10.1016/j.foodpol.2007.07.001

Countryman, A.M., Francois, J.F., and Rojas-Romagosa, H. 2016. Melting ice caps: Implications for Asian trade with North America and Europe. International Journal of Trade and Global Markets 9(4):325–369.
https://doi.org/10.1504/IJTGM.2016.081148

Crombie, J., Brown, L., Lizzio, J., and Hood, G. 2008. Climatch user manual. Canberra, ACT: Australian Government Bureau of Rural Sciences.

Dennis, A. 2006. The impact of regional trade agreements and trade facilitation in the Middle East and North Africa region (February 1, 2001). World Bank Policy Research Working Paper No. 3837.
https://ssrn.com/abstract=922963

Drake, J.M., and Lodge, D.M. 2007. Hull fouling is a risk factor for intercontinental species exchange in aquatic ecosystems. Aquatic Invasions 2(2):121–131.
https://doi.org/10.3391/ai.2007.2.2.7

Eguíluz, V.M., Fernández-Gracia, J., Irigoien, X., and Duarte, C.M. 2016. A quantitative assessment of Arctic shipping in 2010–2014. Scientific Reports 6: 30682.
https://doi.org/10.1038/srep30682

Faury, O., and Cariou, P. 2016. The Northern Sea Route competitiveness for oil tankers. Transportation Research Part A: Policy and Practice 94:461–469.
https://doi.org/10.1016/j.tra.2016.09.026

Hertel, T., ed. 1997. Global trade analysis: Modeling and applications. Cambridge: Cambridge University Press.

———. 2013. Global applied general equilibrium analysis using the Global Trade Analysis Project framework. Handbook of Computable General Equilibrium Modeling 1:815–876.
https://doi.org/10.1016/B978-0-444-59568-3.00012-2

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., and Jarvis, A. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25(15):1965–1978.
https://doi.org/10.1002/joc.1276

Hong, N. 2012. The melting Arctic and its impact on China's maritime transport. Research in Transportation Economics 35(1):50–57.
https://doi.org/10.1016/j.retrec.2011.11.003

Horan, R.D., and Lupi, F. 2005. Tradeable risk permits to prevent future introductions of invasive alien species into the Great Lakes. Ecological Economics 52(3):289–304.
https://doi.org/10.1016/j.ecolecon.2004.06.018

Howeth, J.G., Gantz, C.A., Angermeier, P.L., Frimpong, E.A., Hoff, M.H., Keller, R.P., Mandrak, N.E., et al. 2016. Predicting invasiveness of species in trade: Climate match, trophic guild and fecundity influence establishment and impact of non-native freshwater fishes. Diversity and Distributions 22(2):148–160.
https://doi.org/10.1111/ddi.12391

Jervis, R. 2016. The $5.4 billion HOV lane: Will Panama Canal expansion boost global trade? *USA Today*, June 25.
http://www.usatoday.com/story/news/2016/06/23/panama-canal-expansion-slump/86279016/

Kalous, L., Patoka, J., and Kopecký, O. 2015. European hub for invaders: Risk assessment of freshwater aquarium fishes exported from the Czech Republic. Acta Ichthyologica et Piscatoria 45(3):239–245.
https://search.proquest.com/docview/1728665596?accountid=28147

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

Kerr, R.A. 2012. Experts agree global warming is melting the world rapidly. Science 338(6111):1138.
https://doi.org/10.1126/science.338.6111.1138

Kopecký, O., Kalous, L., and Patoka, J. 2013. Establishment risk from pet-trade freshwater turtles in the European Union. Knowledge and Management of Aquatic Ecosystems 410(02).
https://doi.org/10.1051/kmae/2013057

Liu, M., and Kronbak, J. 2010. The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. Journal of Transport Geography 18(3):434–444.
https://doi.org/10.1016/j.jtrangeo.2009.08.004

Lodge, D.M., Williams, S., MacIsaac, H.J., Hayes, K.R., Leung, B., Reichard, S., Mack, R.N., et al. 2006. Biological invasions: Recommendations for U.S. policy and management. Ecological Applications 16(6):2035–2054.
https://doi.org/10.1890/1051-0761(2006)016[2035:BIRFUP]2.0.CO;2

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.-F., Matsumoto, K., et al. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109(1-2):213–241.
https://doi.org/10.1007/s10584-011-0156-z

Miller, A.W., and Ruiz, G.M. 2014. Arctic shipping and marine invaders. Nature Climate Change 4(6):413–416.
https://doi.org/10.1038/nclimate2244

Molnar, J.L., Gamboa, R.L., Revenga, C., and Spalding, M.D. 2008. Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment 6(9):485–492.
https://doi.org/10.1890/070064

NASA (National Aeronautics and Space Administration). 2013. Salinity.
https://science.nasa.gov/earth-science/oceanography/physical-ocean/salinity

Naylor, R.L., Williams, S.L., and Strong, D.R. 2001. Aquaculture––A gateway for exotic species. Science 294(5547):1655–1656.
https://doi.org/10.1126/science.1064875

Olson, L.J. 2006. The economics of terrestrial invasive species: A review of the literature. Agricultural and Resource Economics Review 35(1):178–194.
https://doi.org/10.1017/S1068280500010145

Perrings, C., Burgiel, S., Lonsdale, M., Mooney, H., and Williamson, M. 2010. International cooperation in the solution to trade-related invasive species risks. Annals of the New York Academy of Sciences 1195(1):198 – 212.
https://doi.org/10.1111/j.1749-6632.2010.05453.x

Pimentel, D., Lach, L., Zuniga, R., and Morrison, D. 2014. Environmental and economic costs associated with non-indigenous species in the United States. In: Pimentel, D., ed. Biological invasions: Economic and environmental costs of alien plant, animal, and microbe species. Boca Raton, Florida: CRC Press. 285 – 303.

R Core Team. 2014. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.
http://www.R-project.org/

Schøyen, H., and Bråthen, S. 2011. The Northern Sea Route versus the Suez Canal: Cases from bulk shipping. Journal of Transport Geography 19(4):977 – 983.
https://doi.org/10.1016/j.jtrangeo.2011.03.003

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

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

Stroeve, J.C., Serreze, M.C., Holland, M.M., Kay, J.E., Malanik, J., and Barrett, A.P. 2012. The Arctic's rapidly shrinking sea ice cover: A research synthesis. Climatic Change 110(3-4):1005 – 1027.
https://doi.org/10.1007/s10584-011-0101-1

Sylvester, F., and MacIsaac, H.J. 2010. Is vessel hull fouling an invasion threat to the Great Lakes? Diversity and Distributions 16(1):132 – 143.
https://doi.org/10.1111/j.1472-4642.2009.00622.x

Wang, M., and Overland, J.E. 2012. A sea ice free summer Arctic within 30 years: An update from CMIP5 models. Geophysical Research Letters 39(18), L18501.
https://doi.org/10.1029/2012GL052868

Ware, C., Berge, J., Sundet, J.H., Kirkpatrick, J.B., Coutts, A.D.M., Jelmert, A., Olsen S.M., Floeri, O., Wisz, M.S., and Alsos, I.G. 2014. Climate change, non-indigenous species and shipping: Assessing the risk of species introduction to a high-Arctic archipelago. Diversity and Distributions 20(1):10 – 19.
https://doi.org/10.1111/ddi.12117

Work, T.T., McCullough, D.G., Cavey, J.F., and Komsa, R. 2005. Arrival rate of nonindigenous insect species into the United States through foreign trade. Biological Invasions 7(2):323 – 332.
https://doi.org/10.1007/s10530-004-1663-x

World Climate. 2008. Future climate data: WorldClim 1.4 downscaled (CMIP5) data.
http://www.worldclim.org/CMIP5v1

Xie, S.-P., Deser, C., Vecchi, G.A., Ma, J., Teng, H., and Wittenberg, A.T. 2010. Global warming pattern formation: Sea surface temperature and rainfall. Journal of Climate 23(4):966 – 986.
https://doi.org/10.1175/2009JCLI3329.1

Xu, J., Wickramarathne, T.L., Chawla, N.V., Grey, E.K., Steinhaeuser, K., Keller, R.P., Drake, J.M., and Lodge, D.M. 2014. Improving management of aquatic invasions by integrating shipping network, ecological, and environmental data: Data mining for social good. In: Proceedings of the 20th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, 24 – 27 August 2014, New York. 1699 – 1708.
https://doi.org/10.1145/2623330.2623364